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IEA DHC | CHP

International Energy Agency
IEA Implementing Agreement on District Heating and Cooling,
including the integration of CHP

Cost benefits and long term behaviour of a new all plastic piping system

IEA Implementing Agreement

on

District Heating and Cooling, including the integration of CHP

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Preface

Introduction

The International Energy Agency (IEA) was established in 1974 in order to strengthen the co-operation between member countries and reduce the dependency on oil and other fossil fuels. Thirty years later, the IEA again drew attention to serious concerns about energy security, investment, the environment and energy poverty. The global situation is resulting in soaring oil and gas prices, the increasing vulnerability of energy supply routes and ever-increasing emissions of climate-destabilising carbon dioxide.

At the 2005 Gleneagles G8 an important role was given to the IEA in advising on alternative energy scenarios and strategies aimed at a clean, clever and competitive energy future. Two years later, at the Heiligendamm G8, it was agreed that “instruments and measures will be adopted to significantly increase the share of combined heat and power (CHP) in the generation of electricity”. District Heating and Cooling is an integral part of the successful growth of CHP: heat networks distribute what would otherwise be waste heat to serve local communities.

The IEA is active in promoting and developing knowledge of District Heating and Cooling: while the DHC programme (below) itself is the major global R&D programme, the IEA Secretariat has also initiated the International DHC/CHP Collaborative, the kick-off event of which took place in March 2, 2007 with a 2-year Work Plan aiming to raise the profile of DHC/CHP among policymakers and industry. More information on the Collaborative is to be found on IEA’s website www.IEA-org.

The major international R&D programme for DHC/CHP

DHC is an integrative technology that can make significant contributions to reducing emissions of carbon dioxide and air pollution and to increasing energy security.

The fundamental idea of DHC is simple but powerful: connect multiple thermal energy users through a piping network to environmentally optimum energy sources, such as combined heat and power (CHP), industrial waste heat and renewable energy sources such as biomass, geothermal and natural sources of heating and cooling.

The ability to assemble and connect thermal loads enables these environmentally optimum sources to be used in a cost-effective way, and also offers ongoing fuel flexibility. By integrating district cooling, carbon-intensive electrically-based air-conditioning, rapidly growing in many countries, can be displaced.

As one of the IEA’s ’Implementing Agreements’, the District Heating & Cooling programme is the major international research programme for this technology. Active now for more than 25 years, the full name of this Implementing Agreement is ‘District Heating and Cooling including the integration of Combined Heat and Power’. Participant countries undertake co-operative actions in energy research, development and demonstration.

Annex VIII

In May 2005 Annex VIII started, with the participation from Canada, Denmark, Finland, the Netherlands, Norway, South Korea, Sweden, United Kingdom, United States of America.

Below you will find the Annex VIII research projects undertaken by the Implementing Agreement “District Heating & Cooling including the Integration of Combined Heat and Power”.

Project title	Company	
New Materials and Constructions for Improving the Quality and Lifetime of District Heating Pipes including Joints – Thermal, Mechanical and Environmental Performance	Chalmers University of Technology Project leader: Ulf Jarfelt	8DHC-08-01
Improved Cogeneration and Heat Utilization in DH Networks	Helsinki University of Technology Project leader: Carl-Johan Fogelholm	8DHC-08-02
District Heating Distribution in Areas with Low Heat Demand Density	ZW Energiteknik Project leader: Heimo Zinko	8DHC-08-03
Assessing the Actual Energy Efficiency of Building Scale Cooling Systems	International District Energy Association Project leader: Robert P. Thornton	8DHC-08-04
Cost Benefits and Long Term Behaviour of a new all Plastic Piping System	Nuon Project leader: Hans Korsman	8DHC-08-05

Benefits of membership

Membership of this implementing agreement fosters sharing of knowledge and current best practice from many countries including those where:

DHC is already a mature industry

DHC is well established but refurbishment is a key issue

DHC is not well established

Membership proves invaluable in enhancing the quality of support given under national programmes. Participant countries benefit through the active participation in the programme of their own consultants and research organisations. Each of the projects is supported by a team of experts, one from each participant country. As well as the final research reports, other benefits include sharing knowledge and ideas and opportunities for further collaboration.

New member countries are very welcome - please simply contact us (see below) to discuss.

Information

General information about the IEA Programme District Heating and Cooling, including the integration of CHP can be obtained from our website www.iea-dhc.org or from:

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The IA DHC/CHP, Annex VIII, also known as the Implementing Agreement District Heating and Cooling, including the Integration of Combined Heat and Power, functions within a framework created by the International Energy Agency (IEA). Views, findings, and publications of the IA DHC/CHP do not necessarily represent the views or policies of all its individual member countries nor of the IEA Secretariat.

List of Abbreviations

Symbol/Abbreviation	Description	Dimension
DH	District heating	[-]
DAA	Define Application Area	[-]
DN	Diameter Nominal	[-]
ECTS	European Credit Transfer System	[-]
EN	European Norm	[-]
EVOH	Ethylene vinyl alcohol - copolymer	[-]
FFI	Fernwärme-Forschungsinstitut	[-]
FWI	Förderverein für Wirtschaftsinformatik e. V.	[-]
HDPE	High density Polyethylene	[-]
IEA	International Energy Association	[-]
Inv. A	Inventory Analysis	[-]
ISO	International Standards Organisation	[-]
LCA	Life Cycle Assessment	[-]
LCEA	Life Cycle Energy Analysis	[-]
LCIA	Life Cycle Inventory Analysis	[-]
LDPE	Low Density Polyethylene	[-]
PB	Polybuthylene	[-]
PB/PE/PE	Complete plastic piping system	[-]
PE	Polyethylene	[-]
PEX	Cross linked polyethylene	[-]
PU	Polybuthylene	[-]
ST 37	Steel 37	[-]
ST/PU/PE	Complete Steel Piping system	[-]
yrs	Years	[years]
f	Heat loss of pre-insulated pipe	[W/m]
h	Distance between ground surface and pipe centre	[m]
l	Lambda	[W/mk]
l c	Thermal conductivity casing	[W/m·K]
l i	Thermal conductivity insulation foam	[W/m·K]
l j	Thermal conductivity ground	[W/m·K]
l m	Thermal conductivity medium pipe	[W/m·K]
r 1	Inner diameter medium pipe	[m]
r 2	Outer diameter medium pipe	[m]
r 3	Inner diameter insolating foam	[m]
r 4	Inner diameter casing	[m]
r 5	Outer diameter casing	[m]
r max	Maximum outer diameter	[m]
T0	Temperature ground surface	[°C]
T1	Temperature medium pipe	[°C]
e.g.	For example	[-]
n/a	Not Applicable	[-]
%	Percentage	[%]
°C	Degree Celsius	[°C]

Executive Summary

The predominant piping system in the District Heating (DH) industry over the last century consists of a steel medium pipe, polyurethane (PU) insulation and a polyethylene (PE) outer casing (abbreviated to St/PU/PE). This system performs very well. However, steel may rust and the insulation properties of PU may suffer under the influence of water. Therefore, joints have to be made with care and require a certain level of workmanship.

From this perspective, an all plastic piping system might have some distinctive advantages. Plastics do not corrode (that is, a lot slower than steel). Some plastics are extremely flexible and allow for transportation on reels for rather large diameters, thus reducing the number of joints. Some plastics may even be welded.

This report focuses on an all plastic piping system, with polybutylene medium pipe, PE foam insulation and an outer casing made of PE (abbreviated to PB/PE/PE systems). Because this is a new piping system, different aspects of the application of this system compared to conventional piping systems are investigated.

Life cycle analysis of the different piping systems shows the impact of several life cycle stages on the environment. One clear conclusion is the dominance of heat loss on the environmental impact. The contribution of heat loss can be subtracted from the long utilization period of district heating systems. The life time of a pre-insulated pipe, which is about fifty years, is very long. Increasing the utilization period of the district heating system only enlarges the contribution of heat loss on the environmental impact.

Enhancing the products performance (e.g. increasing insulation thickness) leads to a lower environmental impact. Increasing insulation thickness can not be done endlessly because there is an optimum between insulation thickness extension (decreasing heat loss) and surface extension (increasing heat loss). For economic reasons the optimum for increasing insulation thickness may be around ten percent of the actual insulation thickness. The production phase will consequently rise in impact contribution, but since the effect of production on the total impact is less than one percent, this increase is acceptable from an energetically point of view.

For both high and low density district networks, costs for materials and installation of the PB/PE/PE system are comparable to conventional St/PU/PE networks. The use of twin pipes only decreases the investment costs due to smaller trenches and lower network lengths. Also, twin pipes (in theory) have lower heat loss which leads to lower costs over its lifetime.

Costs for piping length is the most determining factor in total costs for plastic pipe networks. This is mainly because of high prices per metre due to the stage of development for the PB/PE/PE system. These prices are expected to decrease as the system develops into a final product, causing total investment costs for plastic pipe systems to decrease also.

Installation costs for the plastic pipe system are uncertain, because experience with the system is still very limited. Costs for installation of the PB/PE/PE system therefore can be seen as a maximum, that will decrease as contractors become more experienced with the system.

Three studies are described on the long term behaviour of the new all plastic piping system. The first study concerns an assessment of the thermal insulation by polyethylene foam. The second study describes the risks for corrosion due to oxygen diffusion through plastic piping systems for the total system, heat exchangers, radiators and couplings. The third study presents the quantification of the change in the thermal insulation of the PE foam as a function of the exchange of gas or vapour between foam cells and the environment.

The fraction of open cells was determined experimentally. The final result of these experiments is that the fraction of open cells is not exceeding 6 ± 3 %. The temperature gradient, heat loss and the water flux were calculated for several situations.

The main conclusion of this study by TNO Science and Industry is that insulation properties of PE foam deteriorate significantly when wet, even though the material itself seems to remain intact, whereas PU may degrade. So in order to reach optimum performance, the system needs to be dry.

A major threat to heating systems is the diffusion of oxygen through plastic materials. As a consequence there is a risk for corrosion in the steel and copper components of the total system, e.g. heat exchangers, radiators and couplings. To overcome the diffusion of oxygen through the PB medium pipe, the PB/PE/PE system is supplied with an EVOH coating. This is a diffusion barrier that reduces the ingress of oxygen. Nevertheless there is still a certain amount of diffusion of oxygen, even with the EVOH barrier.

The wall thickness decrease over time of steel components is acceptable in case of an equally distributed corrosion attack, but oxygen may initiate localised corrosion, for instance pitting corrosion. At the joints of the PB tubes with the carbon steel tubes the oxygen levels are at the max and this oxygen will react instantaneously with the carbon steel. The corrosion also takes place at locations with a thin protective layer and with conditions that foster corrosion. The risk of severe localised corrosion (pitting) in the carbon steel parts under the mentioned conditions is not quantitatively predictable. But if pitting occurs, it is an out of control process and corrosion rates of mm/year are possible.

A key issue is to maintain an optimal water quality and prevent ingress of air and salts because the occurrence of pitting corrosion is strongly promoted by the presence of salts, especially chlorine.

Calculations to quantify the ageing of foam insulated pipes for district heating are performed by TNO Science and Industry. The foams studied are PE (polyethylene) foam in the PB/PE/PE system and rigid PU (polyurethane) foam in the steel pipe system.

The initial value for the heat conductivity of the PU foam in the St/PU/PE system is similar to the PE foam of the PB/PE/PE system. The characteristic ageing time is longer for the steel pipe system as a result of the larger medium pipe and casing thickness, which forms a larger barrier for oxygen and nitrogen.

It is expected that the ageing rate of PE and PU foam will be almost identical if both foams are insulated by the same plastic casing. The permeation behaviour of the casing and medium pipe for blowing agent, oxygen and nitrogen is decisive for the ageing rate.

With the study on ageing of the insulation foams and heat loss formulae, the heat loss of both plastic and steel systems are determined and compared. Also measurements are performed to provide an experimental foundation.

The current PB/PE/PE system contains an air gap between the medium pipe and insulation foam, causing higher heat loss results than theoretically predicted. An effective insulation thickness is therefore calculated, resulting in an effectiveness of the insulation foam of 84% with regard to the expected insulation performance.

The geometry of the plastic PB/PE/PE piping system could be optimised by closing the gap between service pipe and insulation foam. Further, heat loss could be decreased by increasing insulation of the piping system. A larger outer casing for each diameter for PB/PE/PE would result in lower lifetime heat loss than St/PU/PE systems series 1 and comparable heat loss to series 2.

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Chapter 1: Introduction

1.1 Background

District heating has a relatively large potential of reducing carbon dioxide emissions compared to alternative methods of building heating. With the growing emphasis of environmental policies on energy saving, sustainability and emission reduction, district heating becomes more interesting both energetically and economically.

The predominant piping system in DH networks in the last few decades are pre-insulated steel piping systems. In some DH projects also copper piping systems are used for distributing hot water. Although this system performs rather well, steel may rust and the insulation properties of PU may suffer under the influence of water. Therefore, joints have to be made with care and require a certain level of workmanship.

From this perspective, an all plastic piping system might have some distinctive advantages. Plastics do not corrode (that is, a lot slower than steel). Some plastics are extremely flexible and allow for transportation on reels for rather large diameters, thus reducing the number of joints. Some plastics may even be welded.

This report focuses on an all plastic piping system, with polybutylene medium pipe, PE foam insulation and an outer casing made of PE (PB/PE/PE). The polybutylene material allows joints to be welded, resulting in a strong connection and fast installation.

The polybutylene pipe can withstand temperatures up to 95 ºC. The PB/PE/PE system is a potentially interesting alternative; nevertheless some aspects must be assessed before implementing the system on a large scale.

1.2 Research goal

The goal in this research is to determine the consequences of using the new polybutylene piping system as an alternative system in district heating networks.

For this goal, the new all plastic piping system is compared to the conventional piping systems for DH. The environmental performance of both systems is determined through a life cycle assessment For an economical comparison between the systems a cost-benefit analysis is made for different distribution network configurations. Eventually, the plastic piping system may be optimised if necessary in regard to pipe geometry or network configuration.

1.3 System boundaries

In the analyses some boundaries are necessary due to the lack of experience and knowledge of the new plastic piping system. In the comparative analysis between the new and conventional piping systems, PB/PE/PE is the considered as the new plastic system and steel piping systems being taken as the conventional system. Generally the series 1 steel piping systems of common piping manufacturers are considered (e.g. Alstom or Isoplus).

As plastic piping systems are generally restricted in regard to temperature and pressure, these systems only have a diameter range up to 110 mm medium pipe thickness. The emphasis therefore lies on DH piping systems applied in local, residential networks with temperatures normally up to 90 ºC and a pressure of 6 bar.

For the heat loss analysis in chapter 6, also series 2 and other plastic systems are compared to the PB/PE/PE system. Occasionally, copper piping systems for the central distribution of hot tap water are applied. These systems are analysed only in the chapter on cost benefits.

1.4 Chapters

Chapter 2 describes the concept of district heating as generally applied in the Netherlands and gives an introduction to the piping systems that will be analysed in this research.

In chapter 3 a comparative life cycle analysis is presented between the new all plastic piping system and the conventional used steel piping system.

Chapter 4 gives a financial cost-benefit analysis between plastic piping network configurations and conventional piping networks. On the basis of standard district heating layout several engineering configurations are presented with their economic consequences.

In chapter 5 several studies with regard to long term behaviour of the plastic piping system during usage are described. Subjects are the insulation capacity of the system, ageing in the long term and the risk of corrosion to customer heating systems.

Chapter 6 is devoted to the heat loss of piping systems. Again the comparison is made between plastic and conventional systems. Theoretical calculations as well as heat loss measurements aim to prove which system performs best.

Finally, in chapter 7 suggestions are introduced to optimise the plastic piping system with regard to geometry and total network system.

1.5 Acknowledgements

This research is part of the IEA District Heating & Cooling Implementing Agreement Annex VIII from 2005 – 2008. During this period the work was guided and provided with experience by an Expert Group composed of members of participating countries. We would like to acknowledge the contribution of these members for their experience and know-how regarding this research. The Expert Group consisted of:

Canada: Chris Snoek – CANMET Energy Technology Centre

Denmark: Chr. Ting Larsen – Løgstør A/S

Finland: Veli-Pekka Sirola – Finnish Energy Industries

Germany: Wilhelm Busse – Stadtwerke Lemgo GmbH

Korea: Shinyoung Im – Korea District Heating Corp.

Norway: Jacob Stang – SINTEF Energy Research and
Rolf Ulseth – Norwegian University of Science and Technology

Sweden: Ture Nordenswan – Swedish District Heating Association

United Kingdom: Jonathan Williams – BRE Watford

Also special thanks to Jan Breen (TNO Science and Industry), Marga van Deelen-Bremer (KEMA Nederland BV) and Thermaflex BV for their contribution to this report.

Chapter 2: Plastic piping systems versus conventional

The analyses in this research are made from the perspective of the Dutch district heating situation. District heating had a market share of ca. 4% of all households in the Netherlands in the year 2005. Individual gas-fired central heating boilers provide the vast majority (94%) of space heating. This is mainly due to the high availability of natural gas in the Netherlands and thus the relatively low costs. Most of the energy plants in the Netherlands are natural gas-fired too.

The success of district heating projects depends on the availability of residual heat in the surrounding area. This heat is most commonly produced by industrial (energy) plants that need cooling water in their processes. The heat, now available for central heating in houses, would otherwise be emitted into the atmosphere. This reuse of heat yields a significant energy saving with regard to separated generation of electricity and heat.

2.1 Standard district heating systems

DH systems as applied in the Netherlands commonly consist of two separated piping networks: primary and secondary networks, both usually with supply and return pipes. A district heating (DH) system is schematically displayed in figure 2.1.

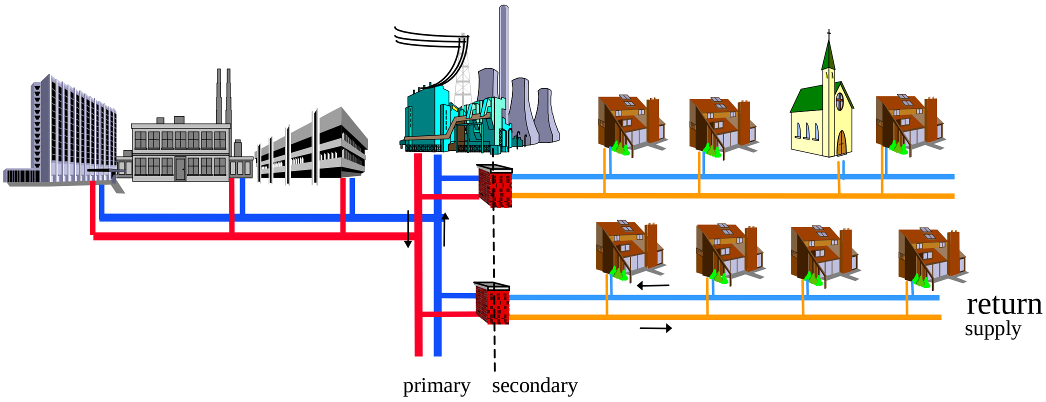

Figure 2.1: Schematic view of a district heating system

2.1.1 Primary DH network

Primary DH systems are used to distribute heat from the residual heat source to the secondary piping network. The distribution is realized using pre-insulated heat distribution pipes. The transport medium is pressurized water (16-40 bar) with temperatures up to 130 ºC. At a substation the heat is transferred into the secondary net by means of a heat exchanger. Pipe diameters vary from DN 50 to DN 1000. The distance between supply and return pipes is 500 mm. For primary piping networks only pre-insulated steel pipes are applied because of the high temperature and pressure conditions. Plastic pipes for instance are generally limited to a temperature of 95 ºC and 6 bar pressure. Costumers with a large heat demand are often connected to the primary network. In this case a heat exchanger separates the primary and customer heat circuits. For residential costumers a secondary DH network is connected to the primary network.

2.1.2 Secondary DH network

Secondary DH networks are used in residential districts. The systems provide heat to consumers by means of pre-insulated heat distribution pipes. The transport medium is pressurized water (6 bar) at 70 ºC. In the substation the primary and secondary networks are separated by a heat exchanger. In general heat distribution in secondary networks have a power range around 5 MW.

At the consumers' premises there are direct systems for central heating and heat exchangers for individual hot water supply. The return temperature of water in the secondary system is approximately 40 ºC. Pipe diameters vary from DN 20 to DN 125. The distance between supply and return pipes is usually up to 400 mm. The water in the secondary network is heated by water from the primary network. This is accompanied by a temperature loss of app. 5 ºC. The secondary network or distribution network is directly connected with the customer substation and central heating network. The design conditions of the secondary network are dependent on the customer network. Newly built houses have most commonly 70°C supply and 40°C return temperature. The maximum pressure is 6 bar. By applying a 70°C supply temperature there is less dependency on the primary supply temperature. Besides that, there is still a temperature difference high enough for relatively normal water flow and the return temperature is often demanded by heat producers. A supply temperature of 70°C is a minimum because of the risk of legionella formation below 60 °C. In the customer substation cold water is heated through a heat exchanger to provide hot tap water.

2.2 Conventional St/PU/PE piping systems

Conventional pre-insulated piping systems for DH as generally applied consist of three material layers: a steel medium pipe, polyurethane insulation layer and polyethylene outer casing St/PU/PE. The service pipe is made of steel (St37) and is used for the transportation of hot water. In case of hot tap water systems the service pipe is made of copper.

A polyurethane (PU) insulation layer is applied around the service pipe. This layer limits the heat loss as a result of heat distribution. The outer casing is made of several mm thick polyethylene (PE) to protect the insulation layer against damage, deterioration and ground load. The optimal insulation thickness is a choice between material and production costs on one hand and costs for the loss of heat on the other. The costs depend on fuel price, supply temperature, lifetime, interest rate, inflation and depreciation.

Figure 2.2: Schematic view of a steel pipe

The different material layers are bonded and can to a certain extent absorb longitudinal forces. Nevertheless, there is a maximum laying length in order to prevent too high a tension in bends. This depends on the temperature difference and the quality and geometry of the pipe.

A disadvantage of the steel piping system is the risk of corrosion in DH networks that shortens the lifetime of the system. This can either be caused by water ingress from the outside due to damage to the outer casing or diffusion of water vapour, or from the inside due to poor quality medium water.

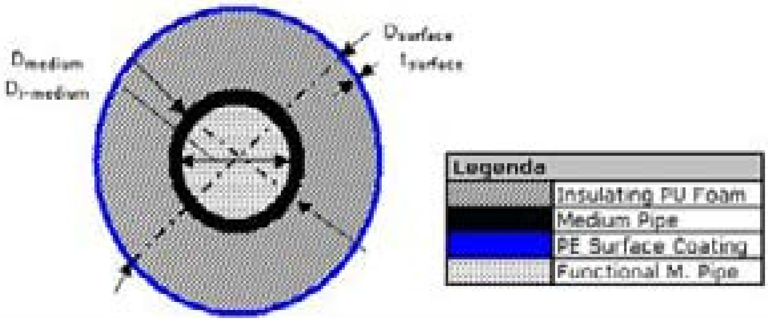

Figure 2.3: Section view of a steel pre-insulated pipe

2.3 Plastic piping systems

The alternative for the conventional piping systems is the use of plastic piping systems. The main advantages are non-corroding materials and the flexible characteristics. The use of plastic systems for district heating is not new: in Scandinavia these systems are commonly used in floor heating and small local networks.

The use of plastic piping systems for DH has a few important restrictions with regard to temperature and pressure. The maximum allowed temperature is usually about 95°C and maximum pressure up to 6 bar. The largest plastic piping diameter is therefore 110 mm. As a consequence, the plastic piping systems are not suitable for the primary DH network from production site to substations.

In plastic piping systems different types of plastics are used for the service pipe. The most commonly used material is PEX (cross linked polyethylene) or PB (polybutylene). The main difference between these materials is that PB is thermoplastic and therefore suitable for welding, whereas PEX is generally bonded with metal press fittings. This involves the use of metal components and is therefore sensitive for corrosion.

The plastic materials used for the service pipe have a certain permeability to gases. Two diffusion processes are relevant to district heating. Firstly, small amounts of oxygen can diffuse through the outer casing, insulation and service pipe into the DH water. If significant amounts of oxygen dissolve in the DH water, this can damage metal components in the DH network such as heat exchangers, (consumer) substations and central heating installations. Detailed research on this subject is presented in chapter 5.

The second diffusion process is water vapour from inside through the different material layers to the ground. There may be a risk that the water vapour condenses in the insulation foam. This would affect the insulation properties of the foam and increase the heat loss of the piping system. This risk is evaluated in chapter 5.

The oxygen diffusion of plastic piping systems is reduced by applying an oxygen diffusion barrier on the surface of the service pipe. This consists of a thin layer of material with an extremely low permeation rate for oxygen.

The insulation in plastic piping systems consists most commonly of PU (polyurethane) or PE (polyethylene) foam. PU foam is the insulation material also used in steel piping systems. The PU foam in PEX piping systems however is flexible and has lower thermal insulation properties. PE foam is applied in the polybutylene piping system. The PE material is non-polar and is more or less water resistant, in contrast to the PU foam in other systems. However, PE foam has a higher transmission coefficient than PU foam and has therefore lower insulation capacity.

Figure 2.4: Example of a plastic twin pipe

The outer casing of plastic piping systems is made of HDPE material. The outer casing protects the insulation from damage and contributes to a certain ring rigidity. This way the system is resistant to ground forces. The outer casing is corrugated to increase the circular rigidity and decrease the bending radius.

For plastic piping systems there are no standards as yet for the construction of the system, as there are for pre-insulated steel systems in EN253. There are many variations possible for plastic piping systems and the technique is still in development.

2.4 PB/PE/PE plastic pipe system

This system consists of a PB service pipe, PE insulation layer and a corrugated PE outer casing PB/PE/PE). Some reasons for the interest in this system in particular are the possibility to weld the couplings, the relative water resistance of the insulation, the highly flexible system and the main production location nearby.

In the PB/PE/PE system the PB service pipe is not attached to the PE insulation foam. The two different materials appear to be very hard to attach to each other. As a consequence there is a risk that water ingress outside the service pipe can cause the entire system to be flooded. Therefore, piping joints in terrain network parts will be made watertight.

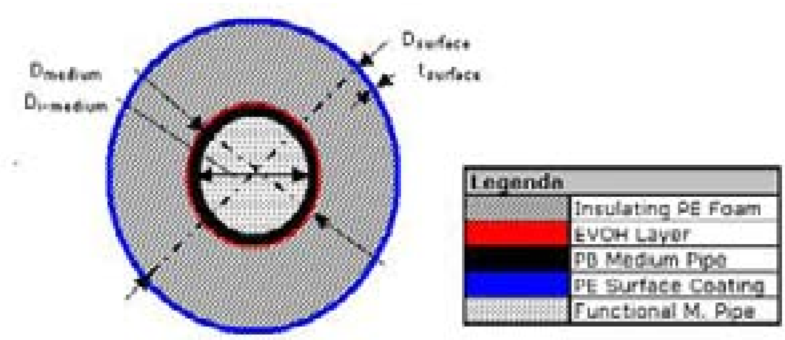

Figure 2.5: Section view of a plastic pre-insulated pipe

Some general information of the PB/PE/PE system is mentioned below.

—Diameter range single pipes 25 mm to 110 mm;

—Diameter range twin pipes 25 mm to 63 mm;

—Temperature range –15 ºC to 95 ºC;

Expected lifetime 50 years.

2.5 Advantages and disadvantages of plastic piping systems

There are several advantages and disadvantages to the use of plastic piping systems for district heating compared to conventional steel piping systems. First will the advantage and disadvantages be summarized, followed by the explanation.

Advantages:

—No corrosion in the network due to the lack of metal parts in plastic piping systems

—Less complicated installation

—Fewer joints in the piping system

—Smaller trenches possible

—Lower surface friction

—Better sound insulation

—Easier engineering of plastic piping systems

Shorter bends and less piping length

Disadvantages:

—Material restrictions

—Diffusion of gasses through plastic

—High material cost

2.5.1 Advantages

An important advantage is the lack of metal parts in the plastic piping network. This prevents the possibility of corrosion in the network due to a reaction of metal with oxygen and water. For steel and copper systems this appears to be a major threat to the lifetime.

Next, plastic piping systems offer the possibility of fast and simple installation. Due to the high flexibility of the system, obstacles and rough ground conditions are less of a problem than is usual with conventional piping systems. Also the low weight of the plastic systems allows them to be laid by only two persons.

The plastic piping systems are produced in long lengths on a reel, while conventional systems come in lengths up to 16 metres. In the field the plastic system can be installed with a minimum of joints, whereas normally a connection must be made every 16 metres. Having fewer joints means saving time and reducing chances of failure, thus reducing costs.

The trenches for conventional pipes are 1 metre wide at a depth of 60 cm. The distance between the steel pipes is usually 40 cm. This space is necessary for welding the pipes on site. The new plastic piping system however is so flexible that the pipe joints can be installed above the ground and then be laid in the trenches. Therefore, the trenches do not have to be as wide as 1 metre. The pipe can be installed directly next to each other. This not only saves in trench digging but also in heat loss. This is further explained in chapter 6.

Plastic service pipes have a surface friction than is ten times lower than that of steel. This results in a lower material resistance and thus lower pressure loss per metre of pipe. For an entire DH network smaller pipe diameters can be applied in order to achieve the same total head loss. This is further explained in chapter 4.

Plastic pipes have better sound insulation than steel pipes. The maximum allowed flow velocity in steel pipes is usually based on sound production and/or pressure loss. For this reason plastic pipes might be suitable for higher flow velocity.

Finally, there is an advantage for engineering a DH network with a plastic piping system. First there are fewer components that have to be drawn in working plans. Also expansion facilities normally applied for steel piping systems are not necessary due to the lower E-modulus and pressure forces in the ground. This all means saving time for engineering a plastic DH network.

2.5.2 Disadvantages

The main disadvantages of plastic piping systems for DH are the restrictions of temperature and pressure. The maximum temperature of most plastic systems is about $95^{o}C$ with a maximum pressure of 600 kPa [1]. Steel systems are suitable for much higher temperatures and pressures. In our case this means the plastic piping system will only be used for the secondary DH network.

A second disadvantage is that most plastics are not diffusion-tight for gases. There is a risk that oxygen may diffuse into the DH water and react with water and metal components in household pipe systems. The dissolved oxygen will cause corrosion in the metal components in household pipe systems.

The final disadvantage is the relatively high material costs. While the introduction of plastic piping systems is a relatively new concept for DH, a certain developing share is included in the costs. At this stage system costs may therefore exceed the costs for conventional systems. It is expected that the price will gradually decrease as competition rises.

Chapter 3: Life cycle assessment DH systems

3.1 Introduction

A life cycle assessment (LCA) focuses on the environmental impact of a product. The environmental impact is determined by evaluating the life cycle of a product. The life cycle reaches from before production phase of the product until replacement and disposal.

During the development of a product, the life cycle assessment is necessary to determine product aspects that need to be improved. A well founded LCA uses the methodology of comparison. As such, a reference product chosen is used as base for comparison. Such a life cycle assessment is called a comparative LCA.

This chapter describes the elementary phases of a life cycle assessment. The goal and scope definition describe the study and its boundaries. The inventory analysis is used to collect all the processes, products and data needed for the study. All this data results in an environmental impact, described in the impact assessment. Interpretation leads to an insight into the importance of process and product relative to the environmental impact, called a sensitivity analysis. Conclusions are described at the end.

Bo Pedersen Weidema's 'Environmental Assessment of Products' [2] is used to conduct the life cycle assessment by means of the LCA software program SimaPro 7.

3.2 Goal and Scope.

The objective of this study is to identify environmental impacts from the product life cycle of the PB/PE/PE piping system for district heating as compared to the conventional St/PU/PE system.

The study uses industry averages and manufacturer data for both systems. Life time is fifty years, based on general experience and manufacturer data. The geographical location of the life cycle assessment is the Schuytgraaf district in the city of Arnhem, the Netherlands. European databases are used for their reliability. The databases describe energy and production processes.

This study is designed and conducted using European conditions. As such, the results are to be read and interpreted in terms of that region alone. Supplementary research is needed if a wider geographical interpretation is to be obtained.

3.2.1 Secondary district heating systems

Secondary district heating systems are used as described in Chapter 2. A short description of both pipes is given again.

Figure 3.1 shows the section view of the PB/PE/PE pre-insulated pipe. A polybutylene (PB) medium pipe with anti-oxygen barrier (EVOH) is placed in a low-density polyethylene (LDPE) insulation foam with an corrugated outer casing of high density polyethylene (HDPE).

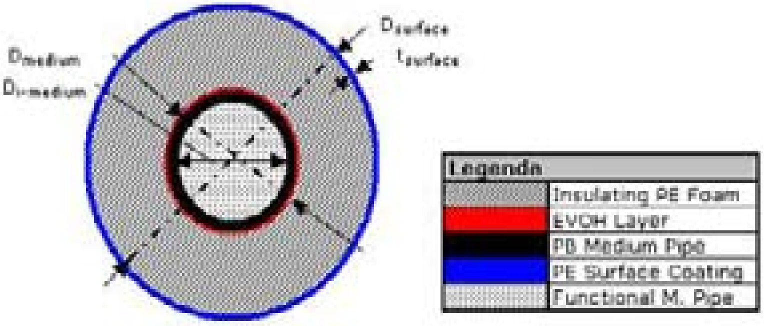

Figure 3.1: Section view of a plastic pre-insulated pipe

Figure 3.2 shows the section view of the St/PU/PE pre-insulated pipe. A steel (St37) medium pipe is placed in a polyurethane (PU) insulation foam with an outer casing of high density polyethylene (HDPE).

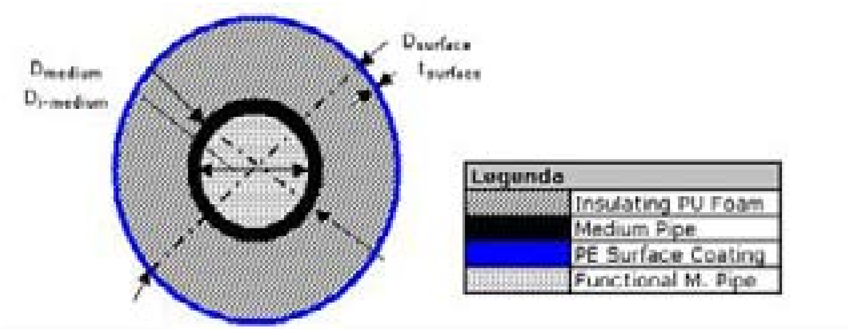

Figure 3.2 Section view of a steel pre-insulated pipe

3.2.2 Functional unit

The base for the entire comparative study is a functional unit. The functional unit encompasses the boundaries of the object studied and it describes the object demands.

The functional unit is a conventional secondary district heating system in the Schuytgraaf district of Arnhem. The secondary district heating system is constructed using the PB/PE/PE piping system and can be used as pilot project when comparing theory with future practical results.

The system encapsulates a total pipe length of approximately 2.5 kilometres to 224 consumers of 14 kilowatt at houses and 10 kilowatt at apartments. The temperatures are 70 ºC for supply flow and 40 ºC for return flow. Ground temperature is assumed at 10 ºC. The system is expected to have a life time of 50 years, based on manufacturer’s data. And a soil cover of the pipes of 0.7 meters is assumed. A simultaneous consumer use during peak load of 55 percent is used. This percentage is based on general company experience data.

Plastic District Heating network

The plastic district heating system is only suitable for use in the secondary network. The primary network provides heat through a substation from where the heat is distributed through the secondary system. The secondary network is constructed in PB63 (DN50) and PB 40 (DN32) with connections to consumers of PB25 (DN20) pipe diameters. All joints are included. The joints are welded, insulated and coated on-site.

Steel District Heating System

The steel pipe district heating system is supplied by several piping manufacturers. As in the plastic district heating system, the heat is distributed from the substation into the secondary network. The secondary network consists of St37 DN20 to St37 DN125 pipes with connections to consumers of DN20. All joints are included. The joints are prefab products and need to be assembled in the field.

3.3 Inventory analysis

The inventory analysis describes all data used to determine the impact assessment. It describes data sources, assumptions, data quality, network components, energy use, heat loss and allocation.

3.3.1 Data Sources

The tool used for this study is the internal LCA software of ESU and BUWAL-services, called SimaPro 7 by Pré Consultants [3] bv, Amersfoort, which supports large amounts of data and is able to model product life cycles. The database contains inventory data taken from industry, research institutes and governmental agencies as well as literature data and model calculations. The following data sources were used:

—PB/PE/PE manufacturer data for the production of the pre-insulated plastic pipes;

—St/PU/PE manufacturer data for the production of the pre-insulated steel pipes;

—BUWAL250 and ETH-ESU data libraries for production of various components and raw materials;

—Environmental reports and other LCA studies.

3.3.2 Assumptions

Not all data for the PB/PE/PE system is available, as the all new plastic piping system is still under development. Data from the conventional piping system is used in the event of data gaps. For example, maintenance on district heating pipes is assumed to be the same in plastic and steel networks and is therefore not relevant to this study. The service life of the network components is taken into account in the calculations.

For both systems, the life time is assumed to be fifty years. Life time data is supplied by pipe manufacturers. Heat loss data for all diameters pipe is supplied by producers. The energy consumption is provided by the European energy mix from the European databases. The European energy mix consists of average data from all European countries. This energy mix is developed by ETHS and relies on general European data.

3.3.3 Data Quality

Thanks to industrial partners, the study relies on good quality primary data for the production of pre-insulated pipes and for the operation of district heating systems. However, no data is available on actual heat losses. The energy use of the components is calculated using a mathematical method by Petter Wallentén [4]. The data quality of both systems for their different life phases is provided in table 3.1.

Table3.1: Data quality of components: ++ very good,+ good, +/- fair, - strongly based on estimations

	Components	Production	Distribution	Application	Life time
Plastic Pipe	++	++	+/-	+/-	+
Steel Pipe	++	+/-	+/-	+/-	++

3.3.4 Network components

Pipe diameters and lengths of the plastic and steel district heating systems in the Netherlands are shown in table 3.2.

Table 3.2: Pipe lengths for the calculation of both district heating systems[1]

Diameter	Steel Meters [m]	Plastic Meters [m]	Life Time	Remark
DN 100 / PB110	N/a	20	50 years	Life time (manufacturer data)
DN 80 / PB90	122	190	50 years	Life time (manufacturer data)
DN 65 / PB75	262	176	50 years	Life time (manufacturer data)
DN 50 / PB63	348	324	50 years	Life time (manufacturer data)
DN 40 / PB50	418	566	50 years	Life time (manufacturer data)
DN 32 / PB 40	2544	1070	50 years	Life time (manufacturer data)
DN 25 / PB32	1160	708	50 years	Life time (manufacturer data)
DN 20 / PB25	N/a	1828	50 years	Life time (manufacturer data)

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[1] Note: table 3.2 highlights the diameter difference between steel and plastic, resulting in different diameter lengths.

3.3.5 Energy use in the systems

The study assesses the Dutch ‘Schuytgraaf’ network and is supposed to be used in European regions. Therefore the European energy mix is assumed for the operation of the district heating systems. The energy use for the production of the components reflects, as far as possible, the country of origin of the component (e.g. the Netherlands for plastic pipes and Denmark for steel pipes). For unknown or various origins, the European energy mix is used (e.g. for raw materials used to produce the components).

3.3.6 Heat loss in the district heating systems

There are differences in the specific heat losses of the components for the plastic and steel systems. Table 3.3 shows the heat loss of all components in the systems. Manufacturer’s data is used to determine the product geometry and heat loss. The mathematical method used was developed by Petter Wallentén.

Table 3.3: Heat loss components of both district heating systems

Diameter	Steel Heat loss [W/m]	Plastic Heat loss [W/m]
DN 100 / PB110	N/a	35.8
DN 80 / PB90	33.1	36.6
DN 65 / PB75	32.4	30.8
DN 50 / PB63	28.7	34.7
DN 40 / PB50	27.1	28.3
DN 32 / PB 40	24.5	29.4
DN 25 / PB32	23.9	24.8
DN 20 / PB25	N/a	21.2

3.3.7 Allocation

Allocation describes the plan used as the basis for the study. The district heating systems are allocated according to the amount of energy used to provide customers their contracted volume of heat. The total energy demand for a year is calculated using drawings of the Schuytgraaf district and calculations from Pipelab, developed by Dr. Pàll Valdimarsson [23]. The energy demand is calculated using the values from Pipelab and standard design criteria.

3.4 Impact assessment

The impact assessment determines the environmental impact per system. First both district heating systems are analysed. Afterwards the total results are examined.

3.4.1 District Heating Systems

Table 3.4 shows selected cumulative resource expenditures and emissions of district heating systems for both plastic and steel. The cumulative resource expenditures provide information on the materials used (e.g. steel which is mainly used in pipes) as well as on the need for primary energy carriers (e.g. coal for conventional power plants).

Table 3.4: Basic results for the LCA calculation of the steel district heating systems

		Plastic DH system	**Steel DH system**
Resources	**Unit**		
Tin	MJ surplus	2.98E3	8.42E3
Nickel	MJ surplus	0.642E3	0.598E3
Lead	MJ surplus	0.386E3	0.728E3
Iron	MJ surplus	1.52E3	2.3E3
Copper	MJ surplus	11.88E3	12.0E3
Bauxite	MJ surplus	0.446E3	0.608E3
Remaining Substances	MJ surplus	0.0824E3	0.607E3
Coal	MJ surplus	5620E3	7690E3
Natural gas	MJ surplus	2870E3	2640E3
Oil	MJ surplus	3060E3	2820E3
Emissions to air			
NH_3	kg	8.9	1.48
CH_4	kg	2.99E5	2.77E5
CO_2	kg	4.34E3	4.30E3
Zinc	Kg	2.34	2.66
NO_x	Kg	4.35E3	4.03E3
SO_x	kg	4.9E3	4.66E3
Emissions to water			
Zinc	kg	2.31	2.86

The demand for resources originates from raw materials used during production and production of energy. Tin, nickel, lead, iron and copper are the main substances for the production of the conventional St/PU/PE system. Coal, natural gas and uranium demand is caused by the energy requirement for production and district heating. The uranium resource demand is caused by a European energy mix used to model the environmental impact of the conventional steel district heating system. When switching to a Dutch energy mix this phenomenon changes.

The air emissions are partly due to processes and partly originate from energy generation. The CO_2 emissions are caused by the district heat demand, the use of plastics and fossil energy consumption. The NO_x and SO_x emissions are linked to the use of fuel oil and natural gas.

Figure 3.3 shows the cumulative expenditures and emissions of the Schuytgraaf scenario, in the case of a plastic system, with the system components and their relative importance.

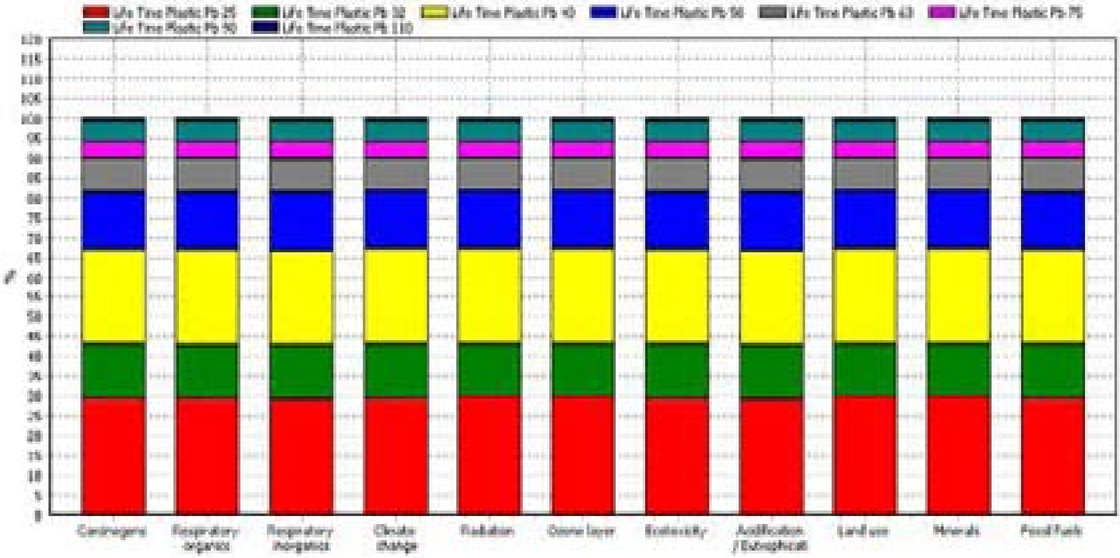


Figure 3.3 Relative share of cumulative expenditures of 'Schuytgraaf' in case of a case plastic system

It is important to notice the major contribution of PB40 and PB25 on the environmental impact. This is explained by their relative large heat loss in comparison with the steel DN20 and DN32 diameters. The other part of its contribution is explained by the long lengths of PB40 and PB25.

Figure 3.4 shows the cumulative expenditures and emissions of the Schuytgraaf scenario, in the case of a steel system, with the system components and their relative importance.

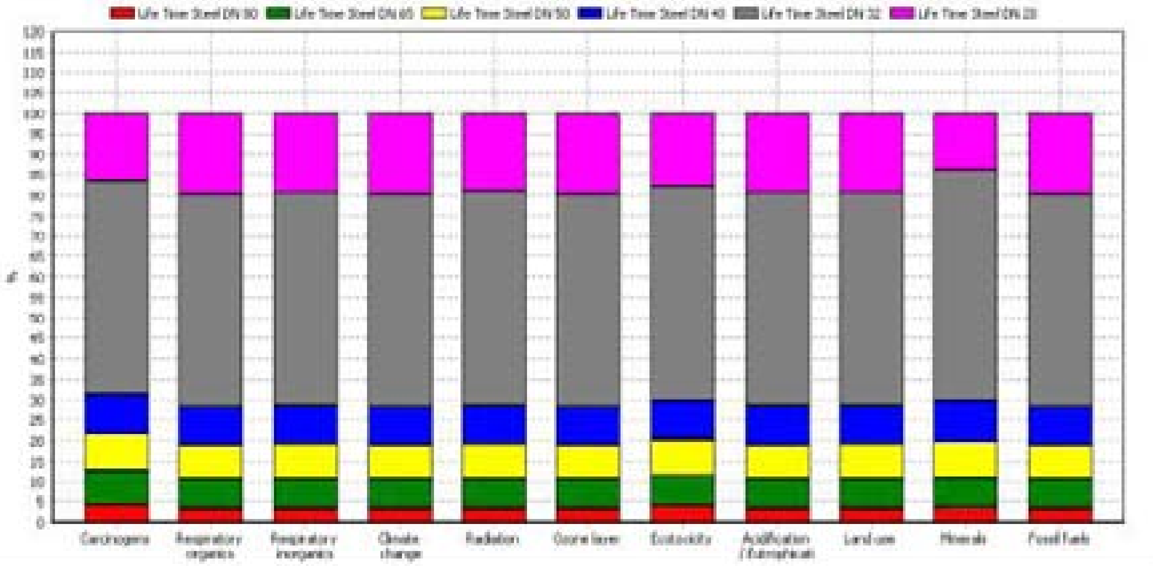


Figure 3.4 Relative share of cumulative expenditures of 'Schuytgraaf' in case of a steel system

In figure 3.4 the DN32 steel diameter dominates the categories. This can be explained due to its long length relative to the other diameter lengths.

3.4.2 Impact assessment results

Table 3.5 shows the results evaluated with the method Eco-Indicator (EI'99) Individualist, Hierarchist and Egalitarian, and the method of the ecological scarcity 1997 (ecopoints). Besides, the cumulative energy demand (renewable and non-renewable) is given.

Table 3.5: Results of the impact assessment of secondary district heating systems in Schuytgraaf

		Steel DH system	**Plastic DH system**
Assessment method	**Unit**		
Cumulative energy demand (non- renewable)	MJ-eq.	6.959E7	7,529E7
Cumulative energy demand (renewable)	MJ-eq.	1.032E6	1.081E6
Greenhouse gas emissions	kg CO2-eq.	8.69E8	9.39E8
Ecological scarcity 1997 (ecopoints)	UBP	1.85E9	1.98E9
EI'99-aggregated, Egalitarian	EI99-points	2.28E5	2.46E5
EI'99-aggregated, Hierarchist	EI99-points	3.74E5	4.06E5
EI'99-aggregated, Individualist	EI99-points	1.18E5	1.13E5

The results are reasonably clear concerning the three system options. Almost all assessment methods show the lowest impact for the St/PU/PE district heating system, except for the EI'99 individualist method. In this case production impact is considered more important over emissions.

The importance of the steel DH system for the greenhouse gas emissions is greater than for the human health and ecosystem quality. Table 3.6 presents the environmental impact score of both and shows the difference.

Table 3.6: Greenhouse effect versus Human Health and Ecosystem Quality

		Steel DH system	Plastic DH system
Assessment method	**Unit**		
Human health	EI99-points	3.37E4	3.57E5
Ecosystem quality	EI99-points	7.2E3	7.29E3
Greenhouse gas emissions	EI99-points	1.87E5	2.03E5

3.5 Interpretation

The PB/PE/PE system is performing worse compared to the St/PU/PE system. Almost all the environmental impact methods show higher scores compared to the conventional St/PU/PE system. This section determines the factor responsible for the large environmental impact of the plastic PB/PE/PE system.

3.5.1 Dominance analysis

The heat loss is most important in the life cycle of district heating systems (see figure 3.5). Despite the fact that a relatively pessimistic scenario for disposal was selected (10 percent incineration, 50 percent take back and 40 percent storage, instead of 100 percent take back), the environmental impacts for this life cycle phase can be neglected. The production, installation and disposal of on metre pipe are responsible only for approximately 1% (plastic) to 1.1% (steel) of the impacts, respectively (figure 3.5).

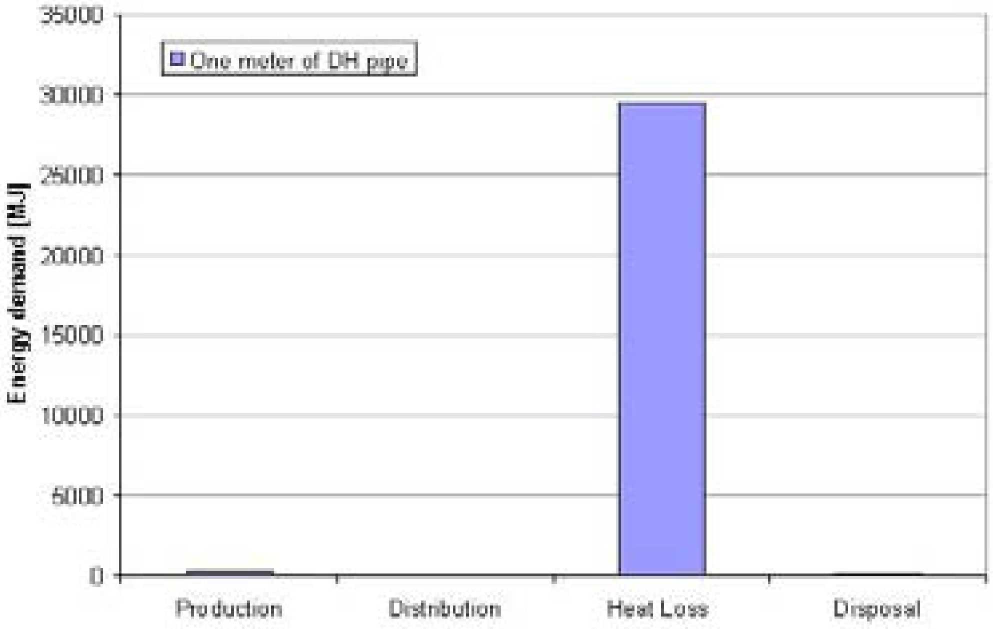


Figure 3.5: Relative contribution of life phases in one-metre district heating pipe

Figure 3.6 gives a detailed picture of the production phase. The production phase encapsulates medium pipe, insulation foam and casing production. Steel is a factor 38% higher compared to plastic pipe production. The results are explainable by the production of iron from raw material. Installation, distribution and disposal are not highlighted due to their low influence on the environmental impact.

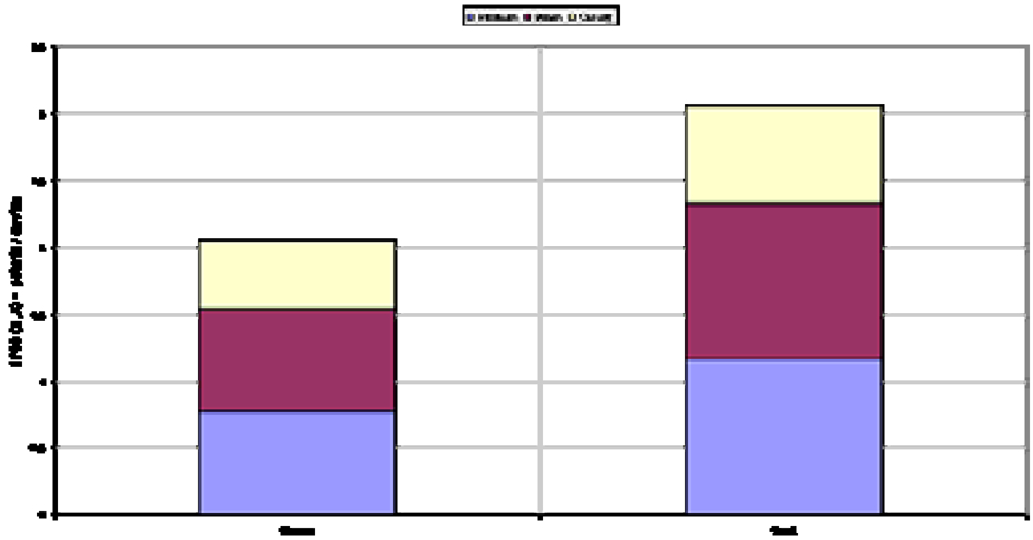


Figure 3.6: Attribution of the Eco-indicator’99 (Hierarchist, average) points for the plastic and steel systems

3.5.2 Sensitivity analysis

Heat loss from pre-insulated pipes

In this chapter the contribution of heat loss on the environmental impact is drawn as a function of life time. Increasing life time from forty to fifty years would decrease the importance of the production, distribution and waste phase to below two percent. This effect can be explained by the increasing demand of heat when increasing life time. The environmental impact of the production phase will decrease, but changes are not relevant due to the large impact of the rising demand for heat.

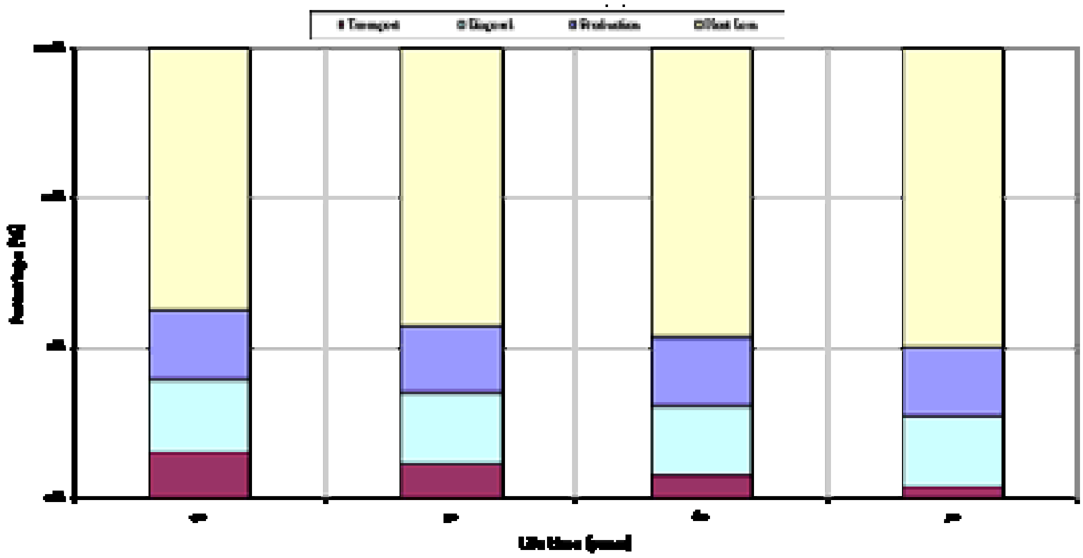


Figure 3.7: Importance of the pre-insulated pipe’s lifetime for the results of the environmental impact assessment

Comparison per metre of pipe (PB75 versus DN65)

When comparing one metre of pipe from the steel system with a metre of pipe from the plastic system, the importance of heat loss is displayed again (See figure 3.8).

In figure 3.8 one metre of PB75 is compared with DN65 resulting in a lower environmental impact of PB/PE/PE. This is explained due to lower heat loss of the diameter PB75 versus DN65 (30.8 W/m for PB75 and 32.4 W/m for DN65).

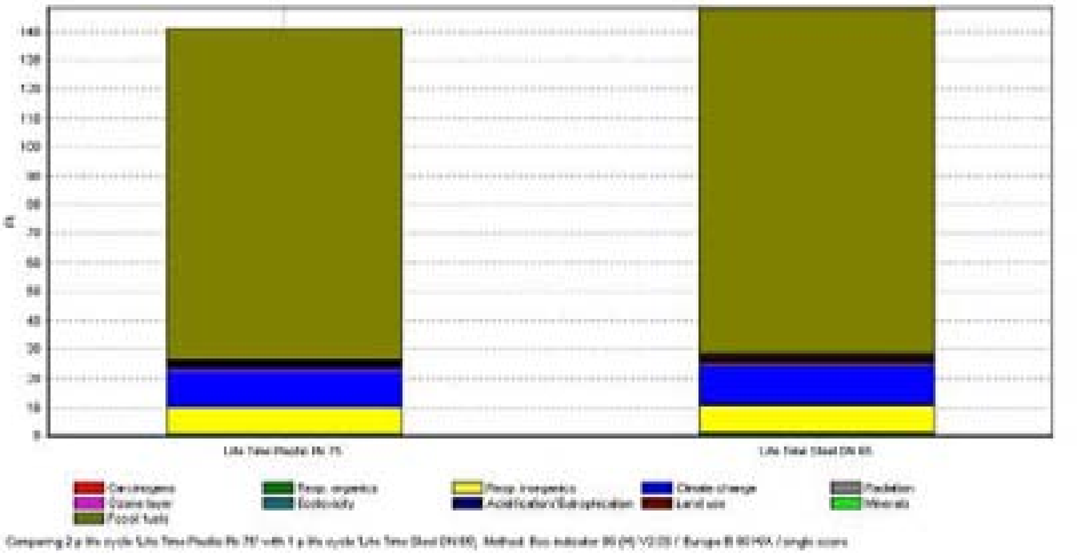


Figure 3.8: Pipe comparison PB75/160 and DN65/140

Off peak situation

During off peak situations a large amount of heat returns unused to the substation. This phenomenon results in higher heat loss on the return pipes.

The phenomenon has been studied using 70/60 ºC supply/return instead of 70/40 ºC. A 22 percent higher heat loss was found by recalculating all diameters used in the functional unit. See figure 3.9. Consequently, the environmental impact rises approximately 22% due to the relationship between heat loss and environmental impact.

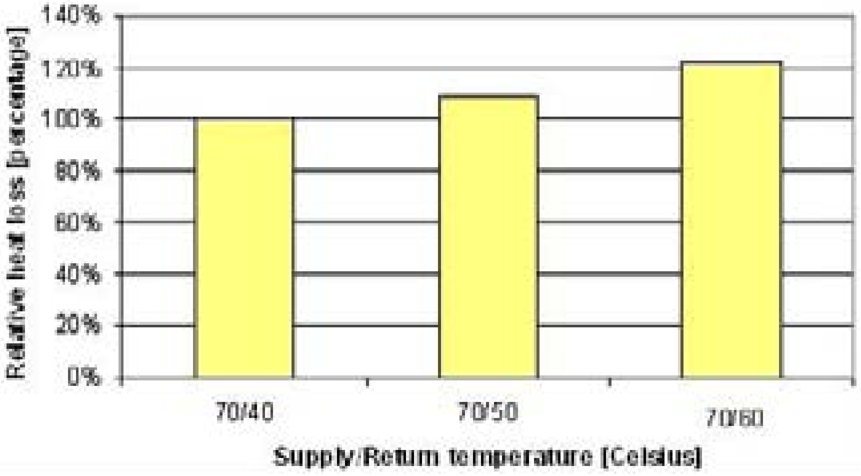


Figure 3.9: Relationship between supply/return temperature and heat loss

A variation in heat-loss and subsequently a variation in environmental impact must be considered. However both supply and return temperature of St/PU/PE and PB/PE/PE are compared under similar conditions, 70/40 ºC.

3.6 Conclusions

3.6.1 System components

From an environmental point of view, the heat loss is the most important element of the district heating system. The heat losses calculated for all pipe diameters thereby contribute the major part of the environment impact. The long life time of district heating systems plays a substantial role. The life time of a pre-insulated pipe, which is about fifty years, is very long. Increasing the utilization period of the district heating system only enlarges the contribution of heat loss to the environmental impact.

Enhancing the product performance (e.g. increasing insulation thickness) leads to a lower environmental impact. Increasing insulation thickness is not endless due to an optimum between insulation thickness extension (decreasing heat loss) and surface extension (increasing heat loss). For economic reasons the optimum insulation thickness extension is around ten percent of the actual insulation thickness. Consequently the impact contribution of the production phase will rise, but since the effect of production on the total impact is less than one percent, this increase is acceptable.

It is not necessary to improve the products ability to be recycled or to enhance distribution and installation, due to the low contribution of these phases to the environmental impact. Making the pipe more recyclable only increases the complexity of the product, thereby negatively influencing the product performance and increasing environmental impact.

3.6.2 Total system performance

Total system performance can be altered by changing district heating network engineering. Overall heat loss remains the same for diameter enlargement in comparison with the conventional system. Increasing medium velocity results in an 8% lower heat loss.

Return temperatures are important for the overall system performance. Increasing return temperature by 20 ºC leads to a heat loss increase of 22%. Environmental impact increase of approximately 22% is the logical consequence.

3.6.3 Further research

The importance of heat loss is the most important aspect of district heating when concentrating on environmental impact. This conclusion is endorsed by the ‘Life Cycle Assessment of District Heating, ALSTOM, Denmark, 1999’ [5] in which heat loss is determined as the most important factor of pre-insulated pipe improvement.

Heat loss can be reduced by optimizing product performance. This is achieved by quality improvement (e.g. insulating foam quality) or by geometry improvement (e.g. decreasing production tolerances or increasing foam layer).

Heat loss optimisation in network engineering is far more complex and leads to small improvements. Control of the return temperatures in district heating networks is a possible and practical solution.

Further research focuses on heat loss due to the large contribution of heat loss to environmental impact.

Chapter 4: Cost benefit analysis

4.1 Introduction

In earlier chapters several practical advantages of the PB/PE/PE piping system are explained. Obviously also costs of these systems compared to conventional piping systems are of great importance. This chapter describes the cost benefit analysis for a PB/PE/PE plastic piping system as compared with the conventional St/PU/PE and Cu/PU/PE systems generally applied in district heating networks.

The analysis clarifies the main differences between applying plastic and steel piping in district heating networks. It also shows on what points the plastic pipe system should improve to decrease network costs. The eventual goal is to have an alternative district heating system at lower costs than conventional systems.

4.2 Standard district types

The analysis of costs for district heating networks is based on several relatively standard new housing developments. In the Netherlands new housing developments are often high-density districts. However, in the last few years the trend has moved towards open-space planning. Therefore, for several common district types the total costs of the district heating network are analysed.

The emphasis lies on secondary DH systems with low temperatures (70-40 ºC supply and return) and low pressure level (PN6). The costs are compared with conventional steel and copper district heating networks at the same conditions. Several existing district types in conventional layout are taken as a reference for this analysis, based on common building areas with certain density and number of consumers. Three standard district types are considered:

high-density district;

low-density district;

high-rise building district.

4.3 Service configurations

Per district type two common service configurations are analysed. These are the individual hot water configuration (IHW) and central hot water configuration (CHW).

The network of the IHW configuration consists of supply and return pipes (usually St/PU/PE) for the distribution of heat for central heating. In the consumer substation a heat exchanger provides the hot tap water.

The network of the CHW configuration consists of supply and return pipes for central heating and a separate circuit (usually Cu/PU/PE) for distribution of hot tap water. The piping diameters for central heating circuit in CHW is generally equal to the piping circuit in the IHW configuration. The extra copper circuit for central hot tap water are therefore additional investment costs in regard to the IHW configuration. These costs are largely compensated by lower costs for the consumer substation that lacks a heat exchanger.

4.4 Network layouts

For the different district types and service configurations several network layouts are analysed. A commonly used tree-type layout is taken as a reference for conventional district heating piping systems. This layout is also analysed for the plastic pipe system. However, for plastic piping systems it may particularly be interesting to apply twin pipe systems, as the connections are more easily made and are therefore cheaper than for steel twin pipe systems. Also a network layout according to the ‘Tichelmann’ principle is analysed.

St/PU/PE tree-type (reference)

The district heating network is constructed using St/PU/PE for the conventional network layout. This configuration is most commonly used to construct the network, the drawings are used one on one for laying pipes and applying parts and diameters. Piping trajectory consist of single supply and return pipes. Figure 4.1 shows the two standard district configurations used for the cost analysis.

PB/PE/PE tree-type single diameters

The conventional network layout is used as a base for the pipe network and applied diameters with the PB/PE/PE system. All available single pipe diameters of the plastic piping system are used for supply and return in the network.

PB/PE/PE tree-type twin all diameters

This network layout is constructed using the PB/PE/PE twin piping system. All twin pipe diameters up to 63 mm are available for constructing the plastic piping network and larger single diameters when necessary.

PB/PE/PE tree-type twin limited diameters

In this configuration a limited range of twin pipe diameters is applied. Twin PB40 and twin PB63 pipe are used as these diameters are required most in networks. For small parts of the network single pipes of PB90 and PB110 are used. House branches are only applied on the two twin diameters. Limited diversity in storage and economies of scale are the benefits of this network layout.

St/PU/PE Tichelmann layout

The Tichelmann network layout consists of a circular network configuration. Supply and return diameters are applied in opposite sizes as the flow runs in the same direction. Figure 4.2 shows the Tichelmann principle. If a separate central hot water circuit is applied (CHW) this network can be laid in a ring layout, following the trajectory of the Tichelmann circuit. The CHW circuit is constructed with single pre-insulated copper piping.

PB/PE/PE Tichelmann layout

The same layout as the steel Tichelmann network. For the CHW part also single plastic pipes are applied.

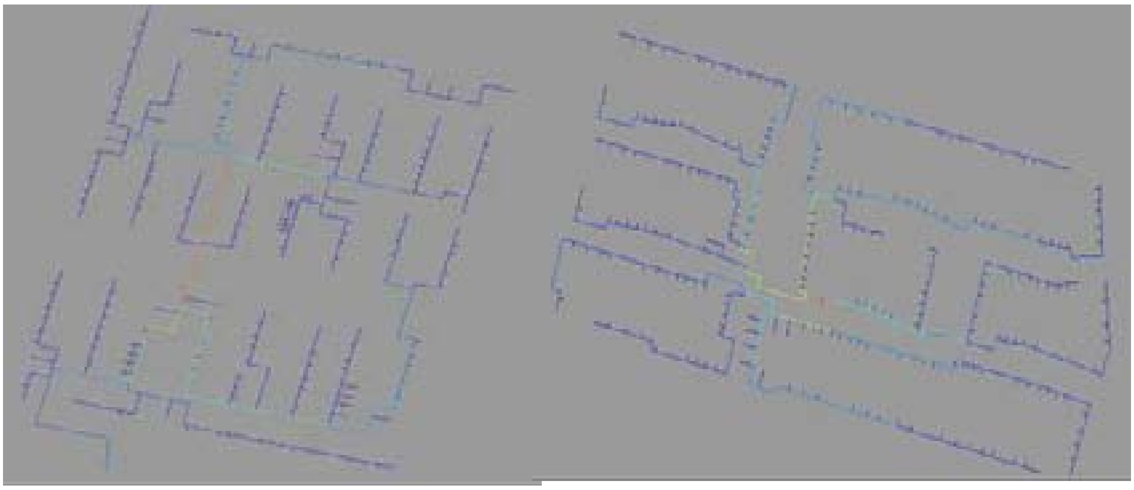


Figure 4.1: Standard network configurations

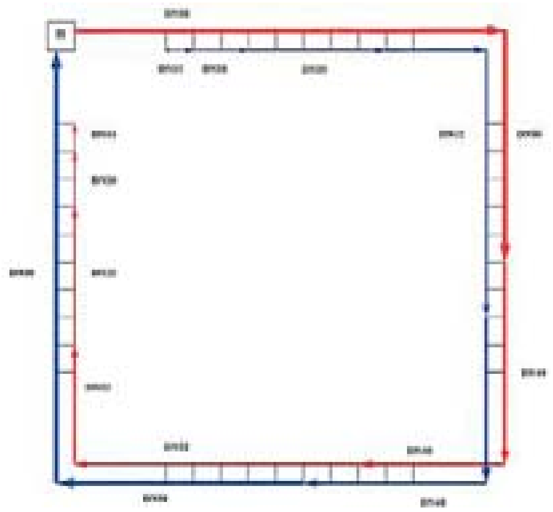


Figure 4.2: Simple Tichelmann network layout

4.5 Cost categories in secondary DH networks

The costs for an entire secondary DH system can generally be divided into several categories:

Engineering and supervision

Piping network, consisting of:

Groundwork

Pipe materials

Network accessory materials

Network installation

Consumer dwelling material and installation

Central substation

Heat loss during utilisation

Maintenance and exploitation

4.5.1 Engineering and supervision

Engineering the secondary network includes the design of the piping trajectory and subsequently drawing the original and as-built design. This phase generally amounts to 10 or 15% of the total costs for secondary networks. Currently there is not much experience in the engineering of plastic piping networks. An advantage for plastic pipe networks is therefore not observed. In the cost analysis the time for engineering for steel and plastic networks is assumed to be equal. However, it should be kept in mind that engineering time for plastic networks is likely to drop significantly, due to the low number of joints and accessories

Supervision is required during installation of the piping network. Saving time during installation also means lower costs for supervision. However, as these costs are relatively low in regard to total costs and it is not yet quantified how much time can be saved, these costs are neglected.

4.5.2 Groundwork

Trenches are dug during groundwork and filled again after pipe laying. For plastic pipe networks the main advantage is that not much space is needed around the pipes. For steel pipe systems this space is required for welding the pipes as they are difficult to band or move. First of all, plastic pipes networks have very low number of joints, especially in the field outside housing blocks. Second, when fittings must be applied the lightweight and flexible plastic system can be moved easily. Trenches for plastic pipes are assumed to suffice with a width of 30 to 50 cm, whereas trenches for steel supply and return pipes are generally 75 to 125 cm wide.

4.5.3 Pipe materials

The actual piping systems in secondary networks differ significantly for plastic pipes in regard to steel pipes. Steel pipe systems are delivered in lengths of 12 or 16 metres. The PB/PE/PE system are delivered on reels in lengths of 100 to 300 metres, depending on the outer diameter. This results in the possibility of having continuous lengths without the need of a connection or joint.

When looking at the used materials for both piping systems, the raw material costs per metre of plastic pipe are generally lower compared to steel pipe systems. Nevertheless, market prices for the plastic pipe system per metre are significantly higher than for steel systems. This relatively low share of raw materials can partly be explained by the novelty of the product and the fact that it is still in a stage of development. Also, the system is not yet produced on such a large scale that economies of scale are as high as for steel systems. The price is expected to decrease over time, as the system is used more widely and evolves out of the stage of development and more suppliers of plastic piping systems provide more competition.

4.5.4 Network accessory materials

A large advantage of plastic pipes is the low number of pipe connections and accessories. For steel pipe networks every twelve metre must be connected with a weld and finished with a joint. Besides that, pre-insulated bends are used for cornering in the network. As the network is often elevated under housing blocks, special bends are used to realise this heightening. For plastic pipe networks most of these accessories can be avoided. Moreover, bends with the PB/PE/PE system are often shorter than for steel bends, as plastic pipe bends have no 90 degrees angle but are more gradually bend. This saves material of approximately 5% per network.

Joints for plastic pipe systems however are sometimes necessary. Connections made in trenches in the field must be finished with watertight joints, mainly because ground water in the Netherlands is relatively high. This causes the piping network to operate under water during several periods per year. For steel pipes the common joints are extra sealed with shrink sleeves. For plastic pipe networks the currently used joint is a wedge joint consisting of two metal shells. Before the PB fittings the different piping compartments are separated by rubber sealing rings (see figure 4.3).

Figure 4.3: An open view of a wedge joint

In a PB/PE/PE DH network much less components are required in the field than in a DH network with a steel piping system. For the main part this is explained by the low amount of joints in the PB/PE/PE system. Also, for a small part this can be explained by lower pipe length due to the flexibility of the PB/PE/PE piping system. In figure 4.4 the amount of field joints is shown required for a low density residential district with almost 200 houses. This excludes the joints needed for making a household connection.

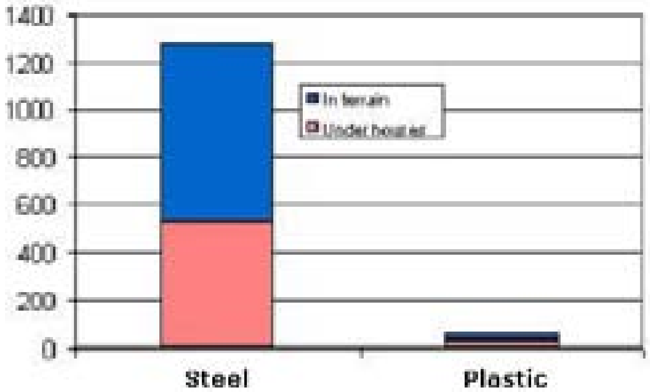


Figure 4.4: Amount of field joints in the low density residential district (excluding household branches)

4.5.5 Network installation

Installation is expected to be the largest cost saving category when compared with steel networks. This is mainly because of the low number of connections and joints, but also because of shorter time for laying pipeline due to low weight and flexibility.

Nevertheless, the costs for installing the plastic network are fairly uncertain. Up to now there is very little practical experience with laying the plastic pipe system. There have been some pilot projects for this system in the Netherlands, but it is difficult to conclude what costs are involved, due to relatively slow installation. Problems with the removal of the EVOH diffusion barrier are an example of slowing down the installation process.

In Scandinavia there is more experience in the application of plastic piping systems over the last decades. According to Klöpsch and Zinko [1] the greatest economic benefit of plastic pipe systems compared to steel is achieved in small diameters, as larger plastic diameters become relatively more expensive. If cost benefits for plastic pipe systems can be found, they are primarily due to lower installation and groundwork costs. Generally, the material costs for plastic pipes are rather high compared to steel pipes. This is also observed in this analysis for the PB/PE/PE system.

The installation tariffs in this analysis are based on the price estimates of three building contractors. However, these estimations are high due to the lack of experience with the system. Therefore, these prices are expected to decrease over time as more experience is gained.

4.5.6 Consumer substations

Consumer substations cost approximately 20 to 25% of the total investment costs for secondary networks. The consumer substations used for plastic piping networks are the same as for conventional steel networks. Therefore in the cost analysis these costs are not included.

Based on cost estimation and subsequent calculation for several district heating projects realised by Nuon, index numbers for investment in district heating networks per household are determined. First of all material prices and costs for construction of the district heating network are researched.

4.5.7 Central substation

The central substation separates the primary and secondary district heating networks by means of a heat exchanger. The costs for a typical central substation are about 15 to 20% of total costs for secondary networks. For both a plastic and steel district heating network the same substation is used. Therefore, the material and installation of the central substation is assumed to be equal for plastic and steel network.

4.5.8 Heat loss

During the utilisation phase of the piping network, the distribution of heat through the network results in a certain amount of heat loss per meter. For the cost analysis the proportion of heat loss in regard to total network costs is theoretically determined. See chapter 6 for detailed information on heat loss.

The net present value of heat loss costs in a secondary DH network can amount up to 25% of total investment costs, dependent on total piping length.

4.5.9 Operation and maintenance

For the total costs of a DH piping network also costs for operation (e.g. pump electricity, water suppletion) and maintenance (e.g. inspection, failure repair) should be considered. However, due to the lack of practical experience with plastic piping systems an accurate estimation of these costs cannot yet be made. Therefore, these costs are not included in this cost analysis.

4.6 Cost analysis low-density district (low-rise)

The network layouts described in the previous paragraph are analysed for configurations concerning individual hot water (IHW) and central hot water (CHW). Calculations of these network layouts per district type result in a recommendation on applying piping systems on the basis of investments for IHW and CHW.

For the low density district network cost analyses are performed. The district consists of 197 houses positioned relatively far from each other (ca. 18.3 houses/ha). The total length of pipe network is 7,674 m for the conventional single pipe layout.

4.6.1 Analysis individual hot water (IHW)

The individual hot water configuration is analysed for the conventional, PB/PE/PE conventional, PB/PE/PE limited twin, PB/PE/PE all twin and Tichelmann configurations. The total investment costs for the secondary piping network are determined by piping material, components, groundwork and installation. Figure 4.5 shows these costs per household for the low density district network.

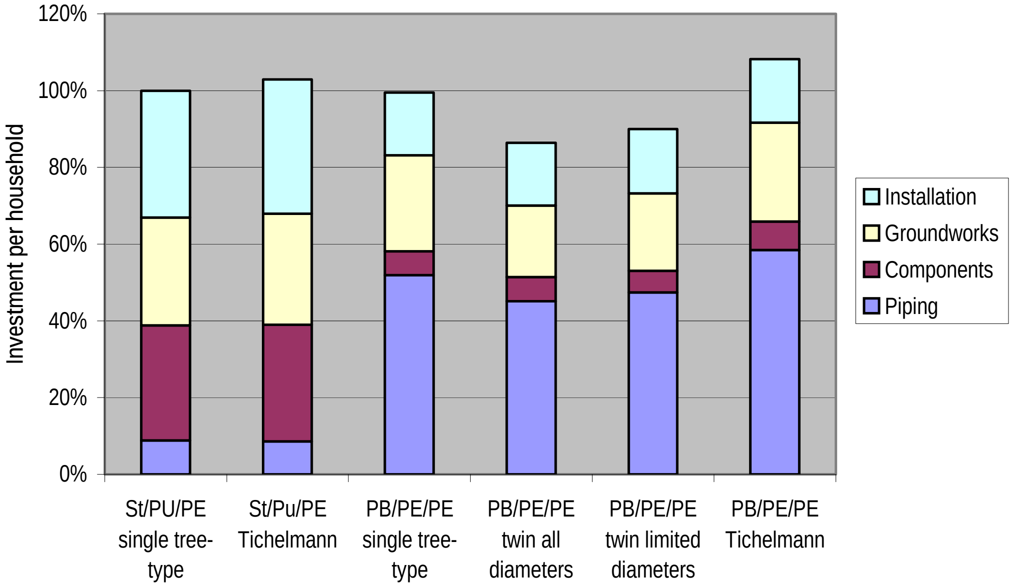


Figure 4.5: Investments per household for individual hot water (low-density district)

Figure 4.5 shows some interesting results. The largest costs for the steel pipe network are in installation and components, due to the many bends and joints and the installation of these components. The use of twin systems for PB/PE/PE result in the lowest costs with a difference of almost 10% compared to conventional steel.

As expected the material costs are in all cases larger for PB/PE/PE compared to steel, especially on the Tichelmann layout. This phenomenon is explained by the use of relatively large diameters for the Tichelmann layout. Figure 4.6 shows the diameter ranges for a conventional network and a Tichelmann network. Especially for the PB/PE/PE system applies that the large diameters for pipe system and components are relatively more expensive, i.e. not linear.

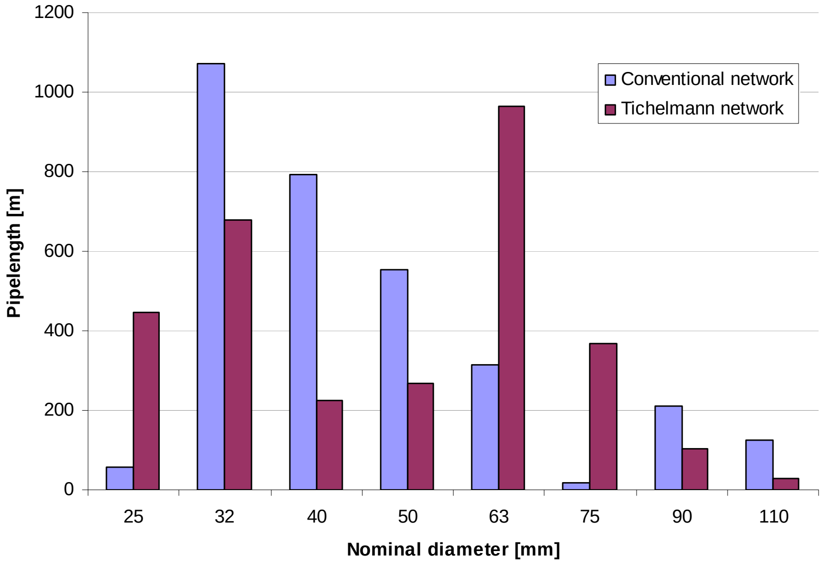


Figure 4.6: Diameter range conventional(tree-type) network versus Tichelmann

4.6.2 Analysis central hot water (CHW)

Next the central hot water configuration is analysed for the conventional and PB/PE/PE piping system. Conventionally this is a Cu/PU/PE system. The layout for hot water pipes is assumed to be the same as the IHW network. Required components are also the same as in the IHW configuration, only translated to their equivalent in Cu/PU/PE and an adapted diameter range.

In a tree type layout the copper piping network requires a circulation pipe to keep a constant temperature. Therefore, a ring layout seems to be a favourable option for CHW due to lacking of a circulation pipe. This configuration can be combined with a Tichelmann layout for central heating.

Figure 4.7 shows the costs per household for the central hot drinkwater part of a low density district network, again divided into four categories.

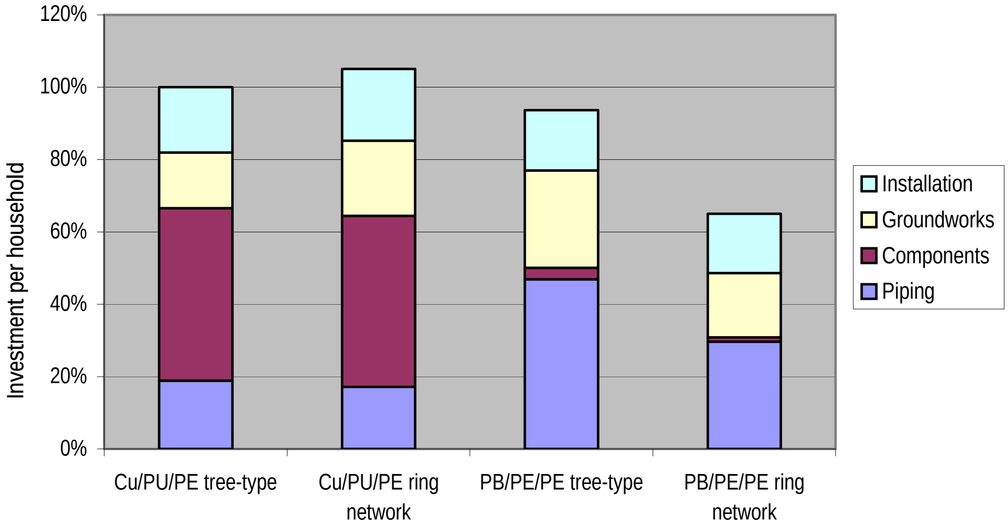


Figure 4.7: Investments per household for central hot water (low-density district)

Figure 4.7 shows an advantage for the PB/PE/PE system compared to the conventional copper system. Remarkably the copper ring layout requires slightly higher costs per household than the copper tree-type network. This can be explained by the fact that the ring network has relatively larger diameters, which mainly shows in the costs for components.

The advantage for the PB/PE/PE system is highlighted again in figure 4.8 where the investments for CHW are summed, consisting of the central heating and central drinking water network.

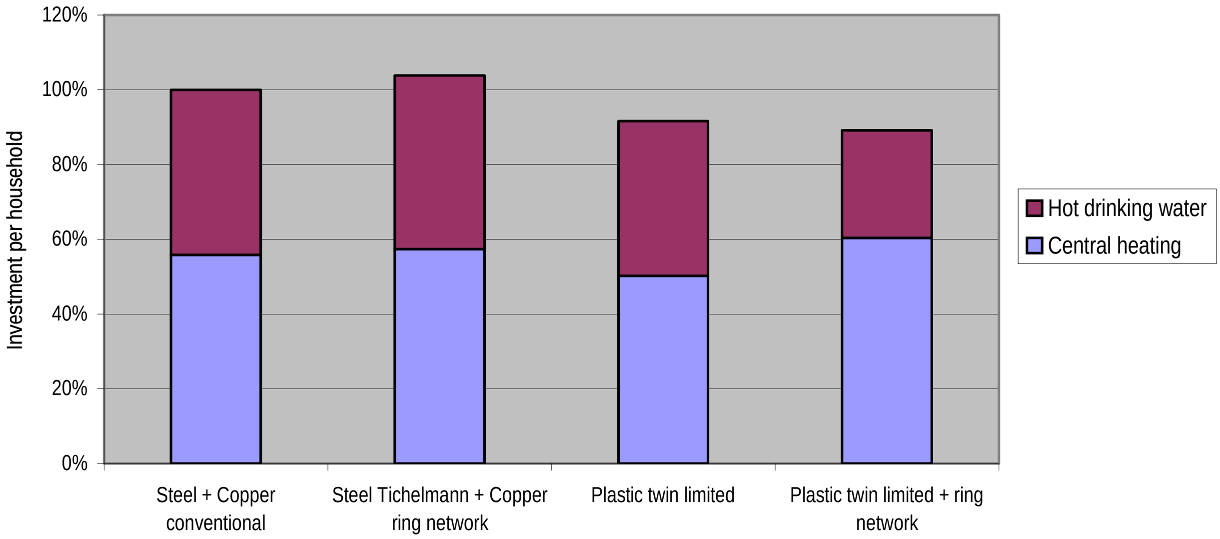


Figure 4.8: Total investments per household for CHW (low-density district)

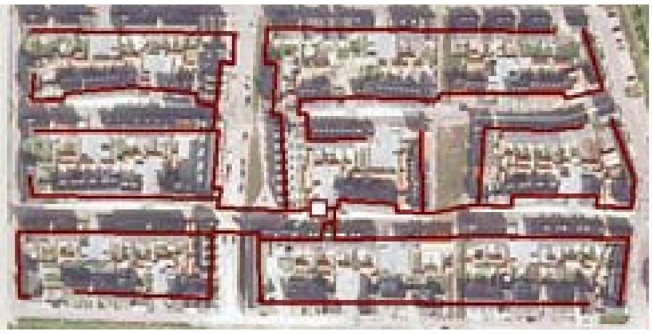
Figure 4.8 shows a small advantage for Tichelmann layout in combination with the PB/PE/PE piping system for central hot water. However, as this layout requires much more effort concerning planning and organisation during realisation and the small cost difference, the tree-type layout with the PB/PE/PE system is the preferred option.

In table 4.1 the total investment costs for low density districts per household.

Configuration Layout	IHW St/PU/PE single tree-type	 PB/PE/PE twin limited diameters	CHW St/PU/PE + Cu/PU/PE single tree-type	 PB/PE/PE twin limited diameters
Piping network	51%	46%	92%	84%
Engineering/supervision	10%	10%	16%	16%
Consumer substation	22%	22%	11%	11%
Central substation	17%	17%	19%	19%
Total	100%	95%	137%	129%

Table 4.1: Total investment costs for low density districts per household

4.7 Cost analysis high-density district (low-rise)



For the high density district network cost analyses are performed. The district consists of 244 houses, relatively close to each other (ca. 46.1 houses/ha). The total length of pipe network is 4,660 m for the conventional single pipe layout.

4.7.1 Analysis individual hot water (IHW)

The individual hot water configuration is analysed for the conventional, PB/PE/PE one on one, PB/PE/PE limited, PB/PE/PE twin and Tichelmann configurations. The installation costs and total costs are determined in the same way as described in paragraph 4.6.1.

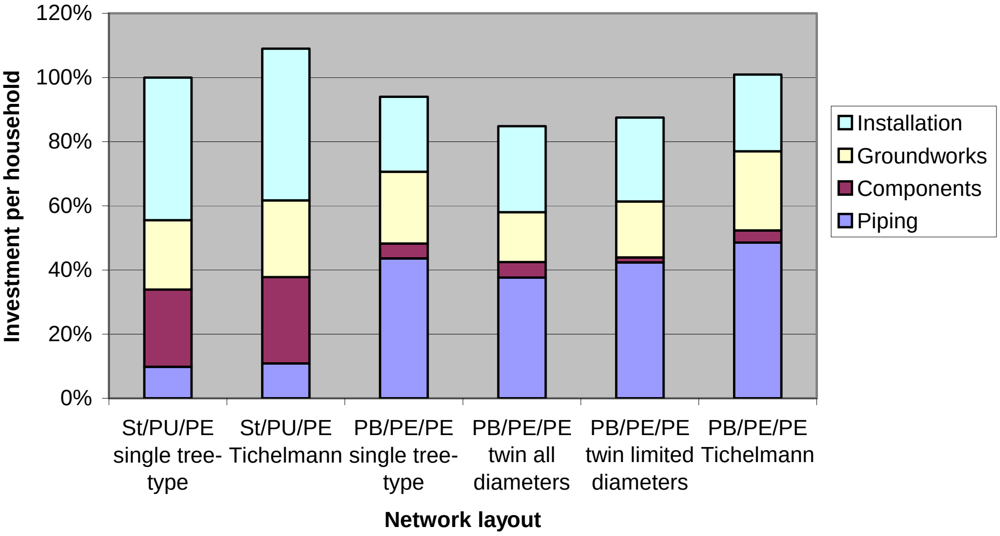


Figure 4.9: Total investments per household for individual hot water(high-density district)

Figure 4.9 shows the total investment costs for the high-density district. In a high-density district the total investments are lower compared to a low-density district, concluding from figure 4.9 and figure 4.5.

Again the largest cost categories for steel pipe networks are in installation and components. For the PB/PE/PE networks the largest costs are in piping material.

The use of PB/PE/PE twin diameters in a tree-type network result in the lowest costs in a high-density district, ca. 6.5% lower than for the steel network. There is a small difference in using limited diameters or all diameters for the twin system. It is likely that in using limited diameters there is an extra cost advantage, due to less stock items and economies of scale.

4.7.2 Analysis central hot water (CHW)

The central hot water configuration is analysed for the conventional system. This is the Cu/PU/PE system. The network for hot water pipes is assumed to be the same as the IHW network. Parts used are also the same as in the IHW network used only with their equivalent in Cu/PU/PE and an adapted diameter range.

The Tichelmann network is favourable option for CHW due to lacking of a circulation network for CHW. The CHW network configuration is therefore used as evaluation of the Tichelmann concept.

Figure 4.10 shows the cost categories for Cu/PU/PE and PB/PE/PE systems for central hot water circuits.

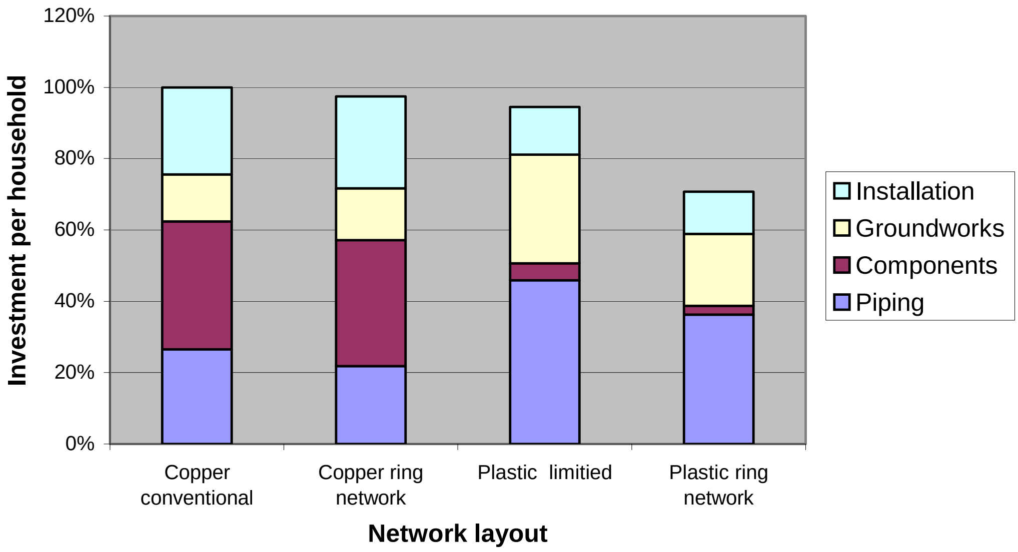


Figure 4.10: Investments per household for central hot water

In the copper network the costs for components is the largest category. The costs for piping material is relatively high compared to steel networks, due to the higher price for copper systems. There is a small advantage for the PB/PE/PE system both for tree-type and ring network.

This advantage is highlighted again when the investments for CHW are summed with the district heating network in figure 4.11.

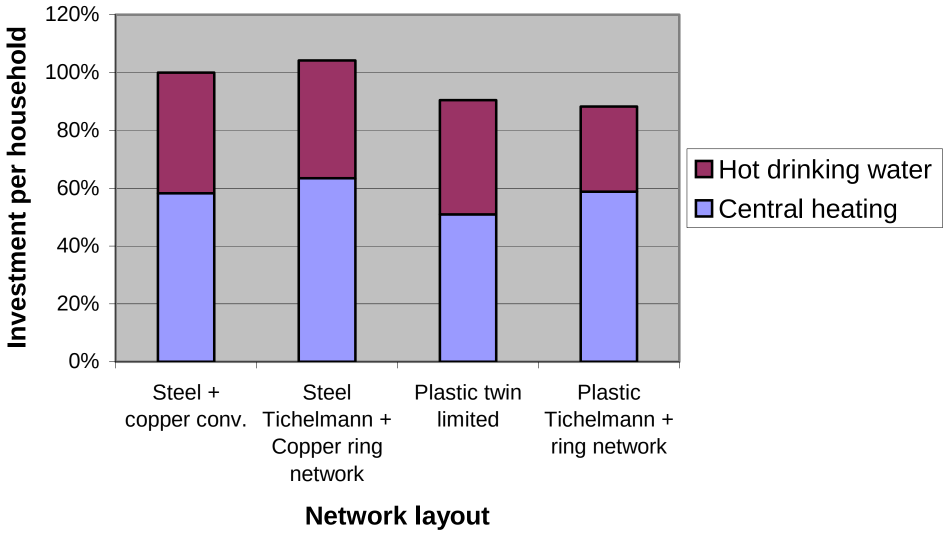


Figure 4.11: Total investments per household for central hot water

Figure 4.11 shows the advantage of Tichelmann network configuration in combination with the PB/PE/PE piping system for central hot water. However, again because of the difficult planning and organisation for Tichelmann the use of tree-type networks with limited twin diameters is preferred.

In table 4.2 the total investment costs for low density districts per household.

Table 4.2 Total investment costs for high density districts per household

Configuration	IHW		CHW	
Layout	St/PU/PE single tree-type	PB/PE/PE twin limited diameters	St/PU/PE + Cu/PU/PE single tree-type	PB/PE/PE twin limited diameters
Piping network	39%	34%	67%	60%
Engineering/supervision	15%	15%	23%	23%
Consumer substation	28%	28%	14%	14%
Central substation	18%	18%	20%	20%
Total	100%	95%	123%	117%

4.8 Cost analysis high-rise building district

Also for the high-rise district network cost analyses have been performed. The district consists of 130 apartments, situated in four high rise buildings (ca. 161.1 houses/ha)

An important difference between high-rise and low-rise building districts are the required safety measures in high-rise buildings. The DH pipes are situated in shafts to reach from the ground floor to the upper floor. In case of fire, the chance of fire spreading should be minimised. The materials in conventional steel and copper systems function as fire decelerator from itself. For the PB/PE/PE systems however, the materials easily melt and the fire can spread. Therefore, between the different floors there has to be a fireproof seal.

Also due to the high flexibility of the PB/PE/PE system, the pipes need to be fixated in the shafts with fixation anchors.

These measures lead to higher investment cost per household for the plastic piping system compared to conventional systems.

Another difference in high-rise buildings is the use of un-insulated service pipes that are insulated afterwards. This makes installation easier and cheaper.

4.8.1 Analysis individual hot water (IHW)

The individual hot water configuration is analysed for conventional network with St/PU/PE piping, PB/PE/PE single pipes and PB/PE/PE twin piping with limited diameters. The total costs are determined in the same way as described in paragraph 4.6.1.

Figure 4.12 shows the total investment costs for the high-rise district.

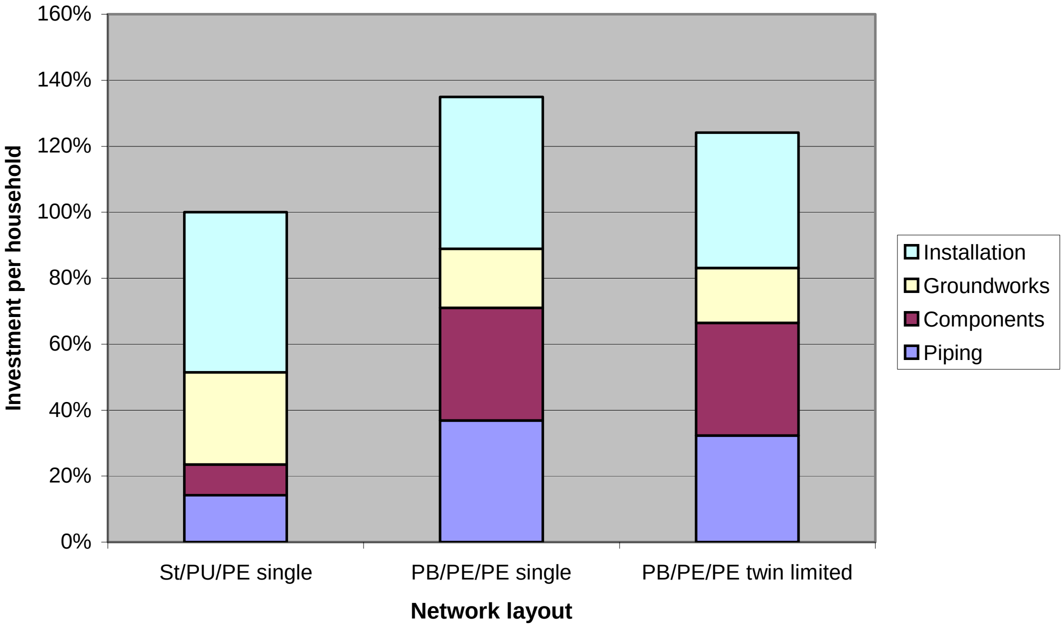


Figure 4.12: Total investments per household for individual hot water

In the high-rise district total investment costs for the St/PU/PE network are significantly lower than plastic networks (ca. 25%). This is primarily caused by the fireproof seals and fixation anchors required for the plastic systems. The investment costs per household for the steel network is also lower than for low-rise district types. This difference is explained by the application of service pipes with separate insulation.

The plastic piping systems in high-rise buildings are more expensive than in high-density districts, again because of the fireproof seals and fixation anchors. Material costs for PB/PE/PE piping are lower, but the costs for components are relatively high.

4.8.2 Analysis central hot water (CHW)

The central hot water configuration is analysed for the conventional system. This is the Cu/PU/PE system. The network for hot water pipes is assumed to be the same as the IHW network. Parts used are also the same as in the IHW network used only with their equivalent in Cu/PU/PE and an adapted diameter range. Figure 4.13 show the investments per household for CHW.

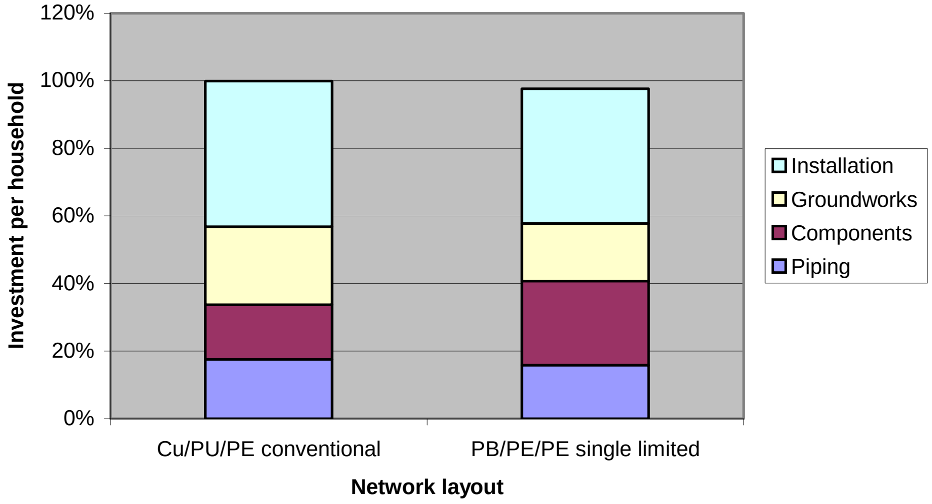


Figure 4.13: Investments per household for central hot water

Figure 4.13 shows the large costs for plastic components due to fireproof seals and fixation anchors. In total This disadvantage is highlighted again when the investments for CHW are summed with the district heating network in figure 4.14.

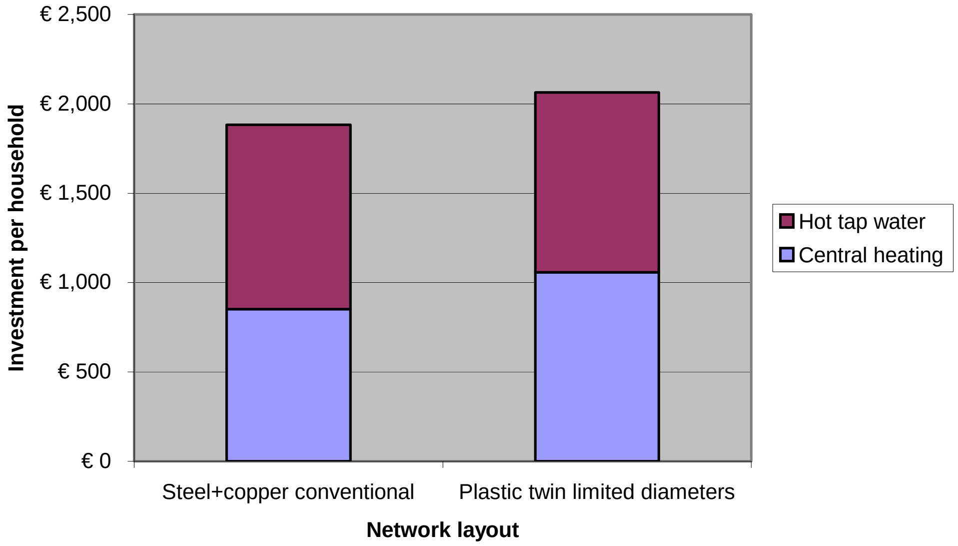


Figure 4.14: Total investments per household for central hot water

In table 4.3 the total investment costs for low density districts per household.

Table 4.3 Total investment costs for high-rise building districts per household

Configuration	IHW		CHW	
Layout	St/PU/PE single tree-type	PB/PE/PE twin limited diameters	St/PU/PE + Cu/PU/PE single tree-type	PB/PE/PE twin limited diameters
Piping network	34%	42%	75%	82%
Engineering/supervision	14%	14%	22%	22%
Consumer substation	29%	29%	15%	15%
Central substation	23%	23%	25%	25%
Total	100%	108%	136%	144%

4.9 Conclusions

The main question in this chapter is: ‘In what situations does the plastic piping system give a cost advantage when compared to the conventional piping system?’ The answer to this question has to be given for three district types.

4.9.1 Low-rise district

In low-rise districts, there is a cost benefit for the PB/PE/PE piping system, when compared to the conventional system. In the low-density district, the theoretical investment for the optimal PB/PE/PE piping system is significantly lower (10%) compared to the optimal conventional system. In the high density district the difference is not that large but still significant with almost 6.5%. The main advantages in the PB/PE/PE system are currently gained from a lower number of joints and lower trench costs.

This conclusion is based on the following application of the PB/PE/PE piping system:

The use of twin pipes, because they have:

Lower material costs.

Lower trench costs.

Lower heat loss.

The use of a limited number of diameters. The current material investments will be about 3% higher, but the following advantages are expected to have higher impact:

Economies of scale: less diameters means higher numbers per diameter

Logistic advantages: especially caused by stock reduction.

An IHW configuration: CHW have higher investments in all situations. The fact that no heat exchanger is required in CHW networks, does not lead to enough savings to cover the extra investment in the grid.

A tree-type layout: Tichelmann configurations are more expensive than the tree-type layout due to larger diameters. For the PB/PE/PE system, the increase of costs for large diameters is exponential.

House connections are made under the housing blocks. Watertight joints are relatively expensive. When connections are made under the housing blocks, a very low number of these joints are required, because underground pipes can be laid in long lengths.

4.9.2 High-rise district

There is currently no cost benefit in high-rise districts for the PB/PE/PE piping system compared to the conventional system. The optimal costs for the plastic system are about 25% higher than the conventional system. The advantages in low rise districts do not hold in this district type: trenches are relatively short and the conventional network requires only a little number of joints as well. On the other hand, the PB/PE/PE system requires some additional investments: fireproof seals and fixation anchors.

4.9.3 Further developments

Piping costs are determining in plastic piping systems. They account for more than 50% of the total investment. Especially the gap between raw material costs and product prices seems to be relatively high. The product prices are market driven, and they may drop when applied numbers increase.

Installation costs for the plastic pipe system are still uncertain. The cost analysis is based on tariffs given by three contractors, having relatively little experience with the system. Costs for installation of the PB/PE/PE system can therefore be seen as a maximum, but they are expected to decrease as contractors become more experienced with the system. The most important areas of improvement in this matter are:

Laying pipes

Connections

Chapter 5: Long term behaviour

5.1 Introduction

This chapter describes several studies concerning the long term behaviour of the plastic piping system. Because the PB/PE/PE system is a new product, the consequences of long term use are not yet known. The characteristics of the materials used may lead to some risk in the long term. Therefore, the research that forms the basis for proving the system in the long term is mainly theoretical.

The first paragraph presents the results of an assessment by TNO Science and Industry of the thermal insulation by polyethylene foam.

The second paragraph explains the risks of corrosion due to oxygen diffusion through plastic piping systems for the total system, heat exchangers, radiators and couplings. The research is performed KEMA Nederland BV.

The third paragraph quantifies the change in the thermal insulation of the PE foam as a function of the exchange of gas or vapour between foam cells and the environment. This study is also carried out by TNO Science and Industry.

5.2 Thermal insulation by PE (polyethylene) foam

5.2.1 Introduction

The most important thermal insulation component in a district heating piping system is the insulation foam. In order to prove the plastic piping system as a good alternative to steel piping systems, the PE insulation foam in the PB/PE/PE system was assessed by TNO Science and Industry. This paragraph presents the assessment of water flux and the heat transfer together with some measurements on the fraction of open cells of the PE foam.

The experiments to quantify the fraction of open cells of the PE foam are presented in paragraph 5.2.2. The limited accuracy of those experiments is explained there.

Calculations on the water flux and the heat transfer are given in chapter 5.2.3. The calculations are based on the experimentally determined fraction of open cells, the averaged cell dimensions in the corresponding PE foam, literature values for the water diffusion coefficients, the water absorption by the foam and the heat conductivity of the different layers. The heat conductivity of an insulated pipe has been determined. The water flux and the water vapour in the cells have been worked out for three situations.

In APPENDIX I a model of the PE foam is explained and a calculation is shown of the water flux through PE foam.

A summary and the conclusions are given at the end of this paragraph.

5.2.2 Experimental

A corrugated PE pipe of about 30 cm with a two cm thick PE foam layer was obtained from manufacturer samples. The foam was lightly bonded to the flexible corrugated PE pipe by a welding procedure. It was stated that the sample would not contain any blowing agent as a result of the ageing history experienced by the sample.

The outer diameter (outer corrugation) amounted to 125 mm, the wall thickness of the corrugated PE pipe was about 1 mm and the thickness of the PE foam layer about 20 mm.

A number of specimens were cut from the PE foam. The fraction of open cells was determined according to ISO 4590 method 1 with some minor modifications. As a consequence of the given sample, it was impossible to obtain the prescribed size. The size and the weight of the specimens obtained are given in table 5.1. The density has been calculated using those values and amounted to 37.5 ± 1 kg/m^3.

Table 5.1: Size and weight of specimens used to determine the fraction of open cells

Width (mm)	Length (mm)	Thickness (mm)	Weight (g)	Density (kg/m^3)
31.63	40.42	15.40	0.718	36.5
30.24	40.34	10.73	0.482	36.8
32.00	40.20	9.46	0.439	36.1
31.19	40.51	5.54	0.262	37.4
31.00	40.16	5.64	0.257	36.6
31.54	39.96	5.07	0.236	37.0
31.09	40.52	5.06	0.246	38.6
25.06	24.83	15.02	0.365	39.1
25.03	24.88	14.99	0.360	38.6
25.08	25.11	14.81	0.359	38.5
Average				37.5 ± 1.0

The experimental results to calculate the fraction of open cells are shown in figure 5.1. The calculated fraction of open cells amounted to 6 ± 3 %. Although this value is already low, the actual value is probably too high, because the stiffness of the PE foam studied is low. The modulus of the PE foam studied is estimated to be less than 1 MPa, when data from Saechtling [6] is taken into account. A consequence of this low modulus is that a volume increase of about 6 % is expected at an under-pressure of 0.2 bar.

When the calculated fraction of open cells is corrected for the low modulus, the value is reduced to some extent.

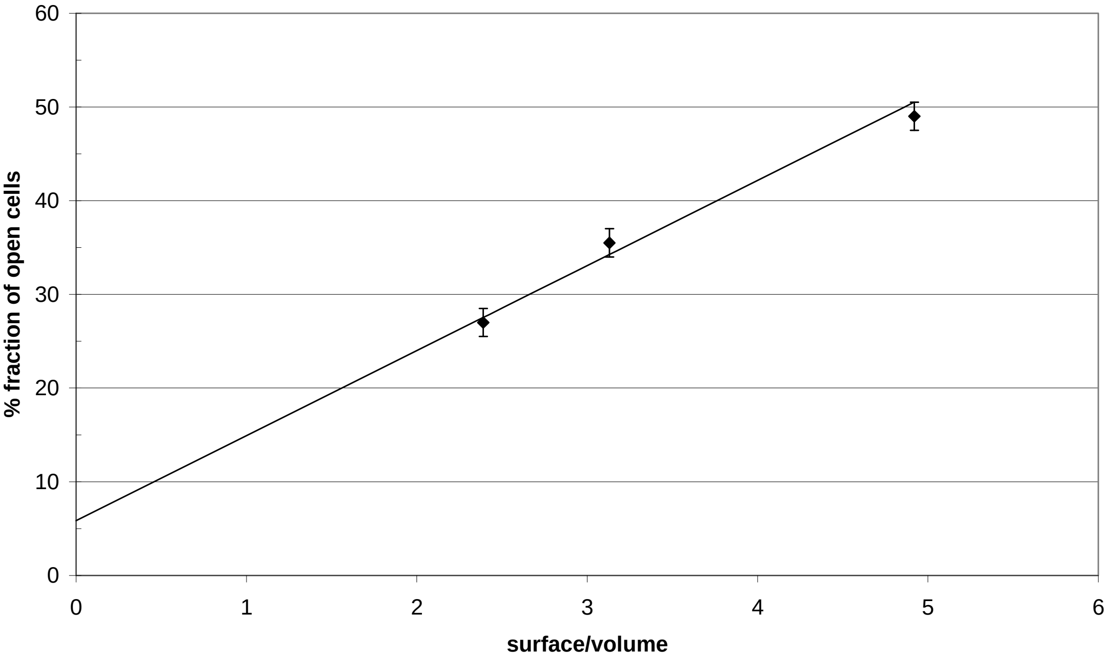


Figure 5.1: Experimental results of fraction of open cells

An additional measurement based on the buoyancy was performed to improve the experimental value of the fraction of open cells. However, the measurements of the buoyancy were greatly scattered due to the accuracy of the applied load cell and a few adhering air bubbles. The application of a detergent and an ultrasonic bath could not solve the latter completely. The calculated values for the fraction of open cells based on the additional measurements varied between 0 and 8%. As a consequence, two values have been included for the calculation performed in paragraph 5.2.3, namely 0 and 6%.

5.2.3 *Calculations*

Characteristics of PE foam:

Density: 38 kg/m^3

Cell size: ∅ ~ 1 mm

Cell wall thickness: 20-100 µm

Fraction of open cells: 0 and 6 %

One thermally bonded intersection along the length of the pipe.

Data from literature

Transport properties of water vapour in LD (low density) PE and HD (high density) PE at ambient temperature found in literature are presented in Appendix II table 2. The coefficients mentioned in Appendix II table 1 are expected to show an increase of a factor of 3-10 per 30 °C.

The PB pipe was included in the calculation of the heat transfer and the water transport. The water permeation coefficient of PB amounts to 0.47-0.74 g/m^2/day when a thickness of 1 mm is assumed. A value for the water diffusion coefficient in PB was not found. The effect of the barrier layer of the PB has been ignored here.

Composition of thermally insulated pipe

The composition of the insulated pipe studied is shown in figure 5.2.

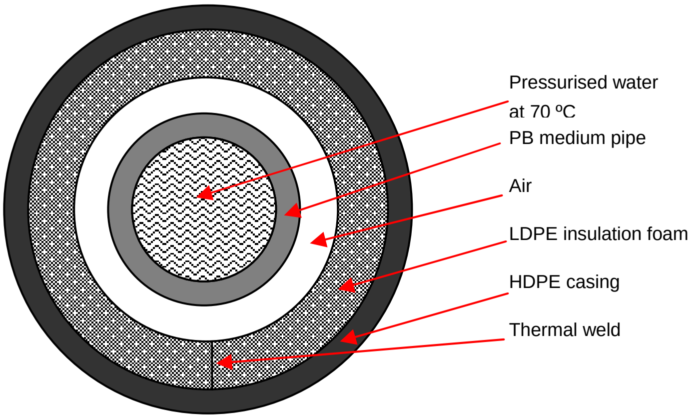


Figure 5.2: Schematic illustration of the insulated flexible district heating pipe

The dimensions of the insulated PB/PE/PE pipe studied are given in table 5.2. The dimensions have been applied in the calculations in this report.

Table 5.2: Composition of insulated pipe

Layer	Inner diameter (mm)	Outer diameter (mm)	Wall thickness (mm)
PB pipe	51.4	63	5,8
Air	63	70	3,5
Foam	70	108	19

Corrugated pipe	108	125	1
Soil	110	1000	445

Calculated heat transfer and temperature gradient

The calculation of the water flux depends on the temperature. The diffusion coefficient increases with an increasing temperature. The temperature gradient over the different layers can be calculated for a stationary situation starting from a constant heat flux, Q, from the hot water in the PB pipe to the surrounding soil.

The heat flux per layer, Q_i, is represented by:

$$Q_i = \frac{\lambda_i A_i}{d_i} \Delta T_i \qquad (5.1.1)$$

Where:

Q_i	[W]	Heat conductivity
λ_i	[W/m.K]	Lambda of insulating foam
A_i	[mm^2]	Effective surface
d_i	[mm]	Thickness of the layer
ΔT_i	[-]	Temperature difference over the ith layer

The difference between the inner and outer surface of the thick walled PB pipe is averaged.

The layers considered are mentioned in table 5.2.

From $Q=Q_i=\ldots$, it follows that:

$$\frac{\Delta T_{total}}{Q} = \sum_i \frac{\Delta T_i}{Q} = \sum_i \frac{d_i}{\lambda_i A_i} \qquad (5.1.2)$$

Where:

ΔT_{total}	[-]	Difference in temperature (hot water in PB pipe and in surrounding soil)
Q_i	[W]	Heat conductivity
A_i	[mm^2]	Effective surface
λ_i	[W/m.K]	Thermal conductivity
d_i	[mm]	Thickness of the layer

The applied values for λ_i, A_i and d_i and the calculated values for the temperature gradient over the layers are presented in tables 5.5 and 5.6.

Three situations are considered:

watertight PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe and hot water temperature of 65 °C;

leaking PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe and hot water temperature of 65 °C;

watertight PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe, leaking PB pipe and hot water temperature of 65 °C.

Situation II is almost identical to situation I. As the calculation in Appendix I shows, there is a net water flux to the soil. A leaking PE pipe leads to an increase in heat capacity of this layer. However, the influence of the higher heat capacity is limited because the PB wall is relatively small. The bonded intersection in the foam layer will increase the heat conductivity to some extent. It is expected that this increase is comparable with an additional fraction of open cells of 2 %.

The values presented in table 5.3a can be applied as long as no water condensation occurs in the open cells.

Table 5.3a: Situation II: no intersection considered in the PE foam; fraction of open cells is zero

Layer	l_i (W/m.K)	d_i (mm)	A_i (m^2)	$l_i A_i/d_i$	Fraction**	T (°C)
Hot water						65
PB	0.23	5.8	0.18	7.13	1	62
Air	0.03	3.5	0.21	1.79	1	51
Foam	0.04	19	0.28	0.59	1	16
PE wall corrugated pipe	0.4	1	0.34	54.79	0.4	15
Soil	1[2]	445	1.74	3.92	1	10
DT_{total}	55	°C				
Q	20.6	W/m pipe				

Table 5.3b: Situation II: thermally welded intersection in the PE foam; fraction of open cells is 6%

Layer	l_i (W/m/K)	d_i (mm)	A_i (m^2)	$l_i A_i/d_i$	Fraction	T (°C)
Hot water						65
PB	0.23	5.8	0.18	7.13	1	61
Air	0.03	3.5	0.21	1.79	1	45
Foam	0.07[3]	19	0.28	0.59	1	18
PE wall corrugated pipe	0,4	1	0.34	54.79	0.4	17
Soil	1	445	1.74	3.92	1	10
DT_{total}	55	°C				
Q	28.3	W/m pipe				

---

[2] A value of 1 was chosen and not a value of 2.7, because the soil surrounding the insulated pipe will heat to some extent. As a consequence, the soil in not saturated with water in the direct surroundings of the insulated pipe.

[3] The water heat conductivity is 0.6; 6 % of 0.6 W/m/K is 0.036 and has been rounded down to 0.03 W/m/K. This estimate is conservative, because it is assumed that the water condenses in the open cells. However, the water flux calculations on an intact PB pipe show that water vapour is only present in the open cells. In that case the values presented in table 5.3a should be used.

The closed cells of the PE foam will slowly be filled by water as a result of water condensation. Situation III, the situation with a leak in the PB pipe, is slightly different. The net water flux is higher. The calculated values for this situation can be found in Appendix III table A.5.

Calculated water flux

The water flux is analogous to the heat flux. The water flux, j_i, in the i^{th} layer is shown by:

$$j_i = \frac{D_i A_i}{d_i} \Delta c_i = \frac{D_i A_i}{d_i} c_{i0} \Delta a_i \qquad (5.1.3)$$

Where:

j_i	[g/m^2/s]	Flux in layer I
d_i	[mm]	Thickness of layer I
D_i	[m^2/s]	Water diffusion coefficient
A_i	[mm^2]	Effective surface
Δc_i	[g/l]	Water concentration difference over the i^{th} layer at equilibrium

The calculation is based on the thermodynamic activity, a_i which is defined by $c_{i0}a_i=c_i$. More details about the water flux can be found in the Appendix I.

As in the heat flow calculations, an average diameter was assumed.

The layers considered are mentioned in table 5.2.

From $j=j_i=\ldots$, it follows that:

$$\frac{\Delta a_{total}}{j} = \sum_i \frac{\Delta a_i}{j} = \sum_i \frac{d_i}{D_i A_i c_{i0}} \qquad (5.1.4)$$

Where:

j	[g/m^2/s]	Flux
Δa_{total}	[-]	Difference in activity between hot water and water vapour in the soil
d_i	[mm]	Thickness of layer I
D_i	[-]	Water diffusion coefficient
A_i	[mm^2]	Effective surface
c_{i0}	[g/l]	Water concentration

The overall water flux is dominated by the water flux through the relatively thick wall of the PB pipe provided that no leakage occurs through cracks in the wall of the PB pipe. It is assumed that the diffusion coefficient of water in PB amounts to 2×10^{-11} m^2/s. The exact values for the diffusion coefficient and the water sorption of both PB and the barrier layer are needed for a more accurate calculation of the water flux.

A net water flux from the PB pipe to the soil will occur after equilibrium is reached. This equilibrium is expected to be realized within a couple of days. The net water flux to the soil will be caused by the lower temperature of the soil compared with that of the hot water in the PB pipe. Water will tend to condense in the colder soil.

As a result of the heat transfer, the temperature of the soil surrounding the insulated hot water pipe will be higher than the average soil temperature. Even when the pipe is in groundwater, this groundwater will be absent directly near the pipe. The activity of the water vapour at the outer pipe surface will equal the saturated vapour pressure at the average soil temperature divided by the saturated vapour pressure at the outer surface temperature of the pipe.

The change in temperature and the water activity over the walls of the insulated pipe studied is shown graphically in figure 5.3. The driving force for the water flux after the equilibrium is reached is the condensation of water in the soil at some distance from the insulated pipe.

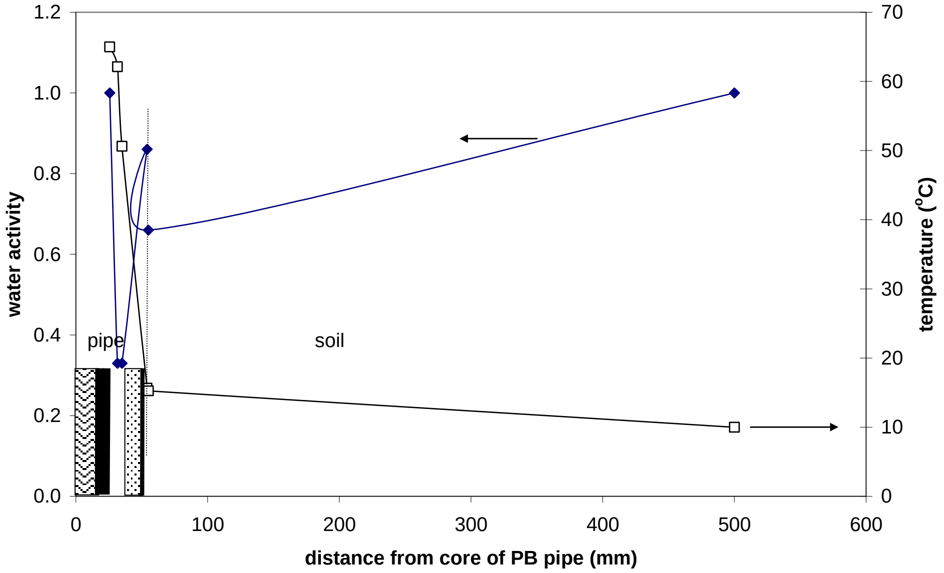


Figure 5.3: Change in the water activity and the temperature (situation 1) over the walls of the insulated pipe and in the soil. The calculation is shown in APPENDIX I

The values corresponding with the situation shown in figure 5.3 are given in table 5.4a. The water activity in the closed cells of the PE foam increases outwards as a result of the decrease of the temperature from the hot water to the soil.

Table 5.4a: Situation II: Water flux through the walls of the insulated pipe studied; situation 1; no intersection in the PE foam; fraction of open cells is zero

Layer	D_i (m^2/s)	d_i (mm)	A_i (m^2)	c_{i0} (g/m^3)	$D_i A_i c_{i0}/d_i$ (g/day/m pipe)	fraction	T (°C)	a_i

Hot water							65	1.00
PB	2.0x10^{-11}	5.8	0.18	1000	0.0054	1	62	0.33
Air	1.0x10^{-6}	3.5	0.21	143	738	1	51	0.33
Foam	1.7x10^{-11}	19	0.28	500	1.06	25	16	0.86
PE wall corrugated pipe	8.3x10^{-12}	1	0.34	500	0.74	1,5	15	0.66
Soil	1.0x10^{-6}	445	1.74	13	4.33	1	10	1.00
J	0.036	(g/day/m pipe)						

Table 5.4b: Water flux through the walls of the insulated pipe studied; situation II; no intersection in the PE foam; fraction of open cells is 6%

layer	D_i (m^2/s)	d_i (mm)	A_i (m^2)	c_{i0} (g/m^3)	$D_i A_i c_{i0}/d_i$ (g/day/m pipe)	Fraction	T (°C)	a_i
Hot water							65	1.00
PB	2.0x10^{-12}	5.8	0.18	1000	0.0054	1	61	0.39
Air	1.0x10^{-6}	3.5	0.21	136	703	1	45	0.39
Foam	1.5x10^{-11}	19	0.28	500	0.99	25	18	0.76
PE wall corrugated pipe	9.0x10^{-12}	1	0.34	500	0.80	1,5	17	0.58
Soil	1.0x10^{-6}	445	1.74	14	4.88	1	10	1.00
j	0.033	(g/day/m pipe)						

The presence of open cells does not affect the water flux to the soil because the water flux through the PB pipe wall is dominant (see remark under table 5.3b).

An analogous argument holds for the absence or presence of cracks in the wall of the outer corrugated PE pipe. The presence of cracks in this corrugated pipe (situation II) will not affect the water flux significantly. Therefore, no additional table is included for this situation.

Situation III, the situation with a leak in the PB pipe, is slightly different. The net water flux is higher. The calculated values for this situation can be found in Appendix III table 5.

The answer to the question “does water condensation occur in the closed PE foam cell?” is yes, but slowly. The fact that the diffusion coefficient in PE decreases as the temperature decreases means that there is a net diffusion of water into the foam.

The diffusion rate is determined by the water flux through the corrugated pipe to the soil and of the water flux through the foam cell walls. If the thickness of the foam cell wall is 0.04 mm, the net flux will be less than 0.4 g/day/m pipe. If the thickness of the foam cell wall is 0.1 mm, the net flux will be less than 0.1 g/day/m pipe. The configuration considered contains about 5.3 litre foam per m. This means that it takes at least 30 years before the closed foam cells are completely filled with water.

The modelling of the water condensation in the foam is uncertain because the structure of the foam is irregular and because interface effects can interfere with the water condensation in the cells. Therefore the recommendation is to determine the water condensation experimentally in the case of a leaking PB pipe. This situation can be simulated by exposure of the inner surface of the foam to hot water for a period of about 6 months and monitoring the weight of the foam.

5.2.4 Summary and conclusions

TNO Science and Industry performed measurements and calculations within the framework of an evaluation study of an insulated plastic pipe system for district heating.

The fraction of open cells was determined experimentally. The accuracy of those measurements was limited due to the appearance of the PE foam under study. The foam deformed under the prescribed under-pressure during the measurements according to ISO 4590. Moreover the buoyancy measurements were not accurate due to the adhering air bubbles. The final result of these experiments was that the fraction of open cells is not exceeding 6 ± 3 %.

The temperature gradient over the different layers of the insulated pipe studied is needed for the calculation of the water flux through the walls of the insulated pipe. Where available, literature data on the diffusion coefficients, the heat conductivities and the water saturation levels were used in the calculations. The sizes of the different pipe walls are estimated using the available pipes and data from the PB/PE/PE brochure.

The temperature gradient and the water flux were calculated for three situations, namely

watertight PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe and hot water temperature of 65 °C;

leaking PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe and hot water temperature of 65 °C;

watertight PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe, leaking PB pipe and hot water temperature of 65 °C.

Situation II seems to be almost identical to situation I and has therefore not been presented separately.

A temperature gradient of 35 ºC and a heat flux of 21 (W/m pipe) has been calculated for situation I provided that the PE foam does not contain open cells. A temperature gradient of 27 ºC and a heat flux of 28 (W/m pipe) has been calculated for situation I when the foam contains 6 % of open cells. The thermal bonding of the intersection in the foam is expected to have a smaller influence on the temperature gradient and the heat flux than 6 % of open cells in which water condenses. The condensation of water in open cells is not probable for the situations I and II.

A water flux to the soil of 36 (mg/day/m pipe) has been calculated for situation I.

A temperature gradient of 46 ºC and a heat flux of 27 (W/m pipe) has been calculated for situation III provided that the PE foam does not contain open cells. A temperature gradient of 41 ºC and a heat flux of 41 (W/m pipe) has been calculated for situation III when the foam contains 6 % of open cells.

A water flux to the soil of 80 (mg/day/m pipe) has been calculated for situation III. However, in this situation slow water condensation occurs in the cells. A preliminary calculation showed that it will take at least 30 years before all cells are filled with water.

5.3 Oxygen diffusion and risk for corrosion

5.3.1 Introduction

A major threat to hot water systems is the diffusion of oxygen through plastic materials. As a consequence there is a risk for corrosion in the steel and copper components of the total system, e.g. heat exchangers, radiators and couplings. To overcome the diffusion of oxygen through the PB medium pipe, the PB/PE/PE system is supplied with an EVOH (ethylene vinyl alcohol) coating. This is a diffusion barrier that reduces the ingress of oxygen. Nevertheless there is still a certain diffusion of oxygen, even with the EVOH barrier.

In the next paragraphs the risk for corrosion is further explained and recommendations are given to minimise this risk. This research is performed by research institute KEMA Nederland BV.

5.3.2 Mechanism

In a district heating system the carbon steel lines are in contact with de-aerated water. Iron is not stable and will dissolve by forming Fe^{2+}. The concentration of Fe^{2+} close to the surface of the steel increases, as does the pH-value. Fe will react with water by forming hydrogen in accordance with:

$Fe + 2\,H_2O \rightarrow Fe(OH)_2 + H_2\uparrow$ (1)

The formation and deposition of $Fe(OH)_2$ gives a first protective layer. In the presence of oxygen $Fe(OH)_2$ can react further to Fe_2O_3 in accordance with:

$4\,Fe(OH)_2 + O2 \rightarrow 2\,Fe_2O_3 + 4\,H_2O$ (2)

On the other hand at temperatures above 80 °C a magnetite (Fe_3O_4) layer is formed directly on the surface of the carbon steel in accordance with:

$3\,Fe + 4\,H_2O \rightarrow Fe_3O_4 + 4\,H_2\uparrow$

This magnetite layer is thicker than the $Fe(OH)_2$ and gives more protection. Nevertheless the protective layer also dissolves, especially in flowing water, in accordance with:

$Fe_3O_4 + H_2 + 2\,H_2O \leftrightarrow 3\,FeOH^+ + 3\,OH^- \rightarrow 3\,Fe(OH)_2$

By dosing NaOH or phosphate as alkalizing agent, the ion OH^- causes the equation to shift to the left, with the consequence that the Fe_3O_4 dissolves less. At pH= 10 the magnetite remains at its lowest solubility.

If the water contains dissolved oxygen (> 20 ppb), the iron can also react under formation of magnetite (3) or hematite (4) depending on the temperature, in accordance with:

$3\,Fe + 2\,O_2 \rightarrow Fe_3O_4$ (3)

$4\,Fe + 3\,O_2 \rightarrow 2\,Fe_2O_3$ (4)

These processes are instantaneous. Therefore the oxygen concentration in the district heating system will be low despite the constant diffusion of oxygen through the PB pipe into the water.

In systems with temperatures < 120 ºC the protection of the formed protective layer ($Fe(OH)_2$, Fe_2O_3, Fe_3O_4) is limited. The layer is porous and comes away from the wall, etc. In the case of installation of PB pipes in existing systems, earlier formed magnetite can be converted to Fe_2O_3, and FeOOH is also often seen.

Despite an optimal water treatment and the presence of a protective layer, the conclusion is that oxygen will always be able to enter the system and corrode carbon steel components.

5.3.3 Calculation and discussion

The parameters in a typical district heating system with 400 connected houses are as follows:

− 482 m^2 PB pipe material (outside surface)

− permeability 0.6 mg/m^2 oxygen per day at 80 °C determined by KIWA

− 4000 m2 carbon steel surface (heat exchangers and radiators) due to 400 houses connected to the system.

Permeability of PB pipe with EVOH

KIWA determined a permeability of 0.6 mg/m^2 oxygen per day for a PB barrier pipe of 25 mm external diameter at a temperature of 80 ± 0.5 ºC.

During the test, water at 80 ºC circulated in the PB tubes, which is compatible with the circumstances in district heating pipes. The outside of the tube was exposed to air at 80 ºC, which is totally different from the circumstances in the soil. The surface of district heating pipes located in the sand is only partly in contact with air: 1 m^3 sand contains an average of ~200 l air (20%).

So calculating with a permeability of 0.6 mg/m^2 per day is a worst-case situation. Therefore calculations were also made with a permeability of 0.3 and 0.12 mg/m^2 per day, respectively 50% and 20% of the permeability determined by KIWA .

On the other hand a higher permeation is possible as well, in the case of damage to the EVOH layer. Further determination of the influence of the difference between the test conditions and the actual circumstances in practice was not part of the research.

Corrosion of the carbon steel surface

Corrosion products that can be formed are a mix of $Fe(OH)_2$, $Fe(OH)_3$, FeOOH, Fe_2O_3 and/or Fe_3O_4. If a temperature in the district heating system of 70/40 ºC (new systems) or 90/50 ºC (existing systems) is assumed for the calculations as worst case scenario, 1 mg oxygen will react with 7 mg iron and 10-13 mg corrosion products will be formed.

Based on the above parameters and a permeability of 0.6 mg/m^2 per day, 289 mg (482 x 0.6) oxygen will react with 2 g iron per day. That is about 37 kg of iron in 50 years on a total surface area of 4000 m2. In case of general attack of carbon steel components and a density of iron = 7.8 g/cm^3, the wall thickness decrease is about 1.2 µm in 50 years. If a smaller number of houses (200 ~ 2000 m^2) are connected to the same amount of PB pipe, the wall thickness decrease is about 2.4 µm in 50 years. As well as on the basis of the number of connected houses, the surface area has also been determined on the basis of the amount of radiators in use. This means that during summer the surface area can be reduced to 10% of the total area. In the case of a reduction of the surface area to 400 m^2, a wall thickness decrease of about 12 µm in 50 years can be calculated.

In table 5.4 the same calculations have been made for lower permeability of oxygen.

Table 5.4: Oxygen ingress, corrosion products formation and wall thickness decrease at different oxygen permeability's

permeability	**mg/m2per day**	**0.6**	**0.3**
oxygen ingress	mg/day	289	145
iron consumption	g/day	2.0	1.0
	kg/50 year	37	18.5
corrosion products	kg/50 year	53-71	26-35
wall thickness decrease in case of a carbon steel surface of			

4000 m2	mm/50 year	1.2	0.6
2000 m3	mm/50 year	2.4	1.2
400 m2	mm/50 year	12	5.9

The wall thickness decrease is acceptable in the case of an equally divided corrosion attack, but oxygen may initiate localised corrosion, for instance pitting corrosion. At the joints of the PB tubes with the carbon steel tubes the oxygen levels are at their maximum and, as mentioned before, this oxygen will react instantaneously with the carbon steel. The corrosion takes also place on locations with a thin protective layer and with conditions that foster corrosion. The risk of severe localised corrosion (pitting) in the carbon steel parts under the conditions mentioned is not quantitatively predictable. But if pitting occurs, it is an out of control process and corrosion rates of mm/year are possible.

A key issue is to maintain an optimal water quality and prevent ingress of air and salts because the occurrence of pitting corrosion is strongly promoted by the presence of salts, especially chlorine salts.

Calculations in accordance with BRL5605

According to the BRL5605 (KIWA 1997), the permeability of oxygen should be ≤ 1.6 mg/m^2 per day for a PB pipe at a temperature of 80 ºC. Therefore calculations are made with a permeability of 1.5 mg/m^2 per day as a worst case scenario and calculations with a permeability of 0.3 mg/m^2 based on the assumption that sand contains an average of ~200 l air (20%). The results are described in table 5.5.

Table 5.5: Oxygen ingress, corrosion products formation and wall thickness decrease at different oxygen permeabilities

permeability	mg/m2per day	1.5	0.3
oxygen ingress	mg/day	723	145
iron consumption	g/day	5.1	1.0
	kg/50 year	92	18.5
Corrosion products	kg/50 year	132-176	26-35
wall thickness decrease in case of a carbon steel surface of			
4000 m2	mm/50 year	3.0	0.6
2000 m3	mm/50 year	5.9	1.2
400 m2	mm/50 year	30	5.9

Comparison with a local central heating

To give an impression of the corrosion risk a comparison was made with a local central heating system in a single house. The following parameters were used:

system content: 125 l;

potable water: oxygen 8 mg/l;

annual make up: 5 l;

total refill due to boiler replacement: 1/ 10 years.

Results in 50 years:

By filling the system with potable water 1.0 g O_2 is introduced, this will form 10-13 g of corrosion products. The annual make up will introduce 2.0 g O_2 in 50 years, which will form 20-27 g of corrosion products. In total 70-94 g corrosion products will be formed in 50 years.

In table 5.6 the local central heating is compared with the possible situations in the case of a district heating with PB/EVOH pipe.

In the worst case scenario, the corrosion is four times higher than in a local central heating system, however in the local central heating system oxygen as well as salts such as chlorine salts, are introduced with the potable water.

Table 5.6: Corrosion products at different circumstances, calculated per house

	corrosion products g/ 50 year per house
local central heating	70-94
DH, permeability 0.6 mg/m^3 per day 400 houses connected	132-177
DH, permeability 0.6 mg/m^3 per day 200 houses connected	264-353
DH, permeability 0.3 mg/m^3 per day 400 houses connected	66-88
DH, permeability 0.3 mg/m^3 per day 200 houses connected	132-177
DH, permeability 0.12 mg/m^3 per day 400 houses connected	26-35
DH, permeability 0.12 mg/m^3 per day 200 houses connected	53-71

Transport of corrosion products

Besides the corrosion of the carbon steel surface, problems can occur due to transport of corrosion products. At lower flow velocities some, if not all, will deposit.

In existing systems (without plastic pipes) there are known problems with calorimeters due to deposition of corrosion products. There are also indications of problems with modern house systems due to the more refined techniques used in these systems in combination with transport of corrosion products.

So large amounts of corrosion products, caused by oxygen diffusion by using plastic piping, may give rise to problems with calorimeters and other equipment as result of the earlier mentioned deposition.

5.3.4 Measures and control

As shown, the oxygen in the water system causes corrosion on the carbon steel surface with the consequence that the oxygen levels are expected to be low. But to check the corrosion process it is recommended to measure oxygen and hydrogen. At these levels oxygen and hydrogen should be monitored online.

Long-term corrosion could be observed by placing specimens of the used carbon steel materials at a representative place in the system. After a period of time one of the specimens can be withdrawn to determine the loss of base material.

Iron may be present in the system as dissolved and/or as oxide particles. Removal of the corrosion products may be needed by filtering the water in a bypass system.

Furthermore, up to 80 °C only some of the oxygen scavengers will react with the oxygen and prevent corrosion. It is only recommended to dose an oxygen scavenger if cleaning operations are not successful or the system water quality is not optimal (chlorine concentration and other anions > 10 mg/l). Dosing an oxygen scavenger is to be considered as an emergency measure.

KEMA Guidelines

District heating systems should be filled with demineralised, degassed and alkalised water. The quality of the make-up water should meet the following requirements:

Cation conductivity$_{25}$	<	1 μS/cm
pH25		9.5 – 10.0
Oxygen	<	0.02 mg/l.

For water in district heating systems the requirements are:

pH25	9.5 – 10.0	
Chlorine and other anions	<	10 mg/l
Oxygen	<	0.005 mg/l.

The pH is set by dosing sufficient sodium hydroxide. Chlorine, other anions and oxygen are unwanted too. If oxygen is expected to be higher then normal, extra attention should be paid to cation conductivity and the pH range should be kept to the higher end. 10 mg Cl/l corresponds with a cation conductivity of approximately 125 μS/cm.

Monitoring the chemistry should take place by determine the following parameters according to the aforementioned frequency:

specific and cation conductivity$_{25}$	continuous and recorded
pH	monthly
chlorine	monthly
iron	monthly
nitrogen	monthly
hydrogen	monthly.

5.4 Ageing of closed cell foams by exchange of gases

5.4.1 Introduction

An important functional property of the PB/PE/PE plastic piping system is the thermal insulation. The insulated pipes contain plastic foam as insulation material. This paragraph describes a research by TNO Science and Industry. The subject of this research is to quantify the change in the thermal insulation as a function of the exchange of gas or vapour between foam cells and the environment. The PE (polyethylene) and PU (polyurethane) foams are considered here.

The increase of the heat conductivity of foam after production, during storage and operation is called ageing. This ageing process is related to the exchange of blowing agent from the closed cells by oxygen and nitrogen from the environment. Sometimes an exchange by water vapour will occur. This exchange is ignored here because the water vapour pressure is low compared to the atmospheric pressure and the vapour pressure of the blowing agents applied.

The exchange of blowing agent can have some consequences for the structure of the foam. Foam from which the blowing agent diffuses faster from the cells than oxygen and nitrogen from the air diffuses inwards will lead to under-pressure in the cells. An under-pressure for a long period or an under-pressure directly after production can result in foam shrinkage. This aspect is not considered here because it is assumed that the dimension stability of the foam studied here has been optimised by the manufacturer.

5.4.2 Literature data on heat and mass transfer

General equations hold for the transfer of blowing agents through a cell wall of the foam and for that of oxygen and nitrogen from the air. The stationary flux of the gaseous blowing agent, j_i, through the i^{th} cell layer for an isothermal situation is given by [7]:

$$j_i = \frac{D_i A_i}{d_i} \Delta c_i = \frac{P_i A_i}{d_i} \Delta p_i \qquad (5.3.1)$$

Where:

J_i	[g/m^2/s/atm]	Flux in layer i
d_i	[mm]	Thickness of layer i
D_i	[m^2/s]	Water diffusion coefficient
A_i	[mm^2]	Effective surface
Δc_i	[g/l]	Water concentration difference over the i^{th} layer at equilibrium
P_i	[*mol/N.m*]	Permeation coefficient
Δp_i	[-]	Pressure gradient over the cell wall

The permeation coefficient is used in general for the flux of gases through a thin layer. Several units are in use. The example in Appendix IV shows how different units can be converted.

The values for the permeation coefficients of all relevant gases in PE material are summarised in Appendix IV table A.1 [7,8]. Those values show some temperature dependence.

The permeation of the blowing agent through PE cell walls can be reduced strongly by the addition of small amounts of stearyl stearamide and glycol monostearate [9]. The blowing agent permeation can be reduced by a factor of 10 depending on the concentration of additives applied. The oxygen and nitrogen permeation are slightly reduced by those additives.

The values for the permeation coefficients in PU are summarised in Appendix IV table A.2 [10,11]. Carbon dioxide will be produced during the production of PU foam and can be found in the cells directly after production besides the blowing agent, cyclopentane. Carbon dioxide can also be added to PU material during the processing of the foam. Therefore, carbon dioxide is included in the table. The blowing agent for the PU foam in the St/PU/PE system is cyclopentane. Cyclopentane is a liquid at ambient temperature with a boiling temperature of 49 °C. The vapour pressure up to boiling point is shown in figure 5.4.

Notice that the nitrogen and oxygen permeation coefficients are slightly lower in PU than in PE. When additives are applied in PE in order to decrease the permeation, this difference will become very small.

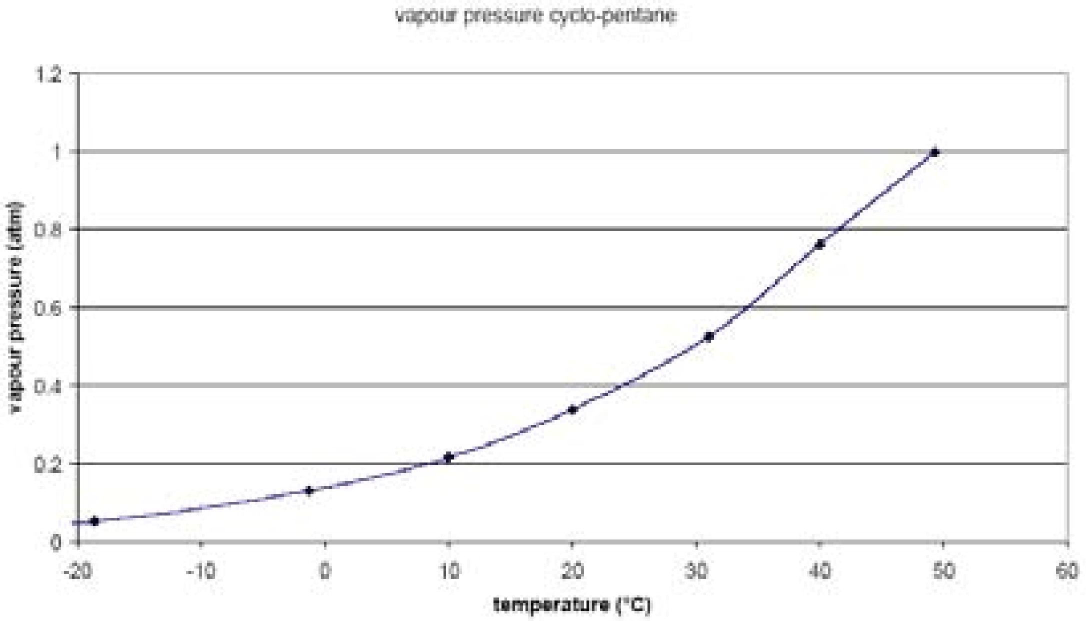


Figure 5.4: Change of cyclo-pentane vapour versus temperature

The applied values for the heat conductivity are summarised in table Appendix IV table A.3. It should be noted that this relates to values at 20-25 °C. A moderate increase is found as the temperature increases. A temperature increase of 30 °C results in an increase of about 10% in the heat conductivity.

5.4.3 Model

Plastic foam can be presented schematically by a series of parallel layers (see figure 5.5). See APPENDIX I for a model about the water flux through PE foam.

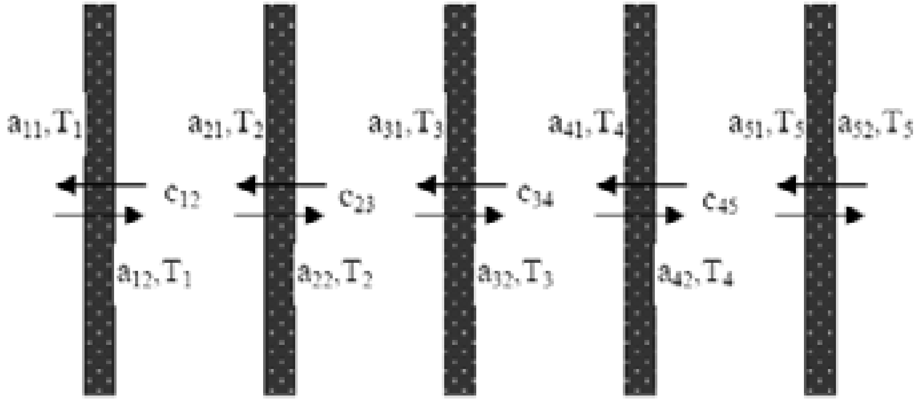


Figure 5.5: Schematic illustration of the gas flux through the plastic foam

Darker layers represent the plastic layers, arrows the flux; the plastic layers experience different temperatures (T_i); the gas activity at the left (a_{i1}) and right (a_{i2}) side of the plastic layer can differ; the gas concentration ($c_{i,i+1}$)[4] is constant between two successive plastic layers.

Pressure will be present in isothermal situations where gas fluxes occur. The layers (cell walls) through which the gases have to diffuse act as gates and as decelerators.

Gate: the stationary flux through a layer will be realised after a certain time, if the concentration on the left and right side of the layer remain constant during that time. The flux is then proportional to the concentration difference over the layer.

Decelerator: a concentration gradient has to be built up in the layer before a stationary state is realised; the flux through the layer is lower during the build-up of the gradient in the layer than in the stationary state. The gradient is realised within some minutes for oxygen and nitrogen gas at 20 °C over a 0.04 mm thick PE layer. It can take 1-2 hours for isobutane gas. The deceleration as a result of the realisation of the gradient can be ignored if it takes several days to obtain the equilibrium over the foam layer.

5.4.4 Calculations

Analogously to another TNO study presented in paragraph 5.2, the 19 mm thick PE foam is assumed to contain 19 equidistant layers with a layer thickness of 0.04 mm.

PE foam with free exchange to air

The calculations are based on the following assumption:

Foam is filled for 100 % with isobutane gas[5] directly after production;

The deceleration as explained in the previous chapter is ignored;

$P_{zuustrof}$ = 1000 [cm^3/m^2.day.atm] for 0.04 mm PE layer;

$P_{nitrogen}$ = 400 [cm^3/m^2.day.atm] for 0.04 mm PE layer;

$P_{isobutane}$ = 2000 [cm^3/m^2.day.atm] for 0.04 mm PE layer;

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[4] A comma has been added between the indices to clarify the first and the second index.

[5] Some air will be introduced during the processing of the foam material. As a consequence, the cells will contain an amount of air directly after production. This fact is ignored in the calculation presented in this chapter.

Thickness of PE layers (cell walls) is 0.04 mm;

Number of layers is 19.

Starting from the diffusion coefficients of the different gases in PE, it has been calculated that the gradient over the cell walls is realised within one hour for the idealised PE foam considered. Therefore the time needed to realise the stationary state has been ignored.

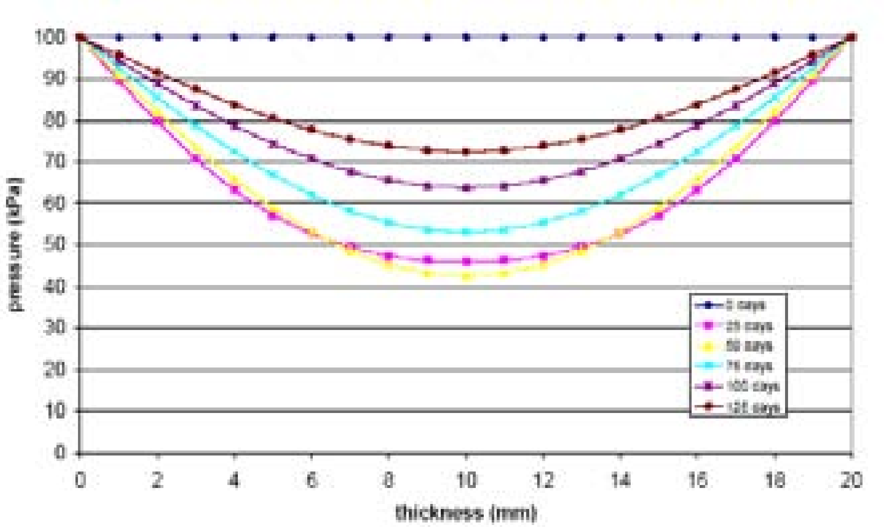

Figure 5.6: Calculated total pressure in 19 mm thick PE foam layer at 20 ºC as a function of the position in thickness direction; free exchange with atmosphere

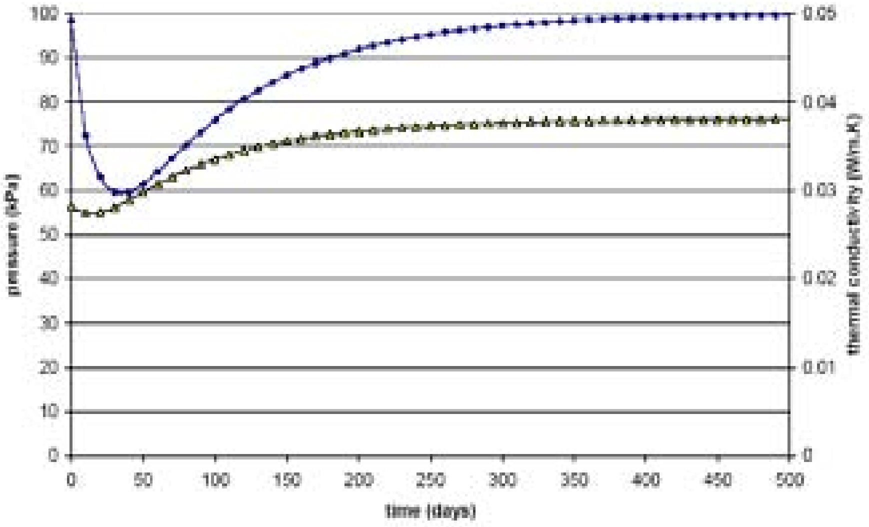

Figure 5.7: Calculated total pressure and heat conductivity (lower curve) in the foam cells versus time for 19 mm PE foam at 20 ºC; free exchange with atmosphere. An average was calculated over the thickness of the foam.

It should be noted from figures 5.6 and 5.7 and Appenidx IV figures A.4 – A.6 that a reduction of the pressure in the cells occurs because isobutane diffuses faster outwards than oxygen and nitrogen inwards. It is assumed that the cell walls are sufficiently rigid to withstand the reduction in pressure. The time needed before the equilibrium is realised will be about one year at ambient temperature and a foam thickness of 19 mm. The difference of the initial value and the final value after ageing of the heat conductivity is about a factor of 1.6. This difference is lower when the heat conductivity of the PE cell wall is taken into account, namely 1.34. The contribution of the PE cell walls to the heat conductivity is about 3 % of the value of solid PE (0.4 W/m.K).

Reeled PB/PE/PE pipe[6]

The geometry of the corrugated pipe with PE foam layer is included (see figure 5.8 and table 5.7) in the calculations. The corrugated structure of the outer pipe results in an enlargement of the effective surface for diffusion of about 60%.

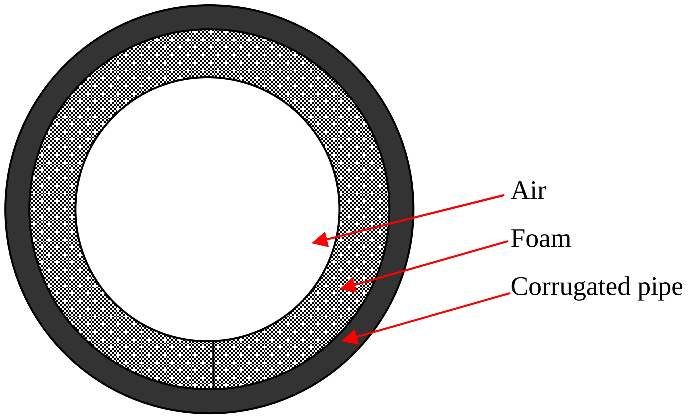

Figure 5.8: Schematic illustration of the PB/PE/PE pipe

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[6] PB hot water pipe is in the PE jacket with the PE foam insulation.

Table 5.7: Composition of insulated PB/PE/PE pipe

Layer	Inner diameter (mm)	Outer diameter (mm)	Wall thickness (mm)
Foam	70	108	19
Corrugated pipe	108	125	1

The following processes will occur:

diffusion of isobutane through the corrugated pipe into the atmosphere and of oxygen and nitrogen inwards; for the calculation is assumed that the insulated pipe is loosely reeled so that the wind can blow freely around the pipe;

diffusion of isobutane to open core and of oxygen and nitrogen from the core into the foam; these processes are not balanced; the higher diffusion of isobutane will cause a certain over-pressure, which will cause a flow of isobutane outwards in the core; consequently oxygen and nitrogen will be sucked into the pipe;

diffusion of air from the pipe ends of the insulated pipe.

The latter process (no. 3) seems to be negligible. The Stokes-Einstein relation was applied to obtain an estimate of the diffusion coefficient of oxygen in air. This estimate results in a diffusion coefficient of around 10^{-7} m^2/s. The length at the end over which air from the environment can dilute air from the core of the pipe is then ca. 3 m after one year. This length increases with the square root of the storage period. After 2 years, it becomes √2 x 3 = 4,2 m. Process no. 3 is therefore not relevant to more than 90% of a 100 long pipe.

A complex modelling is required for an accurate description of process no 2. This process is not relevant to the major part of the insulated pipe only for the open ends. Therefore an estimate has been given for the end and for the non-affected part of the reeled insulated pipe. The estimated length of the affected end parts is estimated to be around 10 – 20 m.

The change of the isobutane pressure in the cells over the thickness of the foam is presented in Appendix IV figure A.12. The 19 mm position is situated at the interface with the corrugated PE pipe.

It should be noted that some equilibrium is reached in the foam on the inner side, because isobutane will accumulate here. Moreover, the diffusion through the 1 mm thick PE jacket progresses slowly.

This progress can be approximated by an exponential relation:

$$\frac{p}{p_0} = 1 - e^{-Ct} \qquad [5.3.2]$$

Where:

p_0	[atm]	Equilibrium pressure
p_t	[atm]	Pressure at time t
C	[]	Constant that equals $P_{nitrogen}$xA/V

The volume, V, is the gas volume in the foam per m:

$V = \frac{1}{4} \pi (d^2_{outer} - d^2_{inner})$ gas fraction $= \frac{1}{4} \pi (0.108^2 – 0.07^2)\ 0.96 = 0.0051\ m^3 = 5100\ cm^3$

The surface, A, through which the permeation occurs:

$A = \pi\ d_{corrugated\ pipe}$ corrugated fraction $= \pi \times 0{,}109 \times 1.6 = 0.55\ m^2$

The permeation coefficient of nitrogen, $P_{nitrogen} = 400\ [cm^3/m^2.day.atm]$ for 0.04 mm PE layer. For 1 mm PE, this becomes 16 $[cm^3/m^2.day.atm]$. The constant C then equals:

$$(16x0.55)/5100 = 0.017$$

65% of the equilibrium concentration is thus reached after about 600 days. The data presented in figure Appendix IV figure A.13 shows that no equilibrium is reached after 500 days and that the heat conductivity after 500 days is 0.033 [W/m.K] whereas the equilibrium value amounts to 0.038.

Infinitely long PB/PE/PE pipe in soil

The geometry of the corrugated pipe with foam layer is taken from table5.7. A 63 mm diameter PB pipe is positioned in the corrugated pipe. A volume of 731 cm^3 per m length remains for air between the foam layer and the PB pipe.

The following processes will occur:

diffusion of isobutane through the corrugated pipe into the atmosphere and of oxygen and nitrogen inwards; it is assumed that the flux of gas in the surrounding soil is fast in comparison with the flux through the corrugated pipe;

diffusion of isobutane to volume between the foam and the PB pipe; some isobutane can diffuse through the PB pipe wall into the flowing hot water.

The flux of isobutane through the PB pipe wall to the flowing hot water is smaller than the flux outwards to the soil through the corrugated PE pipe. The results of the calculations without flux through the PB pipe wall are shown in the Appendix IV figures 5.14 and 5.15.

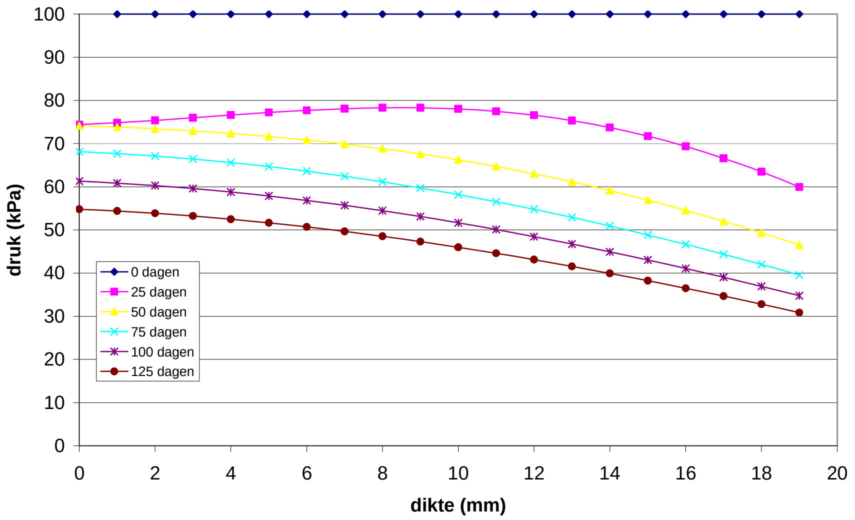

Figure 5.9: Calculated isobutane pressure in 19 mm thick PE foam layer at 20 ºC in an infinitely long corrugated PE jacket as a function of the position in thickness direction.

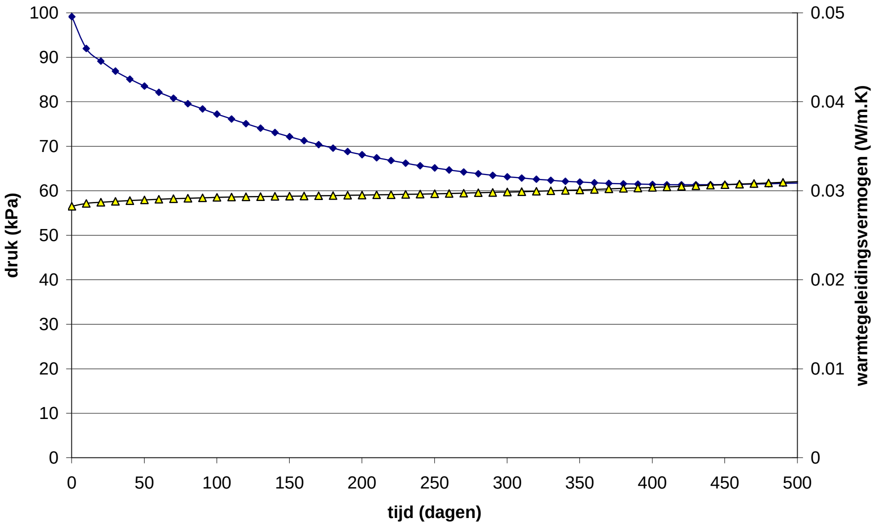

Figure 5.10: Calculated total pressure change and heat conductivity (lower curve) in the foam cells versus time for 19 mm PE foam at 20 ºC; free exchange with atmosphere. An average was calculated over the thickness of the foam NL tekst in figuur

Under the following assumption:

permeation coefficient of isobutane in PB at 65 °C is about a factor of 10 higher than that of isobutane in PE at 20 °C;

wall thickness of BP pipe is a factor of 5.8 larger than that of corrugated PE pipe;

diameter of corrugated PE is a factor of 2 larger than of PB pipe;

corrugated structure results in enlargement of the surface available for permeation of a factor of 1.6

It can be concluded that isobutane is transported twice as fast through the corrugated PE pipe as through the PB pipe wall. However, the rate of increase of heat conductivity in the insulated pipe changes only slightly when the flux through the PB pipe is considered, because the inward flux of air is responsible for the increase in heat conductivity.

No significant correction results from the incorporation of the temperature gradient through the foam, because the corrugated PE pipe is decisive for the time-dependent behaviour and the temperature of the corrugated pipe is almost equal to the soil temperature and some less than 20 °C.

PU foam with free exchange to air

Only one study was found about the heat conductivity of PU foam aged in air [14]. This PU foam was aged at 90 °F (= 32 °C). An increase of about 30% was found after 1 year ageing [11]. The final value for the heat conductivity was about 0,18 [Btu.in/h.ft^2.F] = 0.026 [W/m.K]. The rate of increase is roughly as shown in figure 5.10 for 19 mm thick PE foam. It should be noted that the thickness of the PU foam is slightly thicker (25 mm) than the PE foam (19 mm). It was not possible to validate the values of the permeation coefficients presented in table 5.13. Information on the structure of the foam is needed for this. Nevertheless, the estimated order of magnitude seems correct.

Jacket with PU foam

The PB/PE/PE system consists of an insulated corrugated PE jacket into which the plastic hot water pipe is pushed. In the conventional steel system the PU foam is applied directly around the metal hot water pipe. The situation during storage is thus identical to the situation in the soil, because the metal pipe is diffusion tight. The only difference between the storage and the operation is the temperature.

St/PU/PE system

Some interesting data was found on the St/PU/PE system [15]. This data is shown in Appendix IV figures 5.16 and 5.17. The PE pipe around the PU foam leads to a deceleration of the increase of the heat conductivity. It is likely that the increase will accelerate rather than decelerate after 500 days.

The measured values correspond to the calculated values shown in figure 5.11.

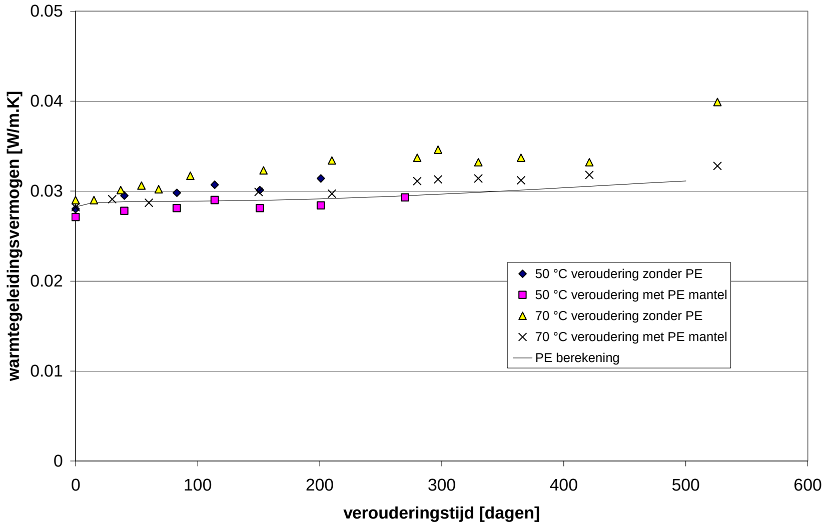

Figure 5.11: Heat conductivity of some DN50 pipe supplies with PU foam versus ageing time [12] and calculated curve (solid line) from figure 5.09

Different insulated pipe systems can be obtained from steel piping manufacturers. Here, a pipe is regarded as consisting of a metal hot water pipe, an insulating polyurethane (PU) foam layer and PE jacket. The blowing agent for PU foam is cyclopentane, carbon dioxide and a small amount of oxygen. Provided that a continuous foam process was applied, the foam density is about 60 kg/m^3 and the closed cell fraction exceeds 88%.

The lowest values for the heat conductivity are found for the smaller diameter (< 315 mm) pipes. A value of 0.024 [W/m.K] has been estimated. The contribution of the polyurethane structure is estimated to be 0.006-0.012 [W/m.K]. The diffusion of air into the cells results in an increase of the heat conductivity of about 0.025 [W/m.K]. The final heat conductivity then becomes 0.031-0.037 [W/m.K]. This value is in agreement with the value predicted by steel pipe manufacturers for the DN 25/90 pipe after about 30 years of use (see figure A.9) [16]. The values found by Holmgren are slightly higher. The extrapolated 50 years value is 0.038 [W/m.K] at the most [17].

It seems that the wall thickness of the jacket increases as the diameter increases[7]. Another explanation can be that a compacted surface layer is formed during the production of the thicker wall pipes. This thicker layer then acts as a barrier for oxygen and nitrogen flux into the cells.

Some calculations to quantify the effect of the wall thickness and the barrier layer are shown in figures 5.12 and 5.13. Figure 5.12 shows calculation as a function of the barrier (jacket or compacted foam). Figure 5.13 shows the effect of the foam layer thickness. The values summarized in table 5.07 are used for the calculations shown in figures 5.12 and 5.13.

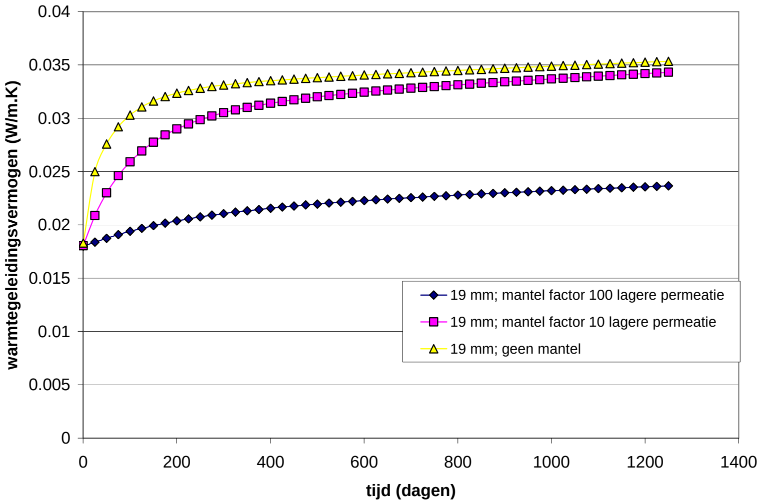

Figure 5.12: Calculated heat conductivity versus time for three different barrier layers (none; one with a 10 times higher barrier than the foam walls; one with a 100 times higher barrier than the foam walls)

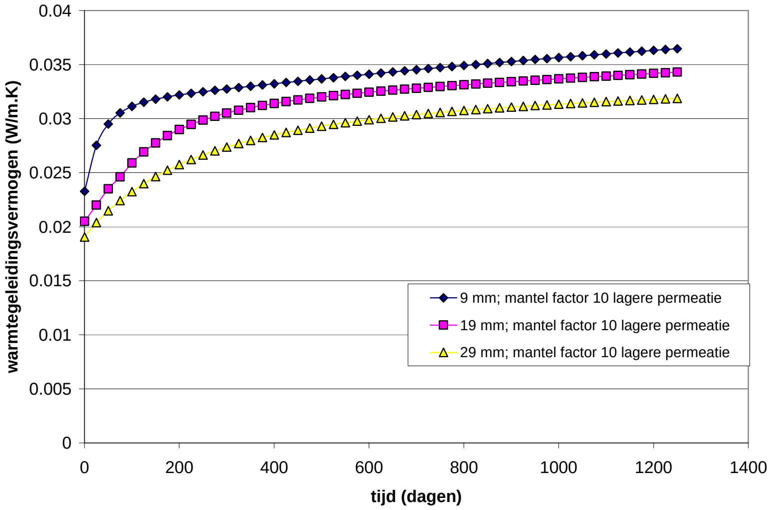

Figure 5.13: Calculated heat conductivity versus time for three different foam layers given a barrier layer with a 10 times higher barrier than the foam walls

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[7] An increasing thickness of the jacket can be related to requirements concerning the circumferential rigidity of the complete pipe.

5.4.5 Discussion

Initial value

To a large extent the production of the insulated PB/PE/PE pipe system determines the initial value of the heat conductivity. The time between production of the foam layer and the application of the jacket is decisive for the initial value. An increase of the heat conductivity of 0.010 [W/m.K] is expected when the jacket is applied after about 1 year (see figure 5.10).

However, the jacket is applied almost directly after the production of the foam. No significant exchange of blowing agent with oxygen and nitrogen from the air will then occur.

From indirect evidence it can be concluded that a small amount of air is already in the cells directly after production (see fig. 5.14). When the blowing agent is completely exchanged with air, the equilibrium value will be about 0.038 [W/m.K] (see figure 5.14).

The calculation presented in this report all started with an initial situation in which 100 % blowing agent is present in the cell but no air

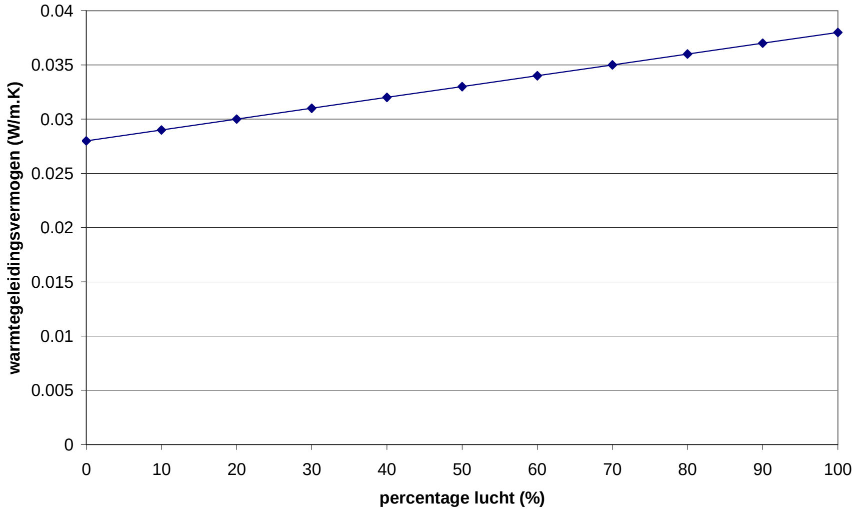


Figure 5.14: Calculated change in heat conductivity with increasing percentage of air in the cells of the PE foam studied

The foam is applied directly on the metal hot water pipe for the steel piping system. No waiting period is used between the production of the foam and the production of the pipe.

Pipe during storage

The PB/PE/PE system is reeled, stored and transported. Some calculation on the storage period can be found in section 5.4.4. The starting point is the value for the heat conductivity directly after production. It is assumed that the insulated pipe is manufactured directly after the foam.

When the foam is stored for a certain period between the production of the foam and the application of the jacket, the initial value (at time 0 days) has to be increased by a value in the range 0-0.010 [W/m.K]. It should be noted that the calculated equilibrium values will never exceed about 0.038 [W/m.K].

The calculations presented in paragraph 5.3.4 are based on values for the permeation coefficient of the blowing agent that are too high. An additive was applied in the PE foam to reduce in particular the permeation of the blowing agent. As a consequence, the permeation rate of the blowing agent will decrease. The effect of a lower permeation rate of the blowing agent is that the pressure in the cell will be almost constant at a value of 100 kPa and will not show the minimum found in the figures 5.02, 5.04, 5.07 and 5.09.

The effect of the lower permeation rate of the blowing agent scarcely affects the change in heat capacity with ageing time. A summary on the influence of the permeation rate of the blowing agent is presented in figure 5.15.

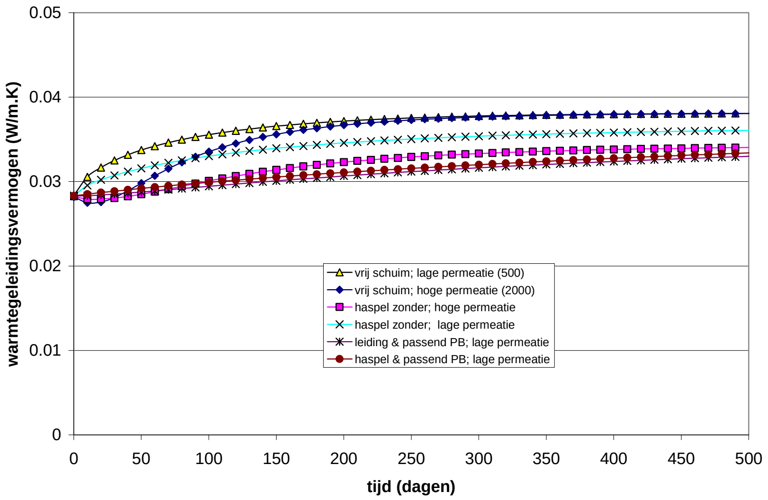


Figure 5.15: Calculated change in heat conductivity versus time for different situations

Foam in air; corrugated PE pipe with foam without PB pipe; corrugated PE pipe with foam and corresponding PB pipe filled with air; corrugated PE pipe with foam and corresponding PB pipe filled with 65 ºC water; low permeation of PE foam material: 500 [cm^3/m^2.day.atm] for 0.04 mm layer; high permeation: 2000 [cm^3/m^2.day.atm] for 0.04 mm layer.

Some caution is needed when interpreting the curves. It is assumed that the foam will not experience any deformation (shrinkage) if there is under-pressure in the cells. This assumption favours the heat conductivity starting with the higher permeation rate of the blowing agent (2000 [cm^3/m^2.day.atm] for 0.04 mm layer). If the PE foam shrinks because of under-pressure in the cell, the thickness of the foam will decrease and herewith the heat conductivity of the layer. An insignificant reduction of the pressure in the cell is found in the calculation using the lower value for the permeation (500 [cm^3/m^2.day.atm] for 0.04 mm layer).

An insignificant reduction of the pressure in the cell is found in the calculation using the lower value for the permeation (500 [cm^3/m^2.day.atm] for 0.04 mm layer).

It should be noted that the change in heat conductivity in time when the PB/PE/PE pipe is reeled (diameter: 70 mm; wall thickness: 6 mm) is almost identical to that of the pipe during water flux.

The argument given above also holds for the conventional steel piping system. Here, the ageing situation during storage will be almost identical to what happens in the ground too, because it has an impermeable metal hot water pipe that blocks the permeation of blowing agent into the hot water. The oxygen and nitrogen flux into the PU foam cells has to be realised completely by permeation through the jacket.

Pipe during operation

The origin of the ageing is the flux of oxygen and nitrogen into the cells. The flux rate is related directly to the ageing rate. An estimate on the ageing rate can be obtained from equation 5.3.2. The characteristic time constant for the PB/PE/PE pipe studied is approximately 2 years. Starting from an initial value for the heat conductivity of 0.028 [W/m.K], it is expected that this value will increase to 0.035 [W/m.K] provided that the wall thickness of the corrugated PE jacket is 1 mm. This value will further increase to 0.038 [W/m.K] based on the assumption and calculation presented in this report.

If it is assumed that some air was already present in the foam cells directly after the foam production, the initial value of the heat conductivity at installation will be about 0.032 [W/m.K] and after 2 years 0.036 [W/m.K]. Here, the equilibrium value of 0.038 [W/m.K] holds too.

The rate at which the foam cells fill with air and lose blowing agent can be reduced by increasing the wall thickness of the jacket (corrugated pipe) (see figure 5.16).

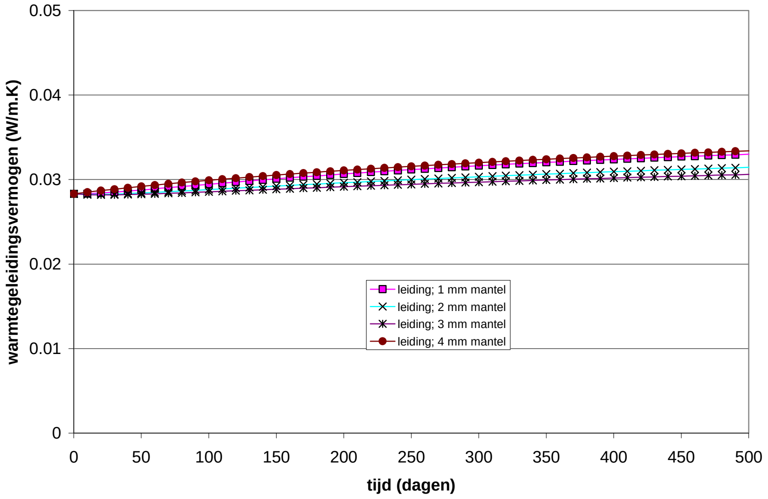


Figure 5.16: Influence of jacket (corrugated pipe) thickness versus the change of the heat conductivity in time

The initial value for the heat conductivity of the steel system is in the range 0.026 to 0.030 [W/m.K]. The rate of increase in the heat conductivity in time depends on the barrier capacity of the jacket. No increase in heat conductivity will be found if the barrier layer is completely air tight. The application of a PE jacket will result in a barrier layer with barrier properties similar to the jacket of the PB/PE/PE system. The expected change of the heat conductivity in time is shown in figure 4.19.

Foam structure

The skin structure of the foam differs from the core structure. The skins show a more compacted cell structure. The permeation of a foam block in air will be reduced by the more compact skin. Calculations show that the exchange can be decelerated by about 10-20%. It is assumed in these calculations that the skin thickness is limited to 1 mm and that the thickness of the cell wall in the skin is identical to that in the core.

The compacted skin of the foam has an undetectable effect on the complete insulated pipe. Therefore the effect of the compacted skin has not been included in the calculations.

Temperature dependence

The temperature dependence has only been partly included in the calculations. The values corresponding to a temperature of 20 °C have been used for the heat conductivity calculations.

The values corresponding with a temperature of 20 °C have been used for the permeation, with one exception. The exception is the permeation through the PB pipe under operating conditions. The temperature of the PB pipe is assumed to be 65 °C.

The values of 20 °C can be justified for the permeation and the heat conductivity of the reeled insulated pipe system. The averaged storage temperature will be about 20 °C.

A temperature gradient holds for the buried insulated pipe. The temperature of the jacket (corrugated pipe) is decisive for the permeation into the foam. The soil temperature will be about

15 °C on average. The jacket will be slightly warmer than the surrounding soil. A calculation using permeation values defined at 20 ºC will thus not introduce a major error.

The heat conductivity of gases increases with increasing temperature; about 10% per 30 °C temperature increase. The calculated value for the heat conductivity of the foam under operation conditions should thus be increased by about 5% provided that the averaged temperature in the foam layer is 35 °C. The calculation with the corrected temperature dependence is not included here because such a calculation hardly shows any affect on the ageing rate.

5.4.6 Summary and conclusions

Calculations to quantify the ageing of foam insulated pipes for district heating are performed within the framework of an assessment of an all plastic alternative. The foams studied are PE (polyethylene) foam in the PB/PE/PE system and PU (polyurethane) foam in the St/PU/PE system.

The ageing, which is related to the increase in the heat conductivity of the system, originates from the exchange of blowing agent with air. The flux of the blowing agent is outwards and that of air inwards.

The exchange of blowing agent can affect the structure of the foam. This effect is expected to be small.

The initial value of the heat conductivity is an important value for the calculations. This value depends on the composition of the gases in the foam cells directly after production. The amount of air in the PE foam is increased starting from directly after production and herewith the heat conductivity is increased.

The production of the St/PU/PE system leaves less time during production for the exchange of blowing agent with air. As a consequence, the initial heat conductivity of the steel pipe system can be slightly lower than that of the PB/PE/PE system.

The ageing situation is expected to be almost identical during storage and during operation for both the St/PU/PE system and the PB/PE/PE system.

Transfer of oxygen and nitrogen from the environment (surrounding soil) to the inner pipe will occur during operation of the insulated hot water pipe for district heating. This transfer is decisive for the ageing rate and the increase of the heat conductivity with increasing operation time. The characteristic ageing time for the PB/PE/PE pipe studied (19 mm PE foam; corrugated PE pipe ∅ 125 mm, 1 mm wall) is approximately 2 years.

The initial value for the heat conductivity of the PU foam in the St/PU/PE system is similar to the PE foam of the PB/PE/PE system. The characteristic ageing time is longer for the steel pipe system as a result of the thicker pipe wall, which forms a higher barrier for oxygen and nitrogen.

It is expected that the ageing rate of PE and PU foam will be almost identical if both foams are insulated by the same plastic jacket. The permeation behaviour of the jacket for blowing agent, oxygen and nitrogen is decisive for the ageing rate.

5.5 Conclusions

5.5.1 Thermal insulation by PE foam

TNO Science and Industry performed measurements and calculations within the framework of an evaluation study of an insulated plastic pipe system for district heating.

The fraction of open cells was determined experimentally. The final result of these experiments was that the fraction of open cells is not exceeding 6 ± 3 %.

The temperature gradient and the water flux were calculated for three situations, namely

Watertight PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe and hot water temperature of 65 °C.

A temperature gradient of 35 ºC and a heat flux of 21 (W/m pipe) has been calculated for situation I provided that the PE foam does not contain open cells.

A temperature gradient of 27 ºC and a heat flux of 28 (W/m pipe) has been calculated for situation I when the foam contains 6 % of open cells. The thermal bonding of the intersection in the foam is expected to yield a smaller influence on the temperature gradient and the heat flux than 6 % of open cells in which water condensates.

A water flux to the soil of 36 (mg/day/m pipe) is calculated for situation I. The condensation of water in open cells is not probable for the situations I and II.

Leaking PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe and hot water temperature of 65 °C.

Situation II seems to be almost identical to situation I and has therefore not been presented separately.

Watertight PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe, leaking PB pipe and hot water temperature of 65 °C.

A temperature gradient of 46 ºC and a heat flux of 27 (W/m pipe) has been calculated for situation III provided that the PE foam does not contain open cells.

A temperature gradient of 41 ºC and a heat flux of 41 (W/m pipe) has been calculated for situation III when the foam contains 6 % of open cells.

A water flux to the soil of 80 (mg/day/m pipe) has been calculated for situation III. However, in this situation slow water condensation occurs in the cells. A preliminary calculation showed that it will take at least 30 years before all cells are filled with water.

5.5.2 Oxygen Diffusion and risk for corrosion

A major thread to hot water systems is the diffusion of oxygen through plastic materials. As a consequence there is a risk for corrosion in the steel and copper components of the total system, e.g. heat exchangers, radiators and couplings. To overcome the diffusion of oxygen through the PB medium pipe, the PB/PE/PE system is supplied with an EVOH coating. This is a diffusion barrier that reduces the ingress of oxygen. Nevertheless there is still a certain diffusion of oxygen, even with the EVOH barrier.

Calculating with a permeability of 0.6 mg/m2 per day is a worst case situation. Oxygen will react with 2 g iron per day, which is about 37 kg iron in 50 years on a total surface of 4000 m^2 (400 houses). In case of general attack of carbon steel components the wall thickness decrease is about 1.2 μm in 50 years. In case of a smaller number of houses (200 ~ 2000 m2) connected to the same amount of PB pipe, the wall thickness decrease is about 2.4 μm in 50 years.

The wall thickness decrease is acceptable in case of an equal divided corrosion attack, but oxygen may initiate localised corrosion, for instance pitting corrosion. At the joints of the PB tubes with the carbon steel tubes the oxygen levels are at the maximum and, as mentioned before, this oxygen will react instantaneously with the carbon steel. The corrosion takes also place on locations with a thin protective layer and with conditions that foster corrosion. The risk of severe localised corrosion (pitting) in the carbon steel parts under the mentioned conditions is not quantitatively predictable. But if pitting occurs, it is an out of control process and corrosion rates of mm/year are possible.

A key issue is to maintain an optimal water quality and prevent ingress of air and salts because the occurrence of pitting corrosion is strongly promoted by the presence of salts especially chlorine.

5.5.3 Ageing of closed cell foams by exchange of gases

Calculations to quantify the ageing of foam insulated pipes for district heating are performed within the framework of an assessment of an all plastic alternative. The foams studied are PE (polyethylene) foam in the PB/PE/PE system and PU (polyurethane) foam in the St/PU/PE system.

The initial value for the heat conductivity of the PU foam in the St/PU/PE system is theoretically similar to the PE foam of the PB/PE/PE system. The characteristic ageing time is longer for the St/PU/PE system as a result of the thicker pipe wall, which forms a higher barrier for oxygen and nitrogen.

It is expected that the ageing rate of PE and PU foam will be almost identical if both foams are insulated by the same plastic jacket. The permeation behaviour of the jacket for blowing agent, oxygen and nitrogen is decisive for the ageing rate.

Chapter 6: Heat loss analysis

6.1 Introduction

This chapter describes the study on the long term thermal behaviour of the PB/PE/PE plastic piping system compared to the conventional alternatives.

The consequence of distributing heat through DH systems is the loss of a certain amount of energy. The determination of heat loss from DH pipes is essential for the assessment of cost-efficiency and environmental performance of a DH network.

Since the plastic PB/PE/PE piping system is relatively new and even still in development, the object is to determine the long term thermal behaviour of this product.

Consequently the heat loss over time is compared to the heat loss of conventional steel systems. Ultimately the goal is to achieve an energetically equal or better alternative with the plastic PB/PE/PE piping system compared to conventional St/PU/PE. The system's geometry may therefore be optimised.

To achieve a well defined heat loss analysis, this chapter consists of three main parts: theoretical heat loss calculation, experimental heat loss tests and a comparison between these two.

6.2 Heat loss calculation of pre-insulated district heating pipes

The heat loss from conventional piping systems such as St/PU/PE is a relatively known subject. These figures are often presented in product manuals of concerning piping systems.

For the plastic PB/PE/PE piping system the long term thermal behaviour is less certain. One thing that is known, is that plastic piping systems usually have a faster ageing process due to higher diffusion of the used materials [18,19].

In order to compare the new plastic piping system with the conventional alternatives it is important to determine the heat losses from the PB/PE/PE system both theoretically and experimentally. For this, heat loss formulae are applied to give the theoretical approach. Because many methods for determination of heat losses are applied by manufacturers also two experimental heat loss tests were initiated to provide comparable and reliable data.

A possible complication in the calculation of heat loss from the PB/PE/PE system is the corrugated outer casing of the system. This mainly serves to protect the system against ground conditions and is corrugated to preserve the system's flexible properties. The grooves are not completely filled with insulation foam. This complicates the heat loss calculation while all known formulae calculate the thermal resistance through each radial material layer. It is difficult to determine the exact material thickness, especially that of the insulation. See figure 6.1 for an illustration.

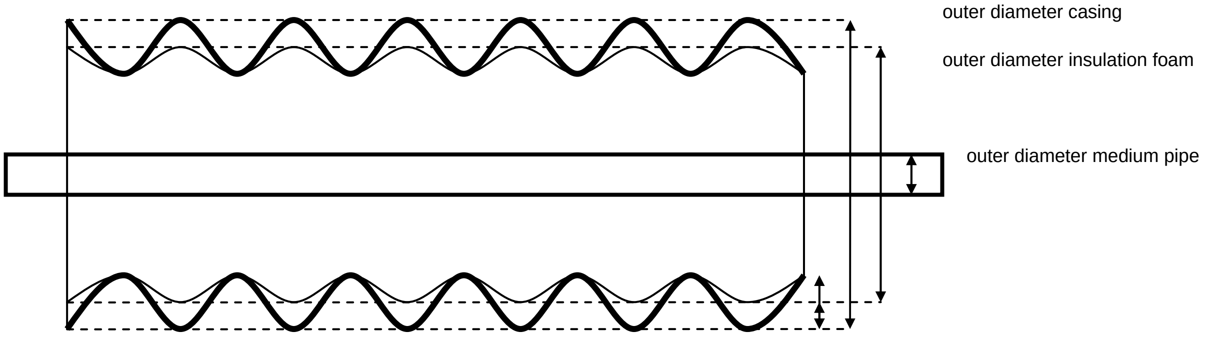


Figure 6.1. Illustration of corrugated plastic piping system

In order to calculate the heat loss for the plastic piping system, the material layers in the system are assumed to be non-corrugated. Therefore, in the heat loss calculation an effective outer diameter is considered. Nevertheless, it is remains uncertain whether the corrugated casing has a positive or negative effect on the total heat loss. On the one hand the corrugated casing has a larger surface area, possibly causing more conduction. On the other hand the air gaps may be resulting in more insulating capacity, after all these gaps can be seen as large closed rings.

6.2.1 Theory

The heat conduction through any plastic insulation foam can be described as the sum of three contributions:

$\lambda_{foam}=\lambda_{gas}+\lambda_{plastic}+\lambda_{radiation}$

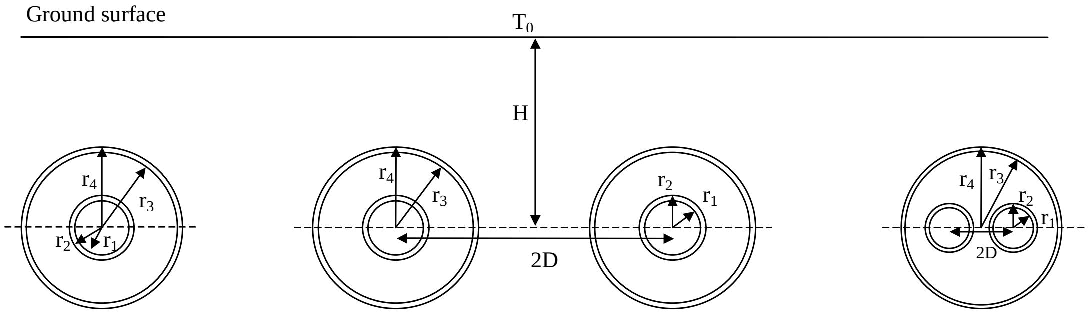
The contribution λ_{gas} is the heat conduction through the cell gas and is determined by the composition of the cell gas (e.g. blowing agents) in the foam and the temperature in the foam. For a typical polyurethane foam used in steel district heating pipes λ_{gas} constitutes approx. 55% of λ_{foam} at 50 ºC[20].

The contribution $\lambda_{plastic}$ is the heat conduction through the plastic structure of the foam cells. This contribution depends on the foam density and to a minor extent on the temperature. For a typical polyurethane foam $\lambda_{plastic}$ constitutes approx. 25% of λ_{foam} at 50 ºC.

The contribution $\lambda_{radiation}$ is the heat transmission through the foam by thermal radiation. The polyurethane material is partially translucent for infrared radiation and a considerable quantity of heat is transmitted by radiation from the warmer parts of the foam to colder parts. The radiation is dependent on the temperature, the foam density and the cell size in the foam. For typical polyurethane foam $\lambda_{radiation}$ constitutes approx. 20% of λ_{foam} at 50 ºC.

6.2.2 Heat loss formulae

The heat losses from DH pipes are calculated with formulae from Wallentén's 'Steady-state heat loss from insulated pipes' [4]. Wallentén gives Eq.(1) for single, Eq.(2) for paired and Eq.(3) for twin pipe systems in the ground.



Single pipe in the ground Two single pipes in the ground Twin pipe in the ground

Eq.(1):

$$\Phi = 2 \cdot \pi \cdot \lambda_g \frac{1}{\ln\left(\frac{2 \cdot H}{r_3}\right) + \frac{\lambda_g}{\lambda_i} \cdot \ln\left(\frac{r_3}{r_2}\right)} \cdot \left(T_1 - T_0\right)$$

Eq.(2):

$$\Phi = 4 \cdot \pi \cdot \lambda_g \frac{1}{\ln\left(\frac{2 \cdot H}{r_3}\right) + \frac{\lambda_g}{\lambda_i} \cdot \ln\left(\frac{r_3}{r_2}\right) + \ln\left(\sqrt{1 + \left(\frac{H}{D}\right)^2}\right)} \cdot \left(\frac{T_1 + T_2}{2} - T_0\right)$$

Eq.(3):

$$\Phi = 4 \cdot \pi \cdot \lambda_i \frac{1}{\frac{2 \cdot \lambda_i}{\lambda_g} \cdot \ln\left(\frac{2 \cdot H}{r_3}\right) + \ln\left(\frac{{r_3}^2}{2 \cdot D \cdot r_2}\right) + \frac{\lambda_i - \lambda_g}{\lambda_i + \lambda_g} \cdot \ln\left(\frac{{r_3}^4}{{r_3}^4 - D^4}\right)} \cdot \left(\frac{T_1 + T_2}{2} - T_0\right)$$

Where:

ϕ	[W/m]	Total heat loss from supply and return pipes
T_1	[ºC]	Supply temperature
T_2	[ºC]	Return temperature
T_0	[ºC]	Temperature on the ground surface
r_2	[m]	Inner radius insulation
r_3	[m]	Outer radius insulation
λ_i	[W/m·K]	Thermal conductivity insulation foam
λ_g	[W/m·K]	Thermal conductivity ground
D	[m]	Half the distance between the centres of the pipes
H	[m]	Depth from the ground surface to the centre of the pipes

In Eq.(1) and Eq.(2) the first term under the line represents the thermal resistance of the ground, the second term is the thermal resistance parameter of the insulation. In Eq.(2) the additional third term represents the thermal influence between two pipes whose centres are 2D apart.

In Eq.(3) for twin pipes a similar structure can be identified. The first term is the resistance between the total pipe and the ground surface. The second term originates from the resistance between two pipes whose centres are 2D apart. The third term is the resistance between the two medium pipes and a circumscribing pipe.

The formulae are simplified since only the insulation layer is taken into account. This may suffice for steel piping systems because of the insignificant thermal resistance of the steel medium pipe. For PB service pipes however, the thermal resistance may have a significant share in the total heat conductivity of the piping system. Therefore, in Eq.(4) the single pipe formula is supplemented with thermal resistance for medium pipe and casing.

Eq.(4):

$$\Phi = 2 \cdot \pi \frac{\left(T_1 - T_0\right)}{\frac{1}{\lambda_m} \cdot \ln\left(\frac{r_2}{r_1}\right) + \frac{1}{\lambda_i} \cdot \ln\left(\frac{r_3}{r_2}\right) + \frac{1}{\lambda_c} \cdot \ln\left(\frac{r_4}{r_3}\right) + \frac{1}{\lambda_g} \cdot \ln\left(\frac{2 \cdot H}{r_{\max}}\right)}$$

Where:

ϕ	[W/m]	Total heat loss from supply and return pipes
T_1	[ºC]	Supply temperature
T_2	[ºC]	Return temperature
T_0	[ºC]	Temperature on the ground surface
r_1	[m]	Inner diameter medium pipe
r_2	[m]	Outer diameter medium pipe
r_3	[m]	Inner diameter casing

r_4	[m]	Outer diameter casing
r_{max}	[m]	Maximum outer diameter corrugated casing
λ_m	[W/m·K]	Thermal conductivity medium pipe
λ_i	[W/m·K]	Thermal conductivity insulation foam
λ_c	[W/m·K]	Thermal conductivity casing
λ_g	[W/m·K]	Thermal conductivity ground
D	[m]	Half the distance between the centres of the pipes
H	[m]	Depth from the ground surface to the centre of the pipes

The influence of taking the service pipe resistance into account in Eq.(1) compared to Eq.(4) is around 3 to 6% for plastic pipes. Modification of the heat loss equation for twin pipe systems will not be done for reasons of simplicity and the small significance of the effect.

6.2.3 Ageing

The λ_i in the Wallentén formulae, makes the most significant contribution in the heat loss calculation of pre-insulated DH pipes. The heat conductivity of insulated foam increases in the course of time, commonly called ageing of the insulation foam. This is caused by the exchange of blowing agents from the closed foam cells by air (oxygen and nitrogen).

Directly after production, conventional polyurethane insulation in steel pipes is mainly filled with a mixture of cyclo-pentane and CO_2. The plastic PB/PE/PE system is mainly filled with a mixture of isobutene and CO_2. These gases have a relatively low heat conductivity compared to the insulating properties of oxygen and nitrogen. See the values below:

Gas:	C-pentane	Isobutene	CO_2	N_2	O_2
λ_{50} (W/m·K)	0.012	0.016	0.017	0.027	0.026

The speed of these diffusion processes primarily depends on the thickness of the casing and the amount of insulation foam surrounding the service pipe. As flexible pipes have relative thin casings and often even corrugated expanding the surface area, the ageing will be faster for flexible pipes than for comparable steel diameters. Moreover, diffusion processes are also possible through the plastic medium pipes, whereas steel pipes are diffusion tight.

The TNO research described in chapter 5.4 [21] provides insight in the increase of the thermal conductivity of the insulation foam over time.

The thermal conductivity of PE foam is calculated to increase approximately 0.009 W/m·K over the lifetime. This meets with practical test reports on the conductivity of PE foam in different stages of degassed foam. Results from research institute FIW München show that the thermal conductivity of the PE foam in fully degassed state amount to 0.040 W/m·K. Another institute FFI Hannover has also measured the conductivity of the PE foam when it is just produced and the process of degassing has not yet started. Results show an initial thermal conductivity of 0.031 W/m·K.

For PU foam in steel pipe systems, literature on thermal conductivity over time is used [11]. The conductivity for typical PU foam increases from 0.029 to 0.038 W/m·K.

An estimation of the conductivity curve in time can be generated with this data. See figure 2 below.

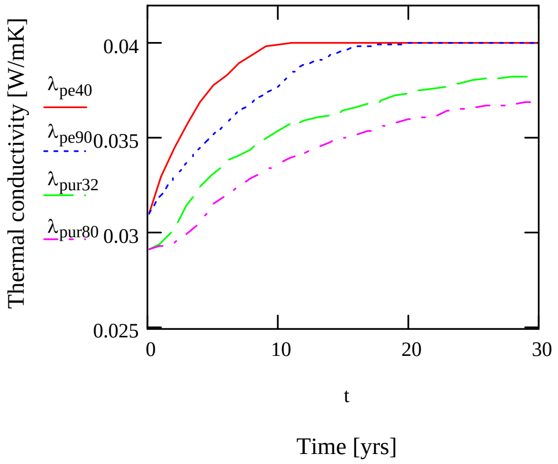


Figure 6.2. Estimated thermal conductivity in time

In order to make a comparison of the long term heat loss between plastic PB/PE/PE systems and conventional systems, an average thermal conductivity of the insulation foam over 50 years can be considered. For PE foam in the PB/PE/PE system this is 0.039 W/mK. For PU foam in the St/PU/PE system series 1 this is about 0.035 W/mK.

6.3 Theoretical heat loss results per diameter

One important condition of the new plastic piping system as alternative for the conventional used steel piping systems is that total network heat losses do not exceed that of the steel pipe network. This can be analysed from several optics, e.g. heat loss per meter pipe, per identical network, per optimal network.

In this chapter the heat loss results are given per diameter.

For the heat loss calculation per diameter, the basic assumptions for both piping systems are equal so that only the material specific conditions differ. The basic assumptions for calculating the heat loss are summarised in table 6.1.

Table 6.1. conditions for heat loss calculation

Supply temperature	70	ºC
Return temperature	40	ºC
Temperature on the ground surface	10	ºC
Thermal conductivity PB	0.22	W/m·K
Thermal conductivity St37	76	W/m·K
Thermal conductivity PE foam average 50 yrs	0.039	W/m·K
Thermal conductivity PU foam average 50 yrs	0.035	W/m·K
Thermal conductivity PE casing	0.43	W/m·K
Thermal conductivity ground	1.5	W/m·K
Distance between the centre of the pipes	0.30	m
Laying depth	0.5	m

An advantage of the plastic PB/PE/PE system is the fact that during installation the pipes can be laid against each other, requiring smaller trenches than for conventional piping systems. Also considering heat loss this is a small advantage, because a smaller distance between the pipes results in lower heat losses. For the PB/PE/PE system this means a 3 to 5% lower heat loss when laying the pipes close to each other, compared to the normal distance applied for steel piping systems. This advantage is not included in the heat loss calculations as only single pipes in the ground are presented.

6.3.1 Comparable diameters

Plastic and steel piping systems apply different notation for the diameter range. The notation of plastic PB/PE/PE pipe diameters used here is not in DN (nominal diameter) but in PB for polybutylene. Moreover, DN values relate to inner diameters, whereas plastic pipes are notated with outer diameters. For example, the inner diameter of a DN20 steel pipe is larger than a PB25 plastic pipe.

Comparable diameters in PB and steel (DN) can be determined by means of the capacity or flow (kg/s) of the pipe at an equal head loss (300 Pa/m). Two main parameters relevant for this are the inner radius of the pipe and material roughness. Plastic piping systems have lower material roughness than steel systems (friction number PB=0.007 mm, St37=0.07 mm) resulting in less relative head loss and higher flow and capacity. Table 6.2 below shows the resulting comparable diameters.

Table 6.2. Comparable diameters for steel and plastic piping systems, based on inner diameter and maximum capacity

PB/PE/PE	Ø$_i$ (mm)	Flow (kg/s)		St/PU/PE	Ø$_i$ (mm)	Flow (kg/s)
PB25	20.4	0.25	-	DN20	21.7	0.25
PB32	26.0	0.47	-	DN25	27.3	0.53
PB40	32.6	0.86	-	DN32	37.2	1.08
PB50	40.8	1.33	-	DN40	43.1	1.61
PB63	51.4	1.94	-	DN50	54.5	2.94
PB75	61.2	3.03	-	DN65	70.3	5.50
PB90	73.6	4.86	-	DN80	82.5	8.75
PB110	90.0	8.17	-	DN100	107.1	17.3

6.3.2 Single pipe systems

The plastic PB/PE/PE system can be compared to the conventional St/PU/PE series 1 piping system used most commonly in Dutch local district heating networks. As an indication, also the better insulated series 2 and another plastic piping systems are presented.

Table 6.3 shows the dimensions of the plastic and steel piping systems, insulation thickness and heat loss, based on the conditions in table 1 and an average conductivity of insulation foam over 50 years.

Table 6.3. Piping geometry and heat loss for the PB/PE/PE system, St/PU/PE systems series 1 and series 2 and PEX/PE/PE [20,22]

PB/PE/PE	Inner diameter medium pipe	Outer diameter medium pipe	Inner diameter casing[8]	Outer diameter casing	Insulation thickness	Heat loss Single pipe (70º)
	[mm]	[mm]	[mm]	[mm]	[mm]	[W/m]
PB25/90	20.4	25	76.3	78.9	25.7	11.9
PB32/90	26	32	76.3	78.9	22.2	14.8
PB40/90	32.6	40	76.3	78.9	18.2	19.1
PB50/125	40.8	50	106.9	109.5	28.5	16.8
PB63/125	51.4	63	106.9	109.5	22.0	22.9
PB75/160	61.2	75	148.0	151.0	36.5	18.7
PB90/160	73.6	90	148.0	151.0	29.0	24.3

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[8] For the corrugated PB/PE/PE piping system the outer diameter of insulation is assumed equal to the minimum inner diameter of the casing.

PB110/200	90	110	183	186	36.5	24.1
St/PU/PE series 1	[mm]	[mm]	[mm]	[mm]	[mm]	[W/m]
DN20/90	22.3	26.9	85.6	90	29.4	10.7
DN25/90	28.5	33.7	85.6	90	26.0	13.1
DN32/110	37.2	42.4	105	110	31.3	13.5
DN40/110	43.1	48.3	105	110	28.4	15.5
DN50/125	54.5	60.3	120	125	29.9	17.4
DN65/140	70.3	76.1	134	140	29.0	20.8
DN80/160	82.5	88.9	154	160	32.6	21.5
DN100/200	107.1	114.3	193.6	200	39.7	22.5
St/PU/PE series 2	[mm]	[mm]	[mm]	[mm]	[mm]	[W/m]
DN20/110	22.3	26.9	107.0	110	38.6	9.2
DN25/110	28.5	33.7	107.0	110	35.2	11.0
DN32/125	37.2	42.4	122.0	125	38.3	12.0
DN40/125	43.1	48.3	122.0	125	35.4	13.6
DN50/140	54.5	60.3	137.0	140	36.9	15.2
DN65/160	70.3	76.1	157.0	160	39.0	17.1
DN80/180	82.5	88.9	177.0	180	42.6	18.0
DN100/225	107.1	114.3	221.6	225	52.4	18.6
PEX/PU/PE[9]	[mm]	[mm]	[mm]	[mm]	[mm]	[W/m]
PEX25/75	20.4	25	72.4	75	23.7	11.3
PEX32/75	26.2	32	72.4	75	20.2	14.4
PEX40/90	32.6	40	87.4	90	23.7	15.0
PEX50/110	40.8	50	107.4	110	28.7	15.4
PEX63/125	51.4	63	122.4	125	29.7	17.5
PEX75/140	61.4	75	137.4	140	32.5	18.6
PEX90/160	73.6	90	157.4	160	33.7	20.6
PEX110/180	90.0	110	177.4	180	33.7	23.6

Hence in most cases the PB/PE/PE system consists of lower insulation thickness than the comparable St/PE/PE diameter. Since also the thermal conductivity of the PE-foam is generally higher PU-foam during lifetime, with these dimensions the heat loss per metre is expected to be higher for the plastic piping system.

See figure 6.3 for the total theoretical heat loss per piping system. The single pipe diameters of PB/PE/PE are performing worse than the comparable St/PU/PE diameters. In order to have an overall equal or better heat loss for PB/PE/PE, a solution can be an increase of the insulation foam for certain diameters.

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[9] Conductivity PU in PEX system based on PU in St/PU/PE. Although this PU foam will assumedly age faster, this is not taken into account due to lack of experimental evidence.

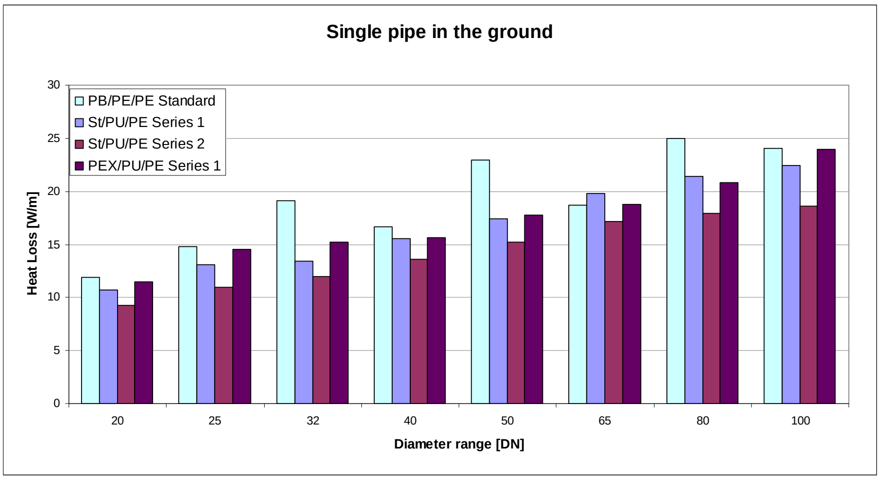

Figure 6.3. Average theoretical heat loss per piping system for a single pipe in the ground.

6.3.3 Twin-pipe systems

Twin pipes generally produce less heat loss than the single pipe alternative. Using Eq.(3) of Wallentén, the thermal resistance of the service pipes and casing are not taken into account. The actual heat loss for plastic pipes will therefore be slightly lower (in the order of 5%). *D* in Eq.(3) is the half distance between both service pipes within the outer casing. The total heat loss from twin pipe systems increases as *D* increases. Therefore, theoretically *D* should be as small as possible.

The geometry of the twin pipe systems can thus be optimised by bringing the medium pipes closer to each other. In theory this distance should be zero to create minimum heat loss. However, this is not practically possible for the manufacturer since the insulation foam should totally surround the service pipe. The distance between the service pipes shall therefore be minimized as much as technically possible.

In table 6.4 the twin pipe geometry and total theoretical heat loss for supply and return operation.

Table 6.4. Piping geometry and heat loss for the twin pipe PB/PE/PE system and St/PU/PE system series 1

PB/PE/PE	Inner diameter service pipe	Outer diameter service pipe	Outer diameter foam	Outer diameter casing	Heat loss Pipe pair (70-40)
	[mm]	[mm]	[mm]	[mm]	
PB25x2/125	20.4	25	106.9	109.5	12.0
PB32x2/125	26	32	106.9	109.5	14.8
PB40x2/160	32.6	40	145.8	148.8	12.9
PB50x2/160	40.8	50	145.8	148.8	18.4
PB63x2/200	51.4	63	183	186	17.7

St/PU/PE series 1					
	[mm]	[mm]	[mm]	[mm]	
DN20x2/125	22.3	26.9	119.0	125	9.2
DN25x2/140	28.5	33.7	134.0	140	9.9
DN32x2/160	37.2	42.4	154.0	160	10.6

DN40x2/160	43.1	48.3	154.0	160	12.5
DN50x2/200	54.5	60.3	193.6	200	12.0

6.4 Experimental

In order to know what the actual heat loss per piping system does, several heat loss measurements were performed. Two separate heat loss tests were developed to determine the heat loss values of both the PB/PE/PE and the conventional St/PU/PE piping system. The results of these tests are compared and analysed.

6.4.1 Long-term field test

The first test concerns a field test consisting of two identical piping loops. The compared piping systems steel DN65/140 DH pipes and plastic PB75/160 DH pipes. Because of flexibility advantages in practice, the PB/PE/PE system is able to cut the corners to some extend. Therefore, the PB/PE/PE circuit is 1 metre shorter at 43 metres compared to the St/PU/PE system with a length of 44 metres.

The heat loss of both circuits is measured by monitoring the power consumption needed to keep the medium temperature on a constant temperature. Both circuits are equipped with heater, pump, temperature sensors, pressure sensors and kWh meters. The circuits are buried under the same circumstances at 1 metre depth.

As an indication, an expected heat loss can be calculated based on the geometry of the piping systems, the medium temperature, soil characteristic and laying depth. As it is unknown to what stage the insulation foam is degassed, the 50 year-average thermal conductivity is assumed. The expected (theoretical) heat loss of the two circuits is 20.8 W/m for the St/PU/PE system and 18.8 W/m for the PB/PE/PE system. This is a difference of around 10% in favour of the plastic system.

From all the sensors specified data is collected every five minutes by computer, resulting in datasheets. The most important parameter in these datasheets is the cumulative energy demand of both systems (kWh). This value is displayed in figure 6.4.

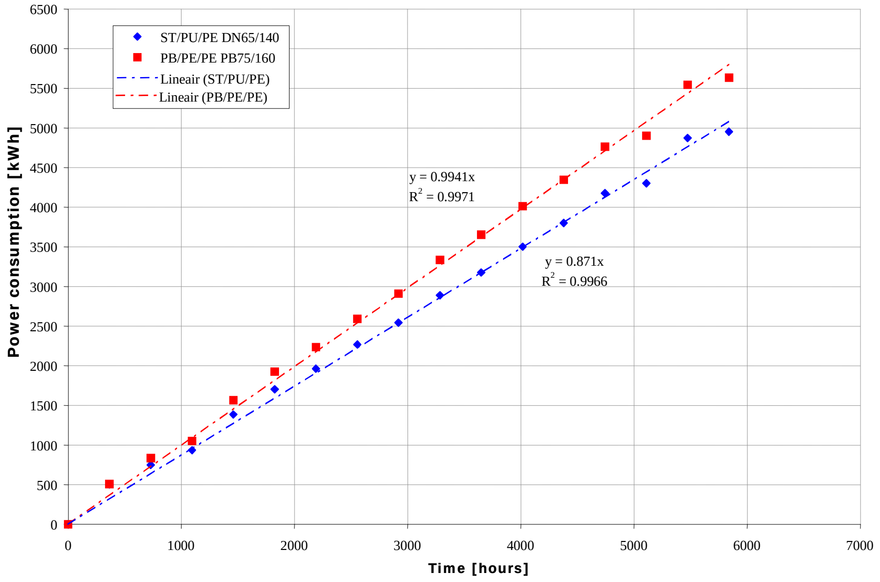

Figure 6.4. Cumulative energy demand in field test at a temperature difference (dT) of 60 ºC

The slope of the energy consumption (kWh) in figure 4 is the average power consumption (W) or heat loss. The heat loss per metre for the PB/PE/PE system is 17% higher compared to the St/PU/PE circuit (see table 6.5).

Table 6.5. Long term field test heat loss results from PB/PE/PE versus conventional St/PU/PE

	Power consumption	Heat loss	Percentage
	[W]	[W/m]	[%]
St/PU/PE DN65/140	871.0	19.8	100
PB/PE/PE PB75/160	994.1	22.6	114

The actual measured heat loss of St/PU/PE is 5% lower than predicted. This is credible as the conductivity of the PU foam was probably lower than the 50 year-average.

For the PB/PE/PE system, the measured heat loss is 23% higher than theoretically predicted. This large difference however cannot only be explained by a higher thermal conductivity of the PE foam, because this exceeds the fully degassed value of 0.040 W/m·K.

This means some assumptions for the calculation of the expected heat loss prove not to be correct. This can be caused by the difficult estimation of ground properties of this field test, but also inaccurate determination of the pipe geometry or foam quality.

6.4.2 Short-term lab test

The long periods of measurement of the field test and uncertain ground properties was an incentive to develop a quicker method for measuring the heat loss. Therefore, a short term lab test was developed.

The test procedure is quite similar to the method described in the standard EN253 and EN ISO 8497. Figure 6.5 shows a schematic view of this lab test.

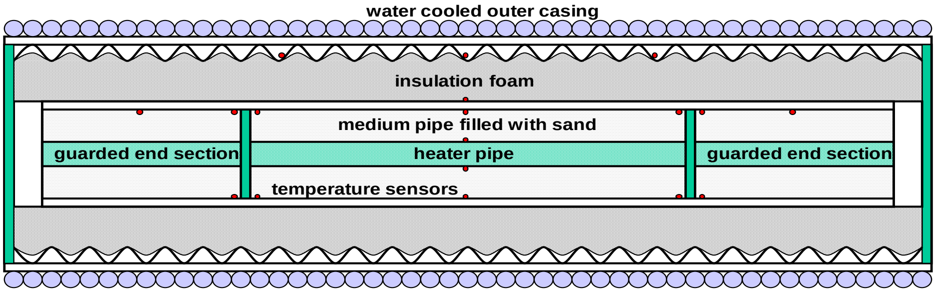

Figure 6.5. Schematic view lab test

The total length of the test apparatus is 2 metres, the actual test section is 1 metre. This test section consists of a heating probe of 1 metre for heating the tested DH pipe from the inside. The test apparatus uses separately heated pipe sections of 50 cm at both ends of the metered test section, called guarded ends. These additional pipe sections are maintained at the same temperature as the test section to eliminate axial heat flow of the test section.

The temperature surrounding the test pipe is conditioned at a constant temperature to create an accurate and adjustable temperature difference over the radial direction of the test section. This simulates the conditions of DH pipes in the ground.

A set of thermocouples on different locations in the test apparatus provides the accurate measurement of test temperatures. The temperature of the test section and guarded ends must be uniform and can thus be checked with these temperature sensors.

The heat loss of the test pipe is equivalent to the total power consumption needed to keep the test section at a constant temperature. The actual power use (W) is determined by multiplying voltage (V) by current (A). From the lab test, data is collected by computer every five minutes resulting in datasheets.

The heat loss in this short-term lab test was measured for a newly produced DN65/140 and a PB75/160 pipe. Also the PB75 sample was measured in fully degassed state after an accelerated ageing process at 80 ºC. As a result the graph in figure 6.6 is generated. The heat loss is equivalent to the power used and is plotted on the y-axis, the temperature difference between medium and casing (dT) is plotted on the x-axis.

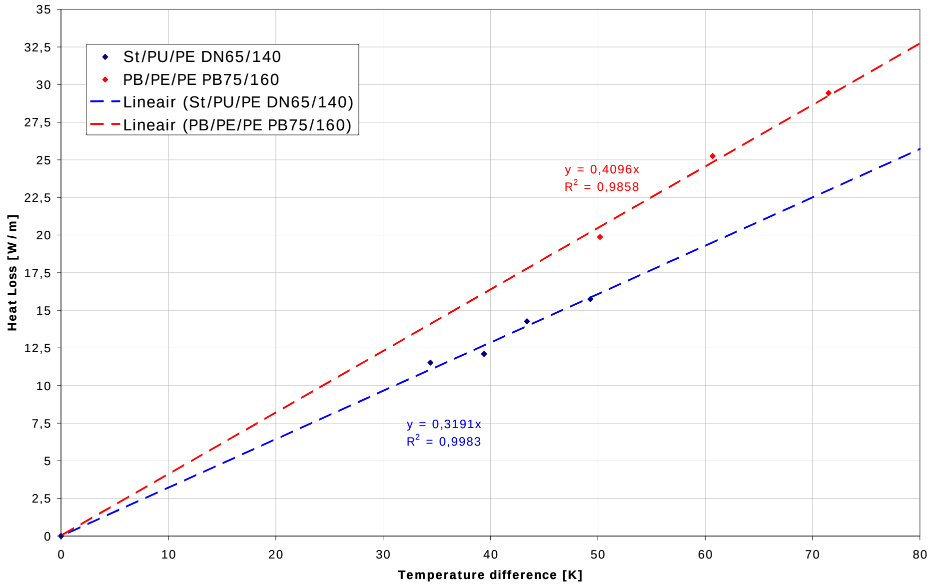

Figure 6.6. Heat loss measurement lab test Nuon Tecno Duiven.

From measured results presented in figure 6, the heat loss per metre pipe can be calculated. These heat losses are presented in table 6.6, at a temperature difference of 60 ºC (70 ºC medium temperature and 10 ºC surface temperature).

Table 6.6. Short term lab test heat loss results from PB/PE/PE versus conventional ST/PU/PE

	Thermal conductivity	Heat loss	Percentage
	[W/mK]	[W/m]	[%]
St/PU/PE DN65/140	0.3191	19.1	100
PB/PE/PE PB75/160	0.4096	24.6	128

Notice that there is only a small increase in heat loss after the PB75 system was degassed. This implies that the diffusion process in the initially measured sample had already started to fair extend. Further calculations for PB/PE/PE are based on the fully degassed measurement as the thermal conductivity of this sample's foam is relatively certain.

Again, the experimental results from table 6 can be compared to the theoretical results. Eq.(3) can be used to calculate the expected heat loss. In order to to generate a comparable theoretical estimation, the last term in de denominator in Eq.(3) can be left out, to create a consistent surrounding temperature.

For both the DN65 and PB75 system the exact geometry of the sample is measured and included in this calculation. For the plastic PB75/160 system it appears that the medium pipe is not narrowly connected to the insulation foam, causing a small air gap.

The expected theoretical value for a DN65/140 is 18.2 W/m, based on an initial thermal conductivity of PU foam of 0.029 W/m·K.

The experimental heat loss for St/PU/PE in this case is 5% higher than theoretically predicted. Besides a small margin of error of the lab test estimated around 2.5%, the difference can be explained by a higher thermal conductivity of the PU foam than theoretically assumed. With a conductivity of 0.0305 W/mK of the newly produced PU foam a heat loss of 19.1 W/m follows. This is credible as the test sample was not immediately measured after production.

For the fully degassed PB75/160 sample the expected heat loss is 23.0 W/m, based on a conductivity of PE foam of 0.040 W/m·K.

The experimental heat loss of the PB/PE/PE system is 10% higher than theoretically predicted. The difference of the results for the PB/PE/PE system can have several causes, discussed in the next paragraph.

6.5 Comparison theoretical and experimental heat loss

The theoretical and experimental heat loss values for PB/PE/PE have a discrepancy of 10% in case of the short term lab test. In contrary to the field test, for the lab test the ground properties are excluded by a constant temperature outside the casing. The 10% discrepancy may be explained by other possible causes.

6.5.1 Possible causes of higher heat loss values

In order to explain the discrepancy between theory and practice of the heat loss performance of the PB/PE/PE system, the production of the PB/PE/PE system is analysed. The production of PB/PE/PE basically consists of three parts: production of the medium pipe, production of the insulation foam and production of the outer casing together with the assemblage of the entire product.

When focusing on the production of the medium pipe, no anomalies are found. Also the production of the outer casing around the insulation foam causes no problems. The casing is injection moulded around the insulation and has accurate dimensions. A deviation of 1 mm of the outer casing thickness results in a typical 0.1% change in heat loss. Also an increase of the outer surface of the casing gives no significant increase in heat loss.

Regarding the foam production the small air gap between the medium pipe and insulation foam is mentioned earlier. During foaming the temperature-pressure relationship is critical for production of the required foam quality. This relationship results in a minimum inner diameter of the insulation foam. This diameter is relatively large in comparison with the outer medium pipe diameter and thereby results in an air gap. The largest disadvantage of this phenomenon is a lower thickness of insulation foam compared to a system where the insulation is narrowly positioned against the medium pipe. Another effect of an extra layer of air is an accelerated ageing process, while air is more easily diffused into the foam cells from the inside.

After foaming, the PE insulation is incised longitudinally in order to insert the medium pipe. Afterwards this incision is welded. This process has the disadvantage of leaving a weld in the insulation with relatively high density foam which has a lower insulating quality and a lower radial insulation thickness compared to normal density insulation foam.

As a result of an air gap between medium pipe and insulation foam, the medium pipe is not exactly positioned in the middle of the piping system. This possibly effects the heat loss. Also the insulation foam beneath the medium pipe may be compressed slightly, resulting in lower insulation thickness.

A last possible cause of higher heat loss is a higher conductivity of the insulation foam than assumed. The degassing process is relatively fast compared to steel systems and the time between foaming and finishing the product is crucial for the presence of blowing agents in the foam. The exact quantity of isobutene may therefore be slightly different in practice than theoretically approached.

In summary, it can be concluded that the discrepancy between theory and practice can be explained by four possible causes:

Less insulating foam than assumed;

Weld in insulating foam;

Eccentrically placed medium pipe in system;

Lower quality of insulating foam (degree of ageing process).

6.5.2 Effective insulation thickness

During the production of the PB/PE/PE system in practice it is difficult to have a narrow connection between medium pipe and the insulation foam. The air gap that is created does not add to the insulation performance of the pipe, especially because it is not compensated in the outer diameter.

To simulate the air gap in the heat loss formulae, Eq.(4) is supplemented with an extra layer of air in Eq.(5). The new variables are thermal conductivity of air λ_a and the new inner radius of the insulation foam r_{2a}.

Eq.(5):

$$\Phi = 2 \cdot \pi \frac{(T_1 - T_0)}{\frac{1}{\lambda_m} \cdot \ln\left(\frac{r_2}{r_1}\right) + \frac{1}{\lambda_a} \cdot \ln\left(\frac{r_{2a}}{r_2}\right) + \frac{1}{\lambda_i} \cdot \ln\left(\frac{r_3}{r_{2a}}\right) + \frac{1}{\lambda_c} \cdot \ln\left(\frac{r_4}{r_3}\right) + \frac{1}{\lambda_g} \cdot \ln\left(\frac{2 \cdot H}{r_{\max}}\right)}$$

In order to match the formula with lab test conditions assumptions are made on the lambda value of the ground (infinite) and the lambda of air with convection (5 W/mK).

An effective insulation thickness can be calculated with Eq.(4) in which side effects, such as lower insulation properties and a weld in the foam, are included. This effective insulation thickness can be calculated with the actual measured heat loss and the assumption of an eventual thermal conductivity of 0.040 W/mK for the degassed insulation foam of the measured PB75/160 test sample.

In the PB75/160 test sample an actual insulation thickness of 34 mm is measured, resulting in an air gap between the medium pipe and insulation of 2.5 mm. Given the experimental heat loss result of 24.6 W/m however, the effective insulation thickness of the PB75/160 is 31.5 mm.

6.5.3 Geometry optimisation

In order to create lower heat loss for the PB/PE/PE system, the system's geometry may be optimised to ensure equal heat loss to e.g. St/PU/PE series 1 or series 2 system. For an adequate comparison, the average expected thermal conductivity of the insulation foams is assumed for 50 years. For PE foam this is 0.039 W/mK and for rigid PU foam this is 0.035 W/mK [11].

For the DN65/140 system the average calculated heat loss in 50 years is 19.8 W/m for a single pipe in the ground, based on the actual geometry of the tested DN65 system and dT of 60 ºC. For the comparable PB75/160 system to equal this heat loss, the insulation thickness can be increased.

Increasing insulation foam has more effect if it is done on the inner diameter of the foam. Therefore, the air gap should be as small as possible. Assuming the air gap of the PB75/160 is already as small as possible with 2.5 mm, the outer insulation foam diameter should be increased with 6.2 mm to an outer diameter of the insulation foam of 160.5 mm in order to have equal heat loss to the DN65/140 system. This means an effective insulation thickness of 37.7 mm and an actual insulation thickness of 40.2 mm.

For the other PB/PE/PE diameters an indicative analysis on the effective insulation thickness can be done, based on the measurements on the PB75/160 system. This results in the following increase of insulation thickness (table 6.7). Also the standard available space between medium pipe and outer casing is mentioned, based on which the initial heat loss in table 3 were calculated.

Table 6.7. Effective insulation thickness of the PB/PE/PE system

PB/PE/PE Standard	Standard available space	Standard actual thickness	Standard effective thickness	Optimal actual thickness to equal series 1	Optimal actual thickness to equal series 2
	[mm]	[mm]	[mm]	[mm]	[mm]
PB25/90	25.7	24.8	24.0	36.7	48.7
PB32/90	22.2	21.1	20.0	32.7	44.7
PB40/90	18.2	16.8	15.5	39.1	48.1
PB50/125	28.5	26.8	25.1	38.8	48.6
PB63/125	22.0	19.8	17.8	41.1	50.9
PB75/160	36.5	34.0	31.5	40.2	50.4
PB90/160	29.0	24.9	23.0	43.3	56.6
PB110/200	36.5	32.8	29.2	50.0	66.0

The 10% discrepancy between theoretical and experimental results in the lab test are explained in the heat loss difference between the actual and effective insulation thickness. Consequently, the average difference between the effective diameter and the total available space for all diameters is 19%. This means the effective thickness of the PB/PE/PE system results in an average 19% higher heat loss than the initially assumed geometry in table 6.3.

This corresponds with an effectiveness of 84% of the insulation foam, both including the air gap and a lower insulation quality.

Although not available in the current range of products, it may be an option to develop a series 2 range of the PB/PE/PE system. The series 2 diameters would have for example a larger size outer casing than standard. As an indication the effective thickness is mentioned in table 6.8.

Table 6.8. Effective insulation thickness of the potential series 2 PB/PE/PE system

PB/PE/PE Series 2	Standard available space	Standard actual thickness	Standard effective thickness	Optimal actual thickness to equal series 1	Optimal actual thickness to equal series 2
	[mm]	[mm]	[mm]	[mm]	[mm]
PB25/125	41.0	40.1	39.3	36.7	48.7
PB32/125	45.2	44.1	43.1	32.7	44.7
PB40/125	41.2	39.9	38.5	39.1	48.1
PB50/160	49.0	47.3	45.7	38.8	48.6
PB63/160	42.5	40.4	38.3	41.1	50.9
PB75/200	54.0	51.5	49.0	40.2	50.4
PB90/200	46.5	43.5	40.5	43.3	56.6
PB110/225	52.0	48.3	44.7	50.0	66.0

The actual thickness of the potential series 2 of PB/PE/PE can be compared with the actual thickness required to equal conventional systems. The series 2 PB/PE/PE results in lower heat loss than the series 1 St/PU/PE system and comparable heat loss to the series 2 system for several diameters.

6.5.4 Expected heat loss in time

Together with the increase of the thermal conductivity in time, an estimation of the long term heat loss of PB75 and DN65 is presented in figure 6.7. The current PB75/160 system (red line) has a higher heat loss than the DN65/140 system (green line). The optimised system (blue dotted line) has an equal average heat loss in 50 years.

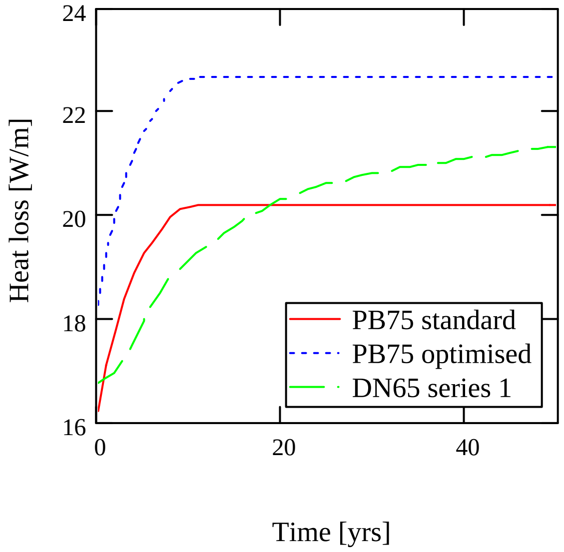

Fig.6.7. Expected long term heat loss for PB75/160 and DN65/140 systems

In figure 8 the average heat loss per DH piping system is presented again, now with the expected heat losses for PB/PE/PE based on experimental results. Also a PB/PE/PE series 2 is included, where each diameter is produced in a larger size outer casing than standard.

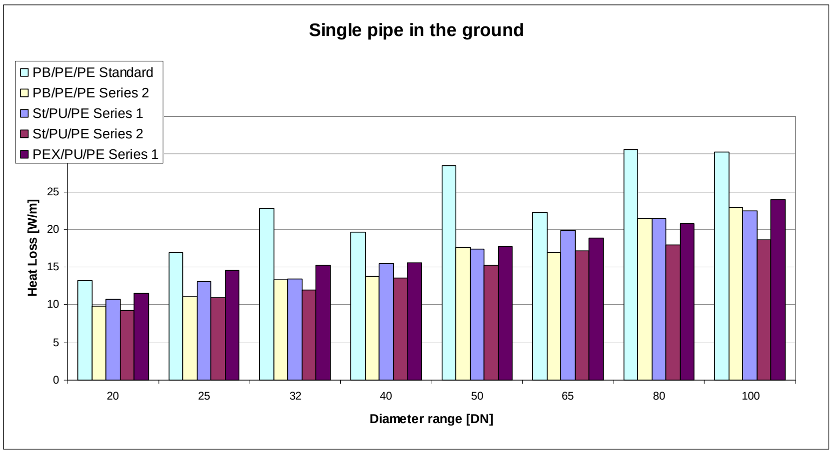

Fig.8. Average expected heat loss per piping system for a single pipe in the ground

The PB/PE/PE series 2 would have lower heat loss than St/PU/PE series 1 and the PEX/PU/PE system. The heat loss is comparable to the St/PU/PE series 2.

6.6 Conclusions

This chapter describes the research of the piping dimensions of PB/PE/PE with respect to the long term thermal behaviour. It seems that the practical advantages of plastic piping systems have the consequence of lower insulating properties. In general, plastic piping systems perform worse on heat loss than steel piping systems, due to flexible insulation foam with higher diffusion rates through casing and medium pipe than rigid foam in St/PU/PE systems.

The heat loss of the standard piping diameters is determined and possible variables for optimisation are given.

Hence in most cases the standard geometry of PB/PE/PE consists of lower insulation thickness than the comparable St/PU/PE system. Given the fact that PE foam has a slightly higher thermal conductivity and plastic piping systems have a faster ageing process, with these dimensions the heat loss per metre is expected to be higher for the PB/PE/PE system.

The theoretical and experimental heat loss values have a discrepancy of 10% for the short term lab test. This can be explained by several causes, that are accounted for in an effective diameter of the PE foam thickness.

Considering an effective diameter for all PB/PE/PE diameters, the PE foam has an effectiveness of 84% with regard to the potential insulation performance, based on available space between medium pipe and outer casing.

The production of the plastic PB/PE/PE piping system can be optimised by closing the gap between medium pipe and insulation foam. Further, heat loss can be decreased by increasing insulation of the piping system. A larger outer casing for each diameter for PB/PE/PE would result in lower lifetime heat loss than St/PU/PE systems series 1 and comparable heat loss to series 2.

Further research is recommended on the experimental ageing process in time of the PB/PE/PE system. The measuring period of the field test was too short to draw any conclusions on this process. Also heat loss of twin pipe systems should be experimentally tested more.

A further study on system optimisation is described in chapter 7.

Chapter 7: System optimisation

7.1 Introduction

The life cycle assessment in chapter 3 clearly shows that heat loss is the dominating factor determining the environmental impact of district heating systems. Insulation of the *pipe* is the obvious, but not the only possible means to reduce heat loss of the district heating *system*. Parts of the new plastic piping system, which consists of a polybutylene medium pipe and polyethylene foam insulation, have properties that differ from conventional systems (steel pipes with PU foam insulation) and which may influence heat loss, advantageously or adversely. The new system is designed to be flexible, continuous, with longer sections on large reels, can be welded and is apt for drinking water. Therefore, it can be used for the distribution of domestic hot water. Flexibility comes at a price: it is more difficult to reach good insulation. However, specific properties may also be employed to reduce heat loss. A few of those possibilities to reduce heat loss will be discussed in this paper, they may apply to other flexible piping systems as well.

7.2 Heat loss drivers

System design parameters may be chosen differently, in order to reduce heat loss. To assess alternatives, the drivers for heat loss are discussed. Most may come across as rather trivial.

7.2.1 Pipe surface

Heat loss is proportional to the outer surface of the medium pipe, and therefore proportional to pipe length. Since this length represents the main function of district heating systems, transport of heat from one place to another, it can hardly be influenced. Flexible systems will have a small advantage compared to rigid piping, because of its ability to cut corners. Cutting corners results in somewhat shorter pipes.

Heat loss is also proportional to the pipe circumference, thus to the diameter of the pipe. It is therefore beneficial to have diameters as small as possible, but on the other hand, the pipe transport capacity is determined by the area of the cross section, which is proportional to the square of the diameter.

7.2.2 Temperature

Heat loss is directly proportional to the temperature difference between medium and environment. For this reason, design supply temperatures have gone down from 90°C to 70°C, which will reduce heat loss by some 25%. For space heating, the supply temperature may be reduced even more, but the production of domestic hot water requires some 70°C for fear of legionella, which may cause legionnaires’ disease.

7.2.3 Thermal conductivity

For pipes in the ground, heat is lost due to thermal conductivity. The thermal conductivity of the ground may vary significantly, but will be in the order of 1.5 W/m.K. The use of thermal insulation around the pipe greatly reduces heat loss, because the conductivity of the insulation material is some 50 times lower at 0.03 W/m.K. Increasing insulation thickness is the obvious way to reduce heat loss, but bringing the medium pipes closer together is another possibility.

7.2.4 Time

The heat loss of a district heating pipe can be determined as thermal power per unit length, W/m. The thermal energy involved of course depends on the amount of time the pipe is in operation. Most systems are in operation the year round, because domestic hot water may be in demand at any time.

7.3 Demand side characteristics

Knowing what drives heat loss, we want pipes as short and thin as possible, at low temperatures, operated for short periods of time. However, our system still needs to fulfil its function, and this imposes limitations on what we can do in reducing length and diameter. If not good enough, we may reduce thermal conductivity by increasing thermal insulation quality or thickness, or lay pipes closer together. Furthermore, we might reduce operating temperatures as well as operating times.

In order to assess limitations and evaluate results, it is of interest to see what functions need to be fulfilled by the system.

7.3.1 Space heating

Most of the energy supplied by District Heating is used for space heating purposes. The objective is to maintain a comfortable indoor temperature around 20°C, which is done by compensating for heat losses to the environment. In first order approximation, these heat losses are proportional to the difference between indoor and outdoor temperature. Several methods are in use to link average daily outdoor temperature to the seasonal consumption of heating energy. The degree-day method supposes an average outdoor temperature ($T_{av\_outdoor}$)above which no heating is needed, and uses the difference with this cut off temperature (T_{cut_off}) as a measure for the amount of heating needed during that day. The sum of which would be a measure for the total heating energy consumption in that year. This may be described as:

$$degreeday_i := \frac{\left(T_{cut\_off} - T_{av\_outdoor_i}\right) + \left|T_{cut\_off} - T_{av\_outdoor_i}\right|}{2} \qquad (1)$$

Datasets for the average outdoor temperature are usually widely available. In figure 7.1 an example for the Netherlands.

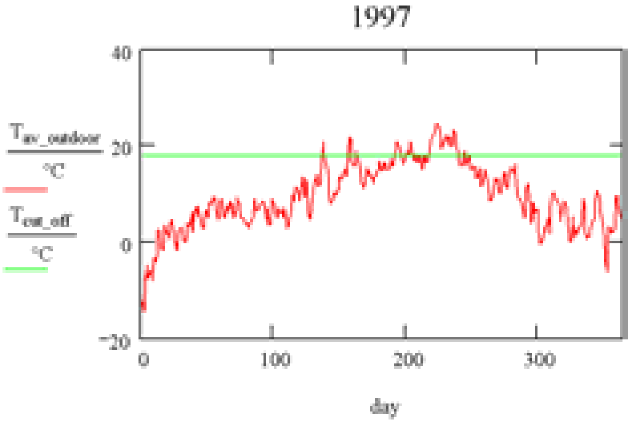

Figure 7.1: One-day averaged outdoor temperature

From this dataset, the number of "degreedays" can be derived.

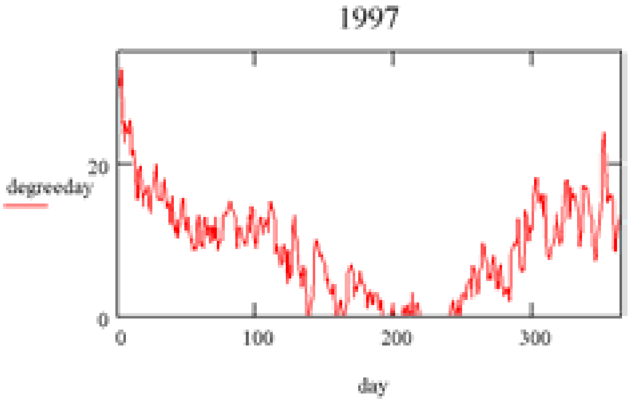

Figure 7.2:Daily energy consumption in "degreedays"

If we sort these daily consumptions (largest first) and divide by the maximum value, we see that the demand drops below 50% fairly quickly, see figure 7.3.

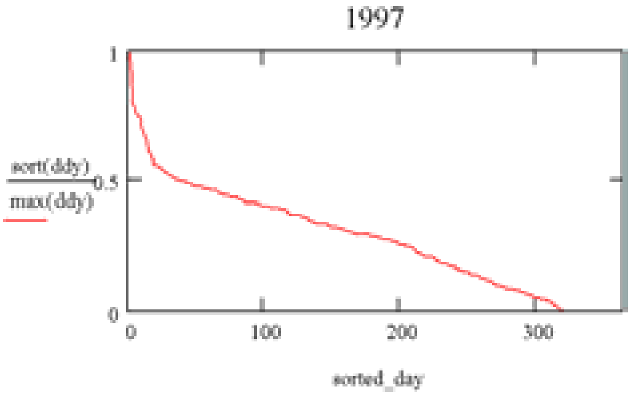

Figure 7.3: Daily energy consumption, sorted

In this case, only 34 days, less than 10%, scores above the 50% power level. Therefore, 90% of the time, the one day averaged required power is below 50% of the design point. Of course, the exact shape of this graph will vary with climate, but the outdoor temperature will vary with the weather everywhere. Since we value our heating the most in the coldest periods, we have to design for a heat load which is quite a bit larger than we will need most of the time.

In this particular case, the number total number of “degreedays” for 1997 (Eelde, the Netherlands) amounts to 3229. If we suppose a certain household to have used 32.29 GJ for space heating alone, which would be a representative amount, each “degreeday” would correspond to 10 MJ. If we plot this as average power per day, we obtain:

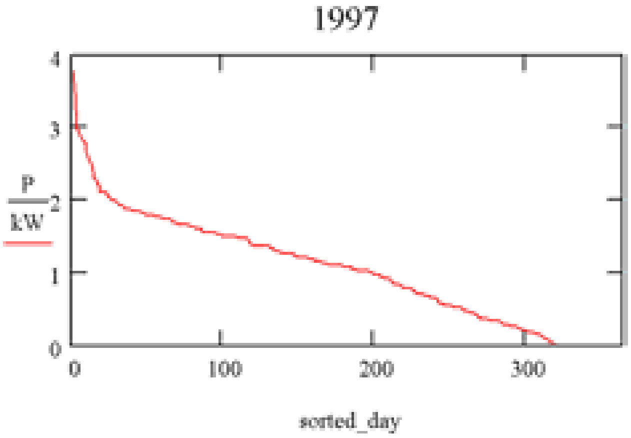

Figure 7.4: One-day averaged power for space heating, one household, sorted

Figure 7.4 suggests that on the average, this particular household looses heat at a rate of no more than 4 kW during the coldest period of 1997, which was just a little bit colder than designed for (-10 °C). This number seems quite a bit off, since a typical house will have for some 16 kW of radiators installed. We know that over dimensioning is not uncommon in district heating, but a factor of 4 would seem rather high.

Two explanations may apply. Firstly, our customers do not tend to trim their radiators to exactly compensate for heat loss at that moment in time, in stead, some on / off behaviour can be observed. In fact, customers often try to reduce energy consumption by reducing the night time temperature, thereby effectively reducing the operating time of their radiators and increasing the amount of power needed, since there are shorter amounts of time available to compensate for heat loss, which goes on all the time. In modern, well insulated houses, this behaviour does hardly contribute to the aim (consumption reduction), because the temperature drop during night times is small. The effect is mainly that the heat capacity of the building mass is being depleted during the night, and has to be refilled in a relatively short period in the morning. In order to do this, rather large radiators have to be, and are, installed. This may roughly account for a factor of 2. Secondly, our users tend *not* to use all the radiators installed. Typically, they prefer a somewhat lower temperature in the bedroom, but since the bedroom lies *within* the insulated shell of the house, the bedrooms are heated by the rooms below. Even without heating, bedroom temperature may be above the required value. For this reason, often only the ground floor is heated (probably bathroom excepted), which may roughly account for the other factor of 2.

Even though this approach may appear somewhat crude, it seems safe to conclude that our customers have plenty of power installed.

Radiator model

Radiators are the standard equipment for space heating based on heated water. In the Netherlands, those systems were usually heated by boilers and designed for a supply temperature of 90°C and a return temperature of 70 °C. District heating, with the transportation of hot water as core business, introduced a different design point for the return temperature: 50°C in stead of 70°C, thereby doubling the network transportation capacity.

In recent years, the trend has been to further reduce design temperatures to 70°C supply and 40°C return. Similar trends can be seen in other countries. For this study, we will use 70/40 as design temperatures for our distribution system.

The behaviour of radiators can be described by:

$$\Delta t_{ln} = \frac{\theta_{supply} - \theta_{return}}{\ln\left(\frac{\theta_{supply} - \theta_{room}}{\theta_{return} - \theta_{room}}\right)} \qquad (2)$$

$$P_{rad} = \left(\frac{\Delta t_{ln}}{\Delta t_{ln0}}\right)^{m} \cdot P_0 \qquad (3)$$

With θ_{supply}, θ_{return} and θ_{room} the supply, return and room temperatures, m being the radiator constant (which may typically vary between 1.2 and 1.4, modelling for differing fractions of convection and radiation). P_{rad} gives the radiator output, with Δt_{ln0} and P_0 the respective value under design conditions. With above formulae (2) and (3), we can calculate how the output of a radiator will vary as a function of the supply temperature, see figure 7.5.

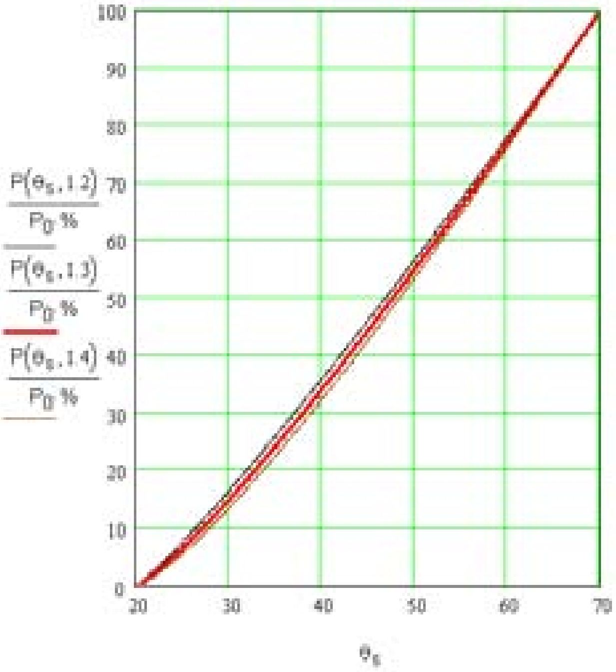

Figure 7.5: Radiator power as function of supply temperature

For this graph, it is supposed that the flow through the radiator remains constant. Note that the power output as function of the supply temperature is not quite a straight line, and that it varies only a little bit with the radiator constant m.

It is also possible to calculate the return temperature under the same condition of nominal flow, see figure 7.6. In practice of course, flow through the radiator may be altered, either by thermostatic radiator valves or by user input. When reducing below nominal flow, power will decrease and cooling will improve. The technical requirements for connection to the district heating network imply that it should not be possible to exceed nominal flow.

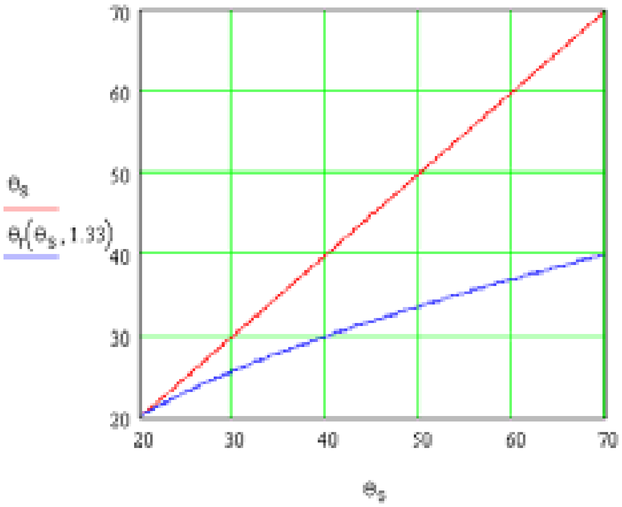

Figure 7.6: Return temperature as function of the supply

From figure 7.3, it follows that for 90% of the time, required power will be below 50% of the design point. In figure 7.5 can be seen that a supply temperature of 50°C is sufficient to supply this demand. Figure 7.6 shows that at nominal flow, the accompanying return temperature will be some 33°C.

7.3.2 Domestic hot water supply

The modern person expects his tap to run plenty of hot water within seconds after opening it. This statement embodies the difficulties with the second district heating product: domestic hot water supply. Even though less energy is involved as compared to space heating, it is expected to be there at any time, in large quantities. Previous chapter's typical household will use 32 GJ for space heating in a year like 1997, and some 7 GJ more for the domestic hot water supply.

On the average, 92 litres of hot water will be used per day, at a rate of maybe 6 litres per minute, sometimes even more. This means that some 25 kW of thermal power has to be available at all times, much more than ever is used for space heating. However, we need this power for brief periods only, typically not much more than 1% of the time. It follows that the one-day averaged power for domestic hot water is not impressive: no more than 222 W in our example, much less than the required power for space heating in winter.

Therefore, the amount of energy is not the problem, it is the rate at which it has to be delivered and the fact that we do not know beforehand when exactly people will want it.

Luckily for District Heating Companies, statistics are on our side, since customers do not operate their taps exactly at the same time. There is of course a chance that two neighbours will take a shower simultaneously, but the chances that ten of the next door neighbours will be doing the same at that exact moment, prove to be quite low. For larger groups at peak times, no more than 10% of all households will be using domestic hot water at the same time, thereby dropping the maximum power demand for domestic hot water below that of space heating. A number of ways are in use to solve the domestic hot water problem.

Local production by heat exchanger

Probably most commonly used. Each household is fitted with a heat exchanger to instantly produce domestic hot water when needed. Quite large surfaces are needed to be able to reach 25 kW, but this is not much of a problem with modern plate heat exchangers. However, cooling may suffer a little, and good temperature regulation is costly. Heat loss seems a small problem, because the heat exchanger contains small volumes and heats up very quickly. Therefore, instant power is no problem, provided district heating water with sufficient temperature (65-70°C) is instantly available.

This may prove the Achilles heel of this solution, because the district heating network needs to be maintained at high temperatures for 100 % of the time, to be ready for the 1 % of the time that domestic hot water needs to be produced. During space heating operation, this is less of a problem, but even during winter, this may not be 24 hours a day, because of night time setback. If few radiators are in operation, there is little cooling and return temperatures will rise in order to maintain sufficient supply temperature.

So there will be supplementary heat losses, both in supply and return, especially when space heating is out of operation. On a yearly basis, this may be quite a lot of time, during which the supply temperature will be 70°C and the return may rise to 60°C.

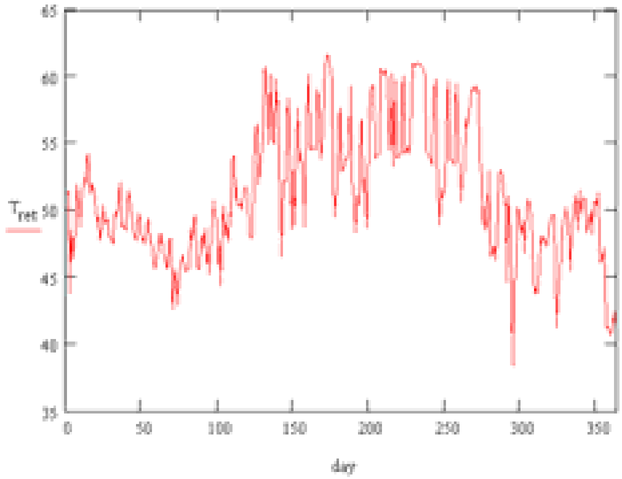

Figure 7.7: One-day averaged return temperature

As can be seen in figure 7.7, the measured return temperature is highest during summer, but still not very low in the cold season. This is probably caused by relatively low operating times of the heating systems.

The high return temperatures may easily give rise to heat losses in the same order of the one-day averaged power demand for domestic hot water: 222 W per household.

Local production with storage

As solution to the high instantaneous power demand for domestic hot water, sometimes a hot water tank is promoted. Even though power demand may indeed drop considerably, this solution is not without drawbacks.

First off, it solves a problem that is not really there once larger amounts of houses are connected, as is the case with district heating. As we have seen, the simultaneous use of domestic hot water drops quite quickly with the number of users connected. As a result, the distributed heat buffers are of little use reducing production or transport capacity requirements. Furthermore, cooling may be poor once the tanks are full, and the tanks themselves will contribute to heat losses considerably, whilst the network still has to be available at all times. As we have demonstrated in the previous section, this leads to considerable heat losses as well.

This option will not be investigated any further in this study.

Distribution of domestic hot water

In some district heating systems, a separate network is in use for the distribution of domestic hot water. Since drinking water normally contains oxygen, standard steel pipes are not an option. Copper is widely used, but is prone to different types of corrosion, which puts limitations on chemical composition and speed of the water. Polybutylene may serve as an alternative medium pipe, without those limitations.

Main disadvantage of domestic hot water distribution is of course, that a separate distribution network needs to be installed. The temperature of the domestic hot water has to be at least 60°C, so some sort of circulation of the network is required, even though there will be no return flow from our customers. This is traditionally done by a (smaller) circulation pipe within the same insulation, but it is also feasible to install one pipe in a ring-like structure, effectively creating a three pipe district heating system. Additional pipe surface will mean additional heat loss, but on the other hand, the standard district heating distribution network no longer needs to service the domestic hot water production, and may be operated at lower temperature, or even be switched off in summer.

A distinct advantage of the separate distribution of domestic hot water is the possibility to put the heating and reheating processes of the domestic hot water supply in series. This improves cooling significantly during times that domestic hot water is delivered to our customers. For one customer, this is only 1 % of the time, but for several hundred customers, this period is a lot longer, thus significantly reducing return temperatures.

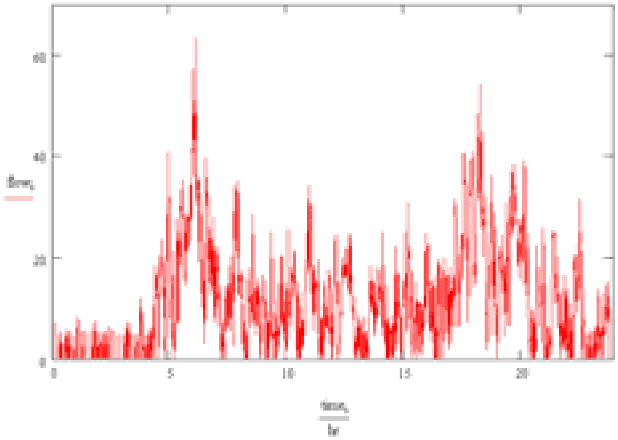

Figure 7.8:Typical one day domestic hot water pattern

Figure 7.8 shows a typical day of domestic hot water use for 105 houses in litres/min. The peak power corresponds to 243 kW, in which case we are producing domestic hot water for around ten users at the same time.

7.4 Options for heat loss reduction

Since there are quite a lot of parameters influencing heat loss, this section will focus on a limited selection of them, just to get an idea of how much each measure might contribute. A reference system will be introduced, to which alternatives will be compared.

7.4.1 Reference system

The reference system features a standard design, with domestic hot water produced locally by means of a heat exchanger. Two St/PU/PE medium pipes are used, situated next to each other, with 38 cm separation to allow for welding.

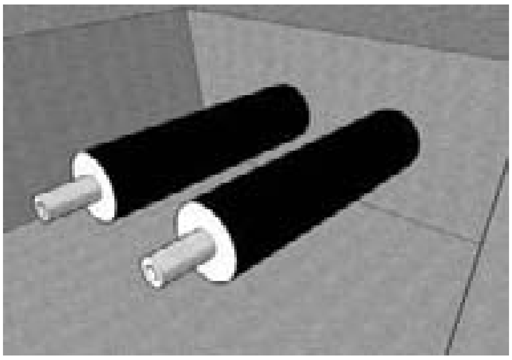

Figure 7.9: Two pipe system

The reference system is installed in a housing estate near Arnhem, the Netherlands, and has been designed using Pipelab, developed by Dr. Pàll Valdimarsson [23]. Standard design criteria were used.

Figure 7.10: Aerial photograph of reference housing estate

A total of 247 houses are connected by 3.02 km of DH network (6.05 km of pipe), 12.2 m per house. The heat losses are calculated using the multipole method by Johan Cleasson and Camilla Persson [24]. Total heat loss for series I St/PU/PE amounts to 72.3 kW or 23.9 W/m (two pipes), at an average supply temperature of 70.5 °C and an average return temperature of 52.8 °C. As shown in figure 7.7, the return temperature rises when heating is off, in order to maintain ample supply temperature.

Using the new PB/PE/PE piping with standard size insulation, yields quite a bit higher heat losses: 87.4 kW for the same network. This is mainly due to less insulation thickness and relatively fast degassing of the PE foam, as shown in chapter 6.

7.4.2 Increase of insulation thickness

An obvious way to reduce heat loss is the use of thicker insulation, as has been done in Series II St/PU/PE. By using Series II piping, heat loss drops by 13% for the standard network to 63.1 kW.

With PB/PE/PE, the improvement is more impressive, as calculations show that heat loss would drop with 26% from 87.4 to 64.6 kW. Not as good as its rigid (Series II) counterpart, but still better than the reference system.

7.4.3 Reduction of pipe surface

Can be achieved in two ways: either by reducing pipe length or by reducing pipe diameter.

Reduction of length

It does seem difficult to reduce pipe length by introducing a flexible system, since distances remain the same and the same route along roads has to be followed. However, “flexible” is a relative notion, the larger diameters can be rather stiff. This leads to a natural tendency to cut corners, thereby reducing pipe length. It is difficult to assess how big this effect may be, in one setup we found 2-3%, but since mechanical properties of polybutylene are such that expansion loops are no longer needed, the effect may be significant.

Furthermore, the network needs to connect a number of points (house connections) that usually are not lined up properly. With flexible pipes, it is much easier to connect those points with straight lines, since bends are available at any desired angle. At present, we have no clue as to how large this effect may be, but it certainly contributes to the reduction of heat loss.

Reduction of diameter

Pipe surface may also be reduced by reducing pipe diameter. The friction factor for hydraulic resistance for polybutylene is significantly lower: k=0.007 mm, compared to k=0,05 mm for steel. In calculation, this leads to slightly smaller diameters. For example: DN50 (54.5 mm) at a design point of 300 Pa/m can carry around 2.9 kg/s. This same amount in polybutylene yields a 3.8% smaller diameter, some 2.1 mm less at 52.4 mm. This almost fits PB63 at 51.4 mm. However, since PB needs to be thicker than steel, the outside diameter of this PB medium pipe is slightly thicker than its steel counterpart: 63 vs. 60.3 mm. Since PB insulates better than steel, there will be little difference in performance between medium pipes due to differences in hydraulic friction factor.

Increase of fluid speed

Then, we may consider an increase of speed in the medium pipes, also resulting in smaller diameters. However, pressure loss is proportional to the square of the speed of the liquid, so available headroom tends to be consumed rather quickly.

In steel distribution networks, speed is limited because of noise considerations. A modest speed increase (smaller diameters, less pipe surface) leads to a heat loss reduction of 6%: 67.7 kW in stead of 72.3 kW (series I). Doing the same for series II, adds another 8% to the 13% heat loss reduction from increased insulation, to reach 58.3 kW, a total reduction of 20% as compared to the reference system. The average heat loss has dropped from 23.9 W to 19.5 W per meter network.

Polybutylene seems to dampen noises quite effectively, and therefore, higher speeds can be allowed. However, our calculations show that since we use fairly high speed in the standard calculation already, there is not a lot of room for improvement left. The ‘high speed’ calculation is just a little bit better at 63.2 kW.

7.4.4 Reduction of temperature by Domestic Hot Water distribution

In paragraph 7.3.2, a three pipe system with separate domestic hot water distribution was introduced as a possible means to reduce the temperature levels in the space heating service pipes.

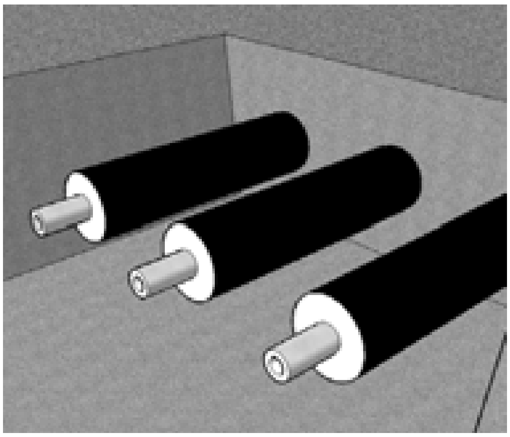

Figure 7.11:Three pipe system

Calculations show that the yearly averaged supply temperature drops to 52°C, the return temperature to 31°C. The (copper) service pipe for domestic hot water Cu42/110 is situated in the middle and is maintained at 65°C. The tree pipes shield each other to a certain extent, further reducing heat loss. For a limited amount of time, (730 h) the two outside pipes are shut down completely, because no space heating is required (reduction of time). If the network is designed to heat up quickly, this shut down period may be extended significantly, thus further reducing heat loss.

For Series I type PU insulated piping, the tree pipe system yields a heat loss of 58.9 kW, a reduction of 13%. For Series 2, the heat loss for the tree pipe system drops further to 51.8 kW.

Since PB/PE/PE is flexible, it is possible to lay the three pipes closer together.

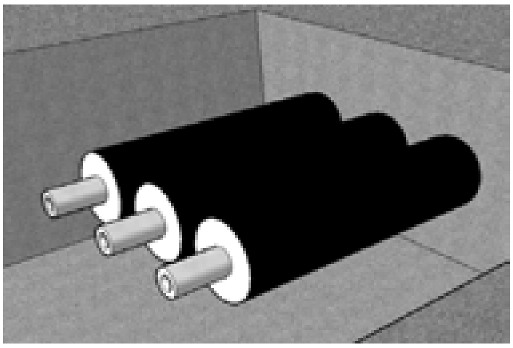

Figure 7.12:Three pipe system, PB/PE/PE

The tree pipe PB/PE/PE system has one PB40/125 domestic hot water pipe in the middle. With standard insulation size, the thee pipe system yields 71.9 kW heat loss, comparable to the reference network. With improved insulation, the heat loss drops to 64.5 kW.

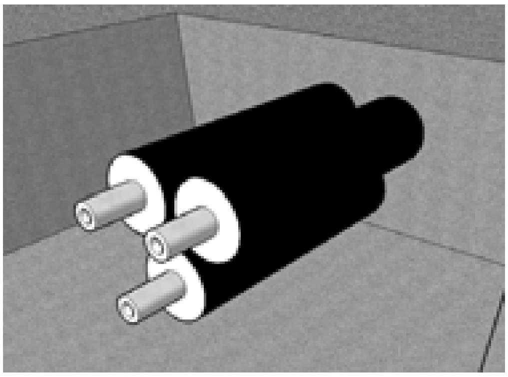

Figure 7.12:Three pipe PB system, bundled

Arranging the pipes in a bundled configuration (figure 7.12), with the domestic hot water pipe below, reduces the heat loss a little further to 63.2 kW. This is comparable to the reference network in Series 2 St/PU/PE.

7.4.5 Overview

In the table below, the heat loss calculation results for 247 houses, 3 km of network (6 km pipe) are summarised.

Table 1 Overview of calculation results

Material	*Description*	*Heat loss [kW]*
St-PUR-PE Series I	Reference system	72.3
St-PUR-PE Series I	High speed	67.7
St-PUR-PE Series II	Standard speed	63.1
St-PUR-PE Series II	High speed	58.3
PB-PE-PE Standard	Standard speed	87.4
PB-PE-PE Improved	Standard speed	64.6
PB-PE-PE Improved	High speed	62.3
St/Cu-PUR-PE Series I	Three pipe system	58.9
St/Cu-PUR-PE Series II	Three pipe system	51.8
PB-PE-PE Standard	Three pipe, line	72.7
PB-PE-PE Improved	Three pipe, line	62.1
PB-PE-PE Improved	Three pipe, bundle	61.6

The calculations for PU insulated rigid systems have been done with pipes listed here:

Table 2 Overview of rigid pipes used

St/Cu-PUR-PE Series I	*St/Cu-PUR-PE Series II*
DN20/90	DN20/110
DN25/90	DN25/110
DN32/110	DN32/125
DN40/110	DN40/125
Cu42/110 (DHW)	Cu42/125 (DHW)
DN50/125	DN50/140
DN65/140	DN65/160
DN80/160	DN80/180
DN100/200	DN100/225

The calculations with the flexible system have been performed with the dimensions listed below:

Table 3 Overview of flexible pipes used

PB-PE-PE Standard	*PB-PE-PE Improved*
PB25/90	PB25/125
PB32/90	PB32/125
PB40/90	PB40/125
PB40/125 (DHW)	PB40/140 (DHW)
PB50/125	PB50/160
PB63/125	PB63/160
PB75/160	PB75/200
PB90/160	PB90/200
PB110/200	PB110/200

7.5 Conclusions

The new flexible PB/PE/PE piping system in its standard configuration is not insulated as effectively as conventional rigid St/PU/PE (Series I) piping. This is mainly due to less insulation thickness and relatively fast degassing of the PE foam. The obvious method to reduce heat loss is to increase insulation thickness. This would lead to comparable heat loss values.

Calculated heat losses for the distribution system are in the range of 240 to 290 W per house, or 20 – 25% of the yearly consumption.

An alternative to reduce heat loss is to install a separate pipe for domestic hot water distribution, thus creating a three pipe system. This allows for lower average temperatures in supply and return. During warm periods, two of the tree pipes can be shut down completely, as no space heating is required. In our calculation, this was done for 730 h/year.

If the network is designed to heat up quickly, this shut down period may be extended significantly, thus further reducing heat loss.

Chapter 8: Conclusions

This report describes several studies in regard with a new all plastic piping system. This polybutylene piping system is generally compared to conventional steel piping systems.

8.1 Life cycle assessment

Life cycle assessment of the different piping systems shows the impact of several life cycle stages to the environment. One clear conclusion is the dominance of heat loss on the environmental impact. The contribution of heat loss can be subtracted from the long utilization period of district heating systems. The life time of a pre-insulated pipe, which is about fifty years, is very long. Increasing the utilization period of the district heating system only enlarges the contribution of heat loss on the environmental impact.

Enhancing the products performance (e.g. increasing insulation thickness) leads to a lower environmental impact. Increasing insulation thickness is not endless due to an optimum between insulation thickness extension (decreasing heat loss) and surface extension (increasing heat loss). Due to economical arguments the optimum for increasing insulation thickness is around ten percent of the actual insulation thickness. The production phase will consequently rise in impact contribution, but since the effects of production are less than one percent on the total impact, this increase is acceptable from an energetically point of view.

8.2 Cost benefit analysis

For both high and low density plastic networks costs for materials and installation are comparable to conventional steel networks. The use of twin pipes only decreases the investment costs due to smaller trenches and lower network lengths. Also, twin pipes have (in theory) lower heat loss which leads to lower costs over its lifetime.

Costs for piping length is the most determining factor in total costs for plastic pipe networks. This is mainly because of high prices per metre due to the stage of development for the PB/PE/PE system. These prices are expected to decrease as the system develops into a final product, causing total investment costs for plastic pipe systems to decrease also.

Installation costs for the plastic pipe system is as yet still uncertain. The cost analysis is based on prices given by three contractors, but also having relatively little experience with the system. Costs for installation of the PB/PE/PE system therefore can be seen as a maximum, that will decrease as contractors become more experienced with the system.

8.3 Long term behaviour

Three studies are made on the long term behaviour of the new all plastic piping system. The first study describes an assessment of the thermal insulation by polyethylene foam. The second study describes the risks for corrosion due to oxygen diffusion through plastic piping systems for the total system, heat exchangers, radiators and couplings. The third study presents the quantification of the change in the thermal insulation of the PE foam as a function of the exchange of gas or vapour between foam cells and the environment.

The fraction of open cells was determined experimentally. The final result of these experiments is that the fraction of open cells is not exceeding 6 ± 3 %. The temperature gradient, heat loss and the water flux were calculated for three situations, namely:

Watertight PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe and hot water temperature of 65 °C;

Leaking PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe and hot water temperature of 65 °C;

Watertight PE outer pipe in groundwater of 10 °C, foam layer between PE outer pipe and PB hot water pipe, leaking PB pipe and hot water temperature of 65 °C.

In the last situation a calculation showed that it will take at least 30 years before all cells are filled with water.

A major thread to hot water systems is the diffusion of oxygen through plastic materials. As a consequence there is a risk for corrosion in the steel and copper components of the total system, e.g. heat exchangers, radiators and couplings. To overcome the diffusion of oxygen through the PB medium pipe, the PB/PE/PE system is supplied with an EVOH coating. This is a diffusion barrier that reduces the ingress of oxygen. Nevertheless there is still a certain diffusion of oxygen, even with the EVOH barrier.

The wall thickness decrease is acceptable in case of an equal divided corrosion attack, but oxygen may initiate localised corrosion, for instance pitting corrosion. At the joints of the PB tubes with the carbon steel tubes the oxygen levels are at the max and, as mentioned before, this oxygen will react instantaneously with the carbon steel. The corrosion takes also place on locations with a thin protective layer and with conditions that foster corrosion. The risk of severe localised corrosion (pitting) in the carbon steel parts under the mentioned conditions is not quantitatively predictable. But if pitting occurs, it is an out of control process and corrosion rates of mm/year are possible.

A key issue is to maintain an optimal water quality and prevent ingress of air and salts because the occurrence of pitting corrosion is strongly promoted by the presence of salts especially chlorine.

Calculations to quantify the ageing of foam insulated pipes for district heating have been performed. The foams studied are PE (polyethylene) foam in the PB/PE/PE system and PU (polyurethane) foam in the steel pipe system.

The initial value for the heat conductivity of the PU foam in the St/PU/PE system is similar to the PE foam of the PB/PE/PE system. The characteristic ageing time is longer for the steel pipe system as a result of the thicker pipe wall, which forms a higher barrier for oxygen and nitrogen.

It is expected that the ageing rate of PE and PU foam will be almost identical if both foams are insulated by the same plastic jacket. The permeation behaviour of the jacket for blowing agent, oxygen and nitrogen is decisive for the ageing rate.

8.4 Heat loss anaysis

The heat loss of the standard piping diameters is determined and possible variables for optimisation are given.

Hence in most cases the standard geometry of PB/PE/PE consists of lower insulation thickness than the comparable St/PU/PE system. Given the fact that PE foam has a slightly higher thermal conductivity and plastic piping systems have a faster ageing process, with these dimensions the heat loss per metre is expected to be higher for the PB/PE/PE system.

The theoretical and experimental heat loss values have a discrepancy of 10% for the short term lab test. This can be explained by several causes, that are accounted for in an effective diameter of the PE foam thickness.

Considering an effective diameter for all PB/PE/PE diameters, the PE foam has an effectiveness of 84% with regard to the potential insulation performance, based on available space between medium pipe and outer casing.

The production of the plastic PB/PE/PE piping system can be optimised by closing the gap between medium pipe and insulation foam. Further, heat loss can be decreased by increasing insulation of the piping system. A larger outer casing for each diameter for PB/PE/PE would result in lower lifetime heat loss than St/PU/PE systems series 1 and comparable heat loss to series 2.

8.5 System optimisation

The new flexible PB/PE/PE piping system in its standard configuration is not insulated as effectively as conventional rigid St/PU/PE (Series I) piping. This is mainly due to less insulation thickness and relatively fast degassing of the PE foam. The obvious method to reduce heat loss is to increase insulation thickness. This would lead to comparable heat loss values.

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If the network is designed to heat up quickly, this shut down period may be extended significantly, thus further reducing heat loss.

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Appendix I: Water flux through PE foam

Model

Plastic foam can be presented schematically by a series of parallel layers (see figure A.1).

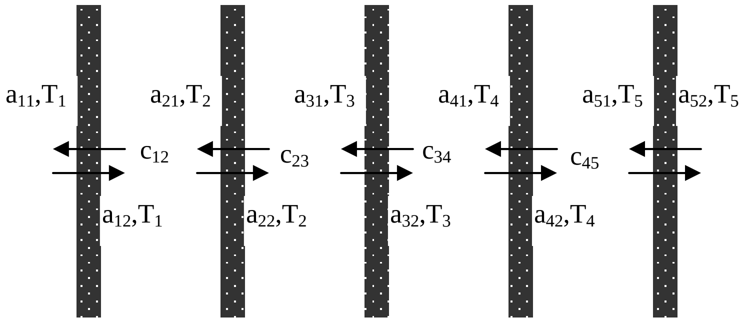


Fig. A.1 Schematic illustration of the water flux through the plastic foam; darker layers represent the plastic layers, arrows represent the flux; the plastic layers experience different temperatures (T_i); the water activity on the left (a_{i1}) and right (a_{i2}) side of the plastic layer can differ; between two successive plastic layers the water vapour concentration ($c_{i,i+1}$)[10] is constant.

Time needed to reach the stationary state

A stationary state will be reached when the conditions on both sides of the foam are constant. Here, constant conditions are assumed for the PB hot water pipe and the soil.

The time, tts, which is needed to realise the stationary state, is represented by:

$$tts \approx n \frac{d^2}{D}$$

Where

n	[n]	Number of plastic layers
d	[mm]	Thickness of the plastic layers
D	[m^2/s]	Water diffusion coefficient in the plastic layers.

Substitution of $d = 0.04$ mm, $D = 1 \times 10^{-11}$ m^2/s and $n=19$ results in 3000 s (= 50 min). Thus a stationary state is realised within an hour for the PE foam in the PB/PE/PE system studied. The time to realise the stationary state has been ignored, because this time is short compared to the operation time of the pipe.

Water flux (stationary state)

The water flux through the ith plastic layer per unit of surface area and of time is represented by:

---

[10] A comma has been added between the indices to clarify the first and the second index.

$$j_i = \frac{D(T_i)}{d_i} c_{i0} \left(a_{i1} - a_{i2} \right)$$

Where:

j_i	[g/day/m pipe]	Water flux trough the i^{the} plastic layer
d_i	[mm]	Thickness of the plastic layer
$D(T_i)$	[-]	Water diffusion coefficient at a temperature T_i
a_{i1}-a_{i2}	[-]	Difference in activity over the i^{th} layer
c_{i0}	[g/l]	Concentration

The absorption of water by the plastic, when the plastic is immersed in water, shows limited temperature dependence. The activation energy for the water absorption by PE and PB is therefore assumed to be 0 kJ/mol. An activation energy of 30 kJ/mol is assumed for the water diffusion in PE.

On the assumption that adsorption phenomena can be ignored at the surface, at equilibrium the following conditions hold good for the activities at the surfaces of the plastic layers (see fig. A.1):

$$a_{i2} = \frac{c_{i,i+1}}{c_{i0d}(T_i)} \quad \text{and} \quad a_{i+1,1} = \frac{c_{i,i+1}}{c_{i0d}(T_{i+1})}$$

Where:

a_{i2}	[-]	Activity of the surface of the plastic layer
$c_{i,i+1}$	[g/l]	Water vapour concentrations in the volume between the i^{th} and the $(i+1)^{th}$ layer
c_{i0d}	[g/l]	Saturated water vapour concentration at the given temperature

Example

Suppose the temperature of the left plastic layer is 52 °C and of the right layer 50 °C and the water vapour concentration in the volume between both layers is 0.08 g/l.

The saturated water vapour concentration is 0.083 g/l at 50 °C and 0.091 g/l at 52°C. Thus the water vapour activity, a_{i2}, on the left surface is 0.08/0.091 = 0.88 and the activity, $a_{i+1,1}$, on the right surface 0.08/0.083 = 0.96.

Saturated water vapour concentration

The saturated water vapour concentration versus the temperature is shown in figure A.2. Notice that the water vapour, even when saturated hardly contributes to the weight of the foam. The maximum contribution to the weight will be 0.16 g/l at 65 °C, which is less than 0.5 % of the density of the foam studied.

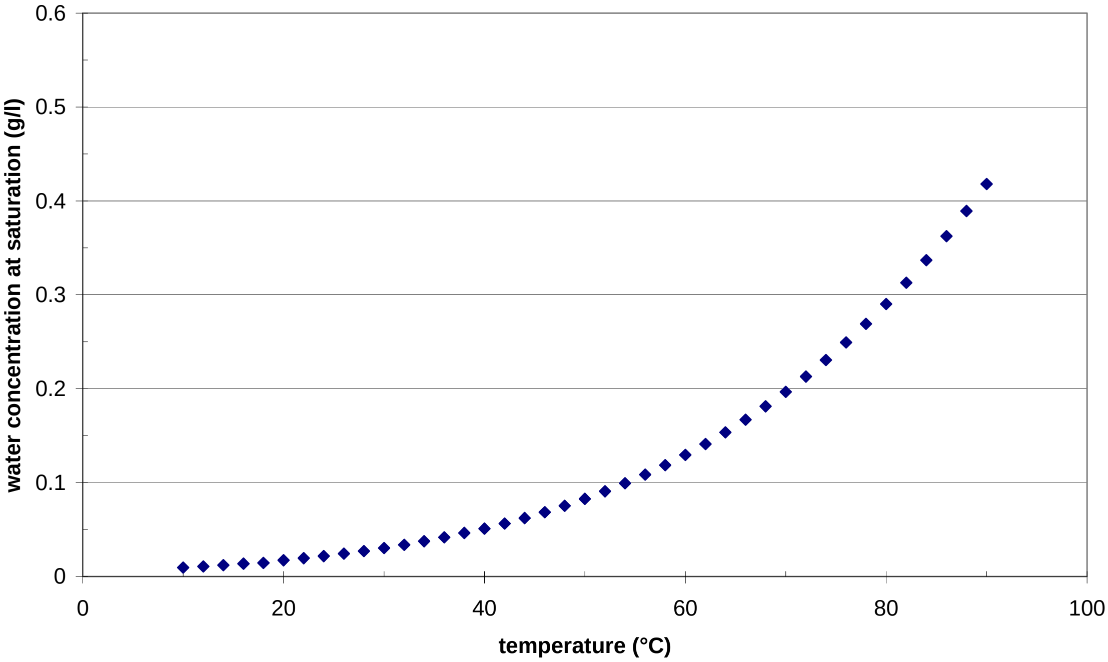


Fig. A.2 Saturated water vapour concentration versus temperature.

7.1.1 Isothermal flux

Isothermal water flux over a foam layer can be modelled simply. The situation with a water flux of 0.03 g/day/m pipe, a water vapour activity of 0.6 at the outer surface and a temperature of 65 ºC is shown in figure A.3. A difference in water vapour activity over the foam of 0.13 was found.

The foam studied consists of a cylinder with an inner radius of 34 mm and an outer radius of 54 mm.

The water concentration in the cells is 0.097 g/l at 54 mm (drain) and 0.12 g/l at 34 mm (feed).

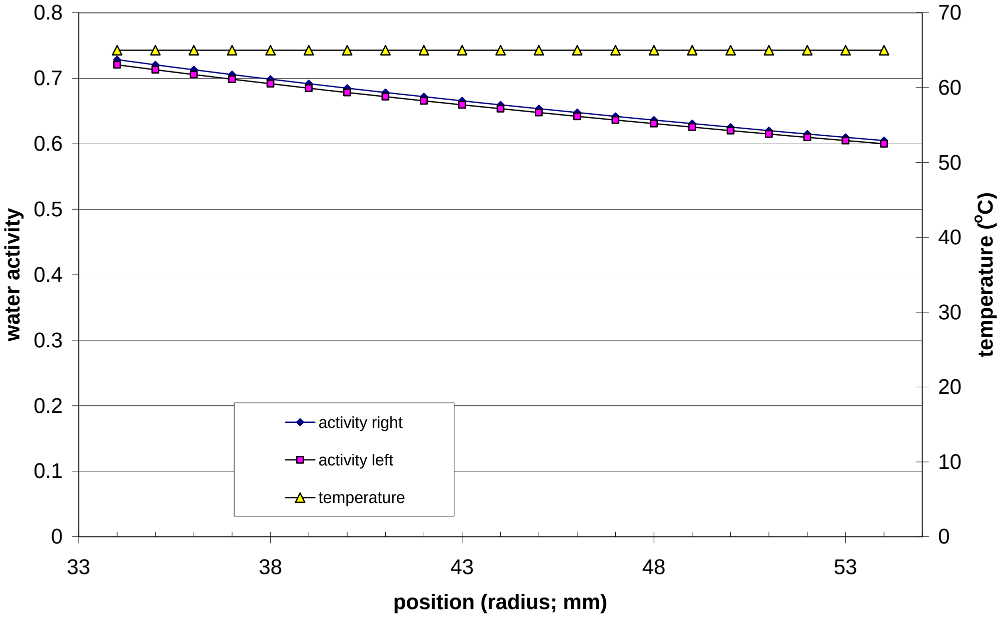


Fig. A.3 Change of water activity over the layers for an isothermal situation (65 °C) and a water flux of 0.03 g/day / m pipe.

7.1.2 Water flux under a temperature gradient

A peculiar phenomenon occurs as a result of the difference in water activity at the plastic surfaces of one cell when a temperature gradient exists over the foam. A difference in water activity is caused by the difference in temperature between both layers. The water flux is towards the side with the lowest temperature. This phenomenon can be compared to the condensation of water on a cold surface.

The water vapour concentrations in the neighbouring cells cause a water flux through the foam despite of the increase in water activity.

Situation 1: moderate water vapour flux from hot water pipe

Figure A.4 shows the situation in which a water flux of 0.03 g/day/m pipe and an activity at the outer surface of 0.6 are assumed at a maximum temperature of 50 °C. This condition results in a difference in water activity over the foam studied of 0.33.

The water concentration in the cells is 0.011 g/l at 54 mm (drain) and 0.024 g/l at 34 mm (feed).

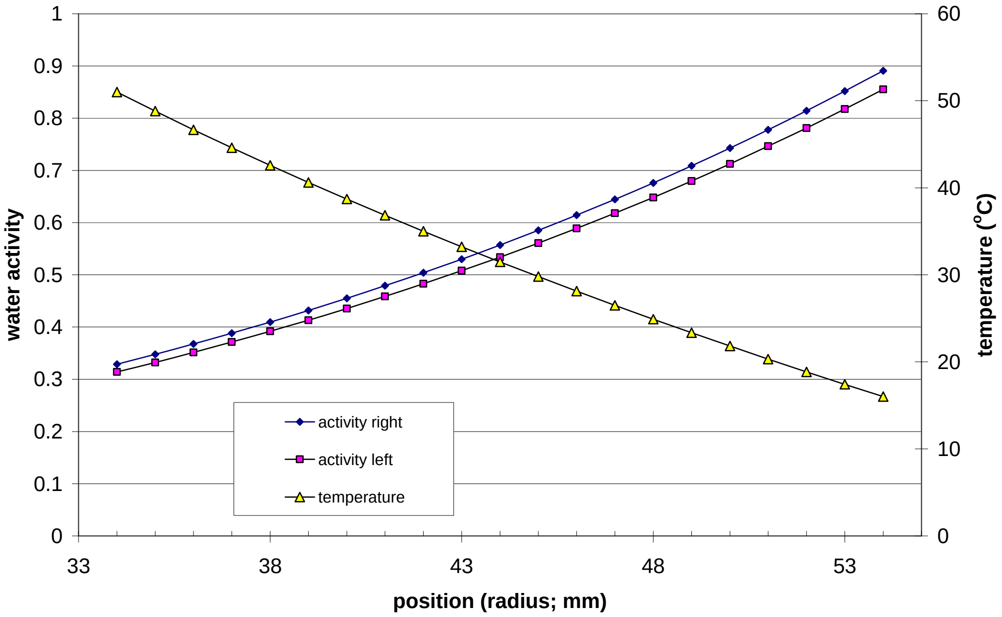


Fig. A.4 Change of activity over plastic layers (difference between ♦ and ■ over one cell wall) and between the cells at a temperature gradient over the foam and a water flux of 0.03 g/day / m pipe.

Situation 2: leaking water pipe

Figure A.5 shows the situation in which leakage occurs in the hot water pipe and hot water is present on the inner side of the PE foam. A maximum temperature of 70 °C is assumed as is a water activity of 0.6 on the outer side of the PE foam.

This situation is characterised by a water activity of 1 on the inner side. The activity of liquid water is equal to that of saturated water vapour. In this situation, it is not possible to realize an equilibrium in which the saturated water vapour pressure in one cell is not exceeded. Consequently, water condensation will occur.

The increased diffusion rate at the higher temperature leads to an accelerated water transport through the cell wall in contact with the hot water. The water flux will stop as soon as saturation is reached in the first cell. Condensation will occur on the right cell wall due to the lower temperature in this cell wall. As a result, the water vapour pressure in the cell is reduced and additional water is transported to the left cell wall. The exact quantity cannot be calculated. This quantity depends on the dynamics of the water vapour in a cell in which a continuous process of evaporation and condensation occurs. A situation will be realised in which a higher water vapour pressure occurs and herewith a smaller gradient over the left cell wall. A pseudo-equilibrium state will form, in which the water flux will be almost constant over the whole foam.

The water concentration in the cells is 0.013 g/l at 54 mm (drain) and 0.19 g/l at 34 mm (feed).

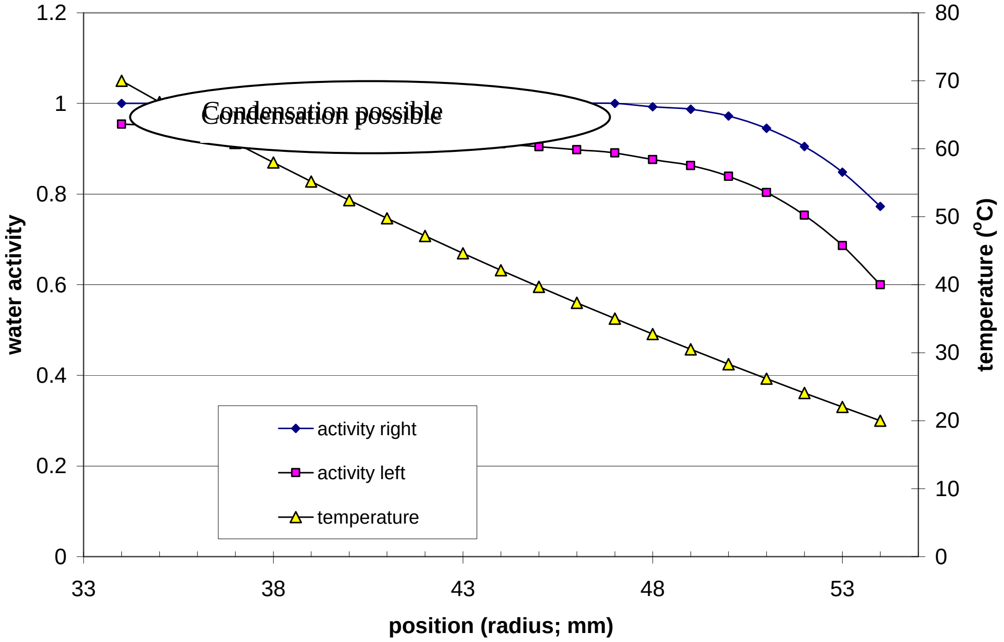


Fig. A.5 Change of activity over plastic layers (difference between ♦ and ■ over one cell wall) and between the cells at a temperature gradient over the foam and a water flux of 0.2 g/day m pipe. A difference in water activity, which is smaller than the one corresponding to water condensation, is needed to realise a water flux of 0.2 g/day/m pipe.

Appendix II: Data tables for the calculation of long term behaviour

Transport properties of water vapour in LD (low density) PE and HD (high density) PE at ambient temperature found in literature are presented in table 5.2. The coefficients mentioned in tables A.1 and A.2 are expected to show an increase of a factor of 3-10 per 30 °C.

Table A.1: Diffusion, sorption and permeation coefficient for water through PE ambient temperature

Coefficient	**LDPE**	**HDPE**
Diffusion	3.5×10^{-11} (m^2/s)	1.0×10^{-11} (m^2/s)
Sorption	< 0.5 kg/m^3	< 0.5 kg/m^3
Permeation	0.07-0.59 g/m^2/day given a thickness of 1 mm	0.02-0.16 g/m^2/day given a thickness of 1

TableA.2: Values for the heat conductivity of some applied materials

Material	**Heat conductivity, λ (W/m/K)**
Air	0.025 (20 °C)
	0.030 (80 °C)
Water	0.60 (20 °C)
	0.67 (80 °C)
PE	0.35-0.5
PB	0.23
PE foam	0.03-0.04
Sand	0.35 (dry)
	2.7 (wet)

The dimensions of the insulated PB/PE/PE pipe system studied are given in table A.3. The dimensions are applied in the calculations in this report.

Table A.3: Composition of insulated pipe

Layer	**Inner diameter (mm)**	**Outer diameter (mm)**	**Wall thickness (mm)**
PB pipe	51.4	63	5,8
Air	63	70	3,5
Foam	70	108	19
Corrugated pipe	108	125	1
Soil	110	1000	445

Appendix III: Thermal insulation by PE foam

Situation II is almost identical to situation I. As the calculation will show, there will be a net water flux to the soil. A leaking PE pipe leads to an increase in heat capacity of this layer. However, the influence of the higher heat capacity is limited because the PB wall is relatively small.

Table A.1: Situation I: no intersection in PE foam; fraction of open cells is ignored

Layer	**l_i (W/m.K)**	**d_i (mm)**	**A_i (m^2)**	**l_i A_i/d_i**	**Fraction****
Hot water					
PB	0.23	5.8	0.18	7.13	1
Air	0.03	3.5	0.21	1.79	1
Foam	0.04	19	0.28	0.59	1
PE wall corrugated pipe	0.4	1	0.34	54.79	0.4
Soil	1*	445	1.74	3.92	1
DT_{total}	55	°C			
Q	20.6	W/m pipe			

* A value of 1 was chosen and not a value of 2.7, because the soil surrounding the insulated pipe will heat to some extent. As a consequence, the soil in not saturated with water in the direct surroundings of the insulated pipe.

**: The presence of air in the corrugations increases the efficiency. A fraction has been introduced to correct λ_i A_i/d_i for this effect.

Table A.2: Situation I: thermally welded intersection in the PE foam; fraction of open cells is 6%

Layer	**l_i (W/m/K)**	**d_i (mm)**	**A_i (m^2)**	**l_i A_i/d_i**	**Fraction**
Hot water					
PB	0.23	5.8	0.18	7.13	1
Air	0.03	3.5	0.21	1.79	1
Foam	0.07#	19	0.28	0.59	1
PE wall corrugated pipe	0,4	1	0.34	54.79	0.4
Soil	1	445	1.74	3.92	1
DT_{total}	55	°C			
Q	28.3	W/m pipe			

#: The water heat conductivity is 0.6. 6 % of 0,6 W/m/K is 0.036 and has been rounded down to 0.03 W/m/K. This estimate is conservative, because it is assumed that the water condenses in the open cells. However, the water flux calculations on an intact PB pipe show that water vapour is only present in the open cells. In that case the values presented in table 5.5a should be used.

The bonded intersection in the foam layer will increase the heat conductivity to some extent. It is expected that this increase is comparable with an additional fraction of open cells of 2 %.

The values presented in table A.1 can be applied as long as no water condensation occurs in the open cells.

TableA.3: Situation II: no intersection considered in the PE foam; fraction of open cells is zero

Layer	**l_i (W/m/K)**	**d_i (mm)**	**A_i (m^2)**	**$l_i A_i/d_i$**	**Fraction***
Hot water					
PB	0.60	5.8	0.18	18.59	1
Air	0.60	3.5	0.21	35.81	1
Foam	0.04	19	0.28	0.59	1
PE wall corrugated pipe	0.4	1	0.34	54.79	0.4
Soil	1	445	1.74	3,92	1
DT_{total}	55	°C			
Q	26.8	W/m pipe			

TableA.4: Situation II: thermally welded intersection in the PE foam; fraction of open cells is 6%

Laag	**l_i (W/m/K)**	**d_i (mm)**	**A_i (m^2)**	**$l_i A_i/d_i$**	**Fraction**
Hot water					
PB	0.60	5.8	0.18	18.59	1
Air	0.60	3.5	0.21	35.81	1
Foam	0.07#	19	0.28	0.59	1
PE wall corrugated pipe	0.4	1	0.34	54.79	0.4
Soil	1	445	1.74	3.92	1
DT_{totaal}	55	°C			
Q	41.5	W/m pipe			

#: The water heat conductivity is 0.6. 6 % of 0.6 W/m/K is 0.036 and has been rounded down to 0.03 W/m/K. The assumption that all open cells are filled with water will be incorrect, even in this situation.

The closed cells of the PE foam will slowly be filled by water as a result of water condensation.

Table A.5: Water flux through the walls of the insulated pipe studied with a leak in the PB pipe; situation III; no intersection in the PE foam; fraction of open cells is zero

	D_i	**d_i**	**A_i**	**c_{i0}**	**$D_i A_i c_{i0}/d_i$**	
layer	**(m^2/s)**	**(mm)**	**(m^2)**	**(g/m^3)**	**(g/day/m pi**	**frac**
Hot water						
PB	$1.0x10^{-6}$	5.8	0.18	1000000	2680000	
Air	$1.0x10^{-6}$	3.5	0.21	1000000	5160000	
Foam	$2.1x10^{-11}$	19	0.28	500	1.36	
PE wall corrugated pipe	$8.9x10^{-12}$	1	0.34	500	0.78	
Soil	$1.0x10^{-6}$	445	1.74	14	4.77	
j	0.08	(g/day/m pipe)				

Situation III, the situation with a leak in the PB pipe, is slightly different. The net water flux is higher. The calculated values for this situation can be found in Appendix III table 5.8.

Appendix IV: Ageing by closed cell foams by exchange of gases

Example

The values for isobutane in LDPE [1] have been selected for this example:

$D_{isobutane} = 1.5 \times 10^{-12}$ [m^2/s];

$c_i =$ 1.9×10^{-3} [mol/N.m] =

1.9×10^{-6} x 1.013×10^{5} [mol/m^3.atm] =

1.9×10^{-6} x 1.013×10^{5} x 58 [g/m^3.atm] =

1.9×10^{-6} x 1.013×10^{5} x 24 [(at 1 atm and 20 °C)/m^3.atm]

$P_i =$ 7.1×10^{-15} [mol.m/s.N] =

7.1×10^{-15} x 1.013×10^{5} x 24 [l(at 1 atm and 20 °C)/m.s.atm] =

7.1×10^{-15} x 1.013×10^{5} x 24 x 1000 x 86400 [cm^3 (at wall thickness of 1 m, 1 atm and 20 °C)/m^2.day.atm] =

7.1×10^{-15} x 1.013×10^{5} x 24 x 1000 x 86400 x 1000 [cm^3 (at wall thickness of 1 mm, 1 atm and 20 °C)/m^2.day.atm] =

1.5×10^{3} [cm^3 (at wall thickness of 1 mm, 1 atm and 20 °C)/m^2.day.atm].

Unfortunately the measurement of the concentration by absorption of a gas is not accurate.

The equation for the permeation coefficient reads:

$$P_i = D_i c_i$$

However the product of the diffusion coefficient and the gas concentration in the polymer is 2.9×10^{-15} [mol/N.m], whereas the value of the permeation coefficient is presented as 7.1×10^{-15} [mol/N.m].

Explanation of the constants applied in the example above:

1.013×10^{5} N/m^2 = 1 atm;

58 g represents 1 mol isobutane

1 mol gas has to be enclosed in a volume of 24 l at 20 ºC to obtain a pressure of 1 atm.

Table A.1: Permeation values for isobutane, oxygen and nitrogen through 1 mm thick LDPE and HDPE layer [1,2,3]

Component	P_i (20 °C) [cm^3/m^2.day.atm]	P_i (60 °C) [cm^3/m^2.
Iso-butane	100-1500	1000-20000
Oxygen	26-190	230-1700
Nitrogen	10-64	90-580

Table A.2: Estimated values for permeation of carbon dioxide, cyclopentane, oxygen and nitrogen through 1 mm thick polyurethane layer [4,5]

Component	P_i (20 °C) [cm^3/m^2.day.atm]	P_i (60 °C) [cm^3/m^2.
Carbon dioxide	500	
Oxygen	9-okt	
Nitrogen	3-okt	
Cyclo-pentane	< 10 (<1x10^{-5} g/m^2.day)	<100 (<1x10^{-4} g/m^2.

TableA.3: Values for heat conductivity of gases and estimated values for the polymer contribution in the foam [6]

Component	Heat conductivity [W/m.K]
Air	0.026
Oxygen	0.027
Nitrogen	0.026
Iso-butane	0.016
Carbon dioxide	0.017
Cyclo-pentaan	0.012
PE foam contribution	0.012*

*) Estimated values.

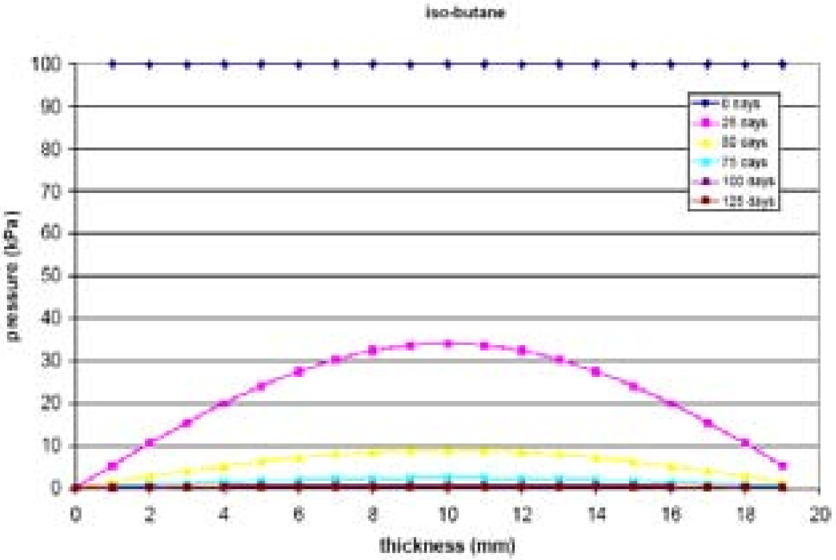


Figure A.4: Calculated isobutane pressure in 19 mm thick PE foam layer at 20ºC as a function of the position in thickness direction; free exchange with atmosphere

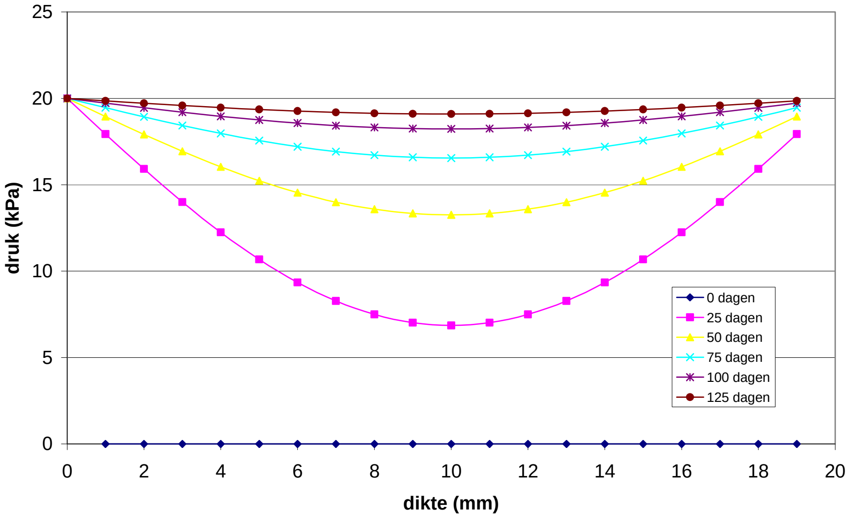


Figure A.5: Calculated oxygen pressure in 19 mm thick PE foam layer at 20ºC as a function of the position in thickness direction; free exchange with atmosphere

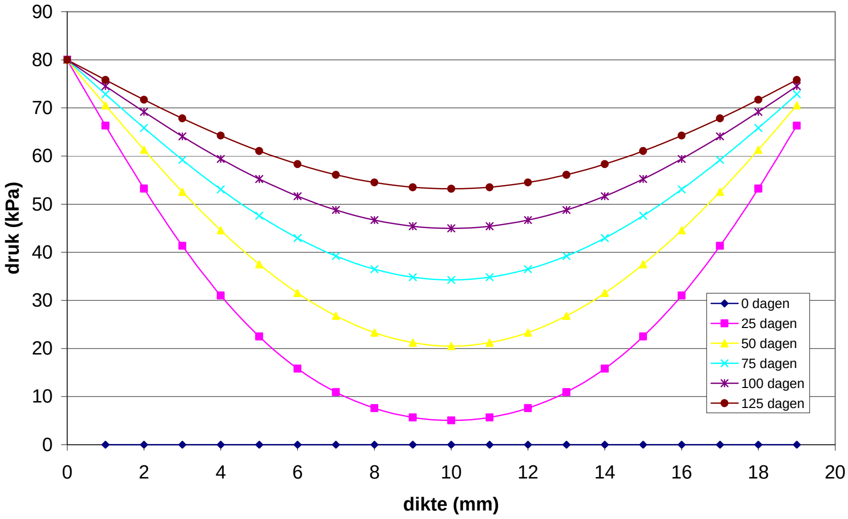


Figure A.6: Calculated nitrogrn pressure in 19 mm thick PE foam layer at 20ºC as a function of the position in thickness direction; free exchange with atmosphere

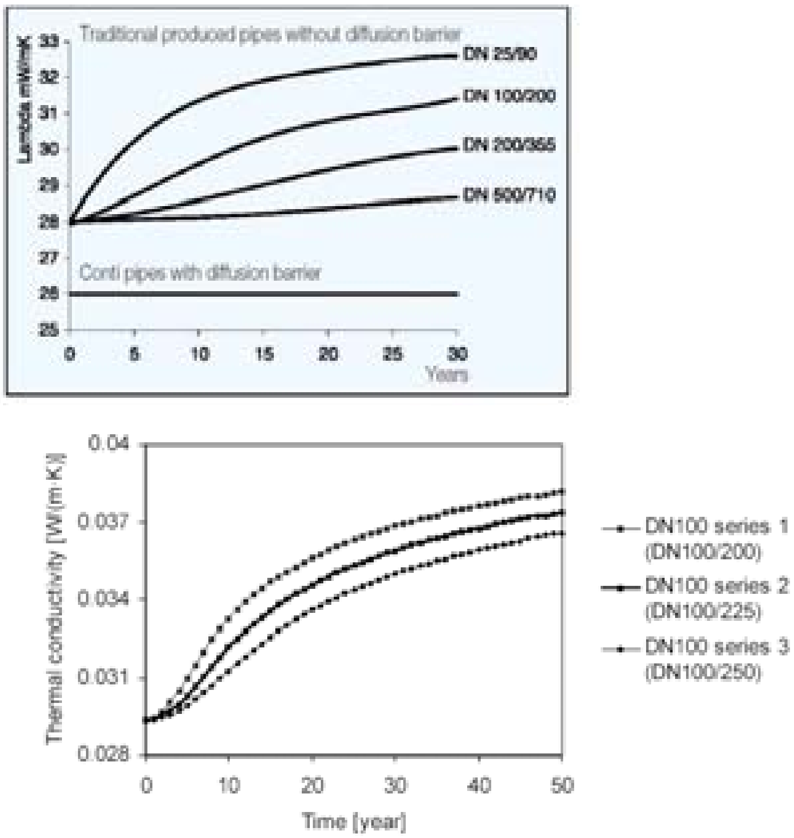


Figure A.9: Heat conductivity versus time for different pipe diameters; copied from Løgstør brochure (upper figure) and Holmgren's thesis (lower figure) [16,17]

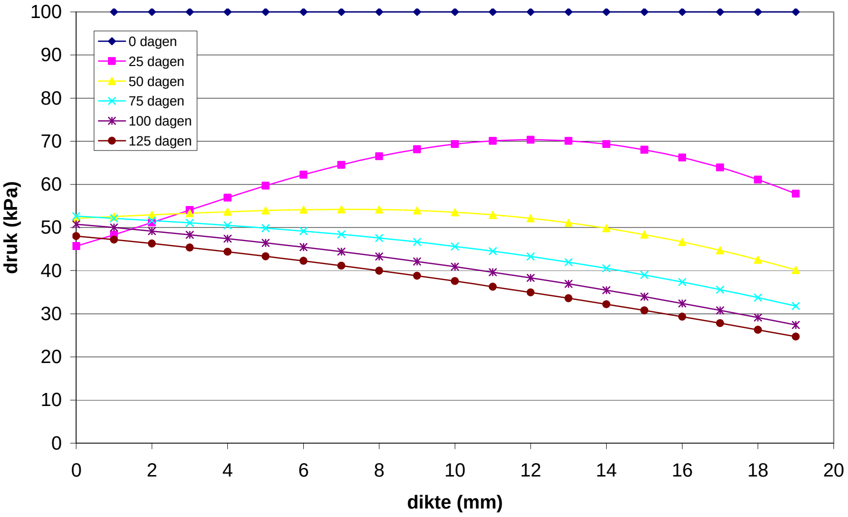
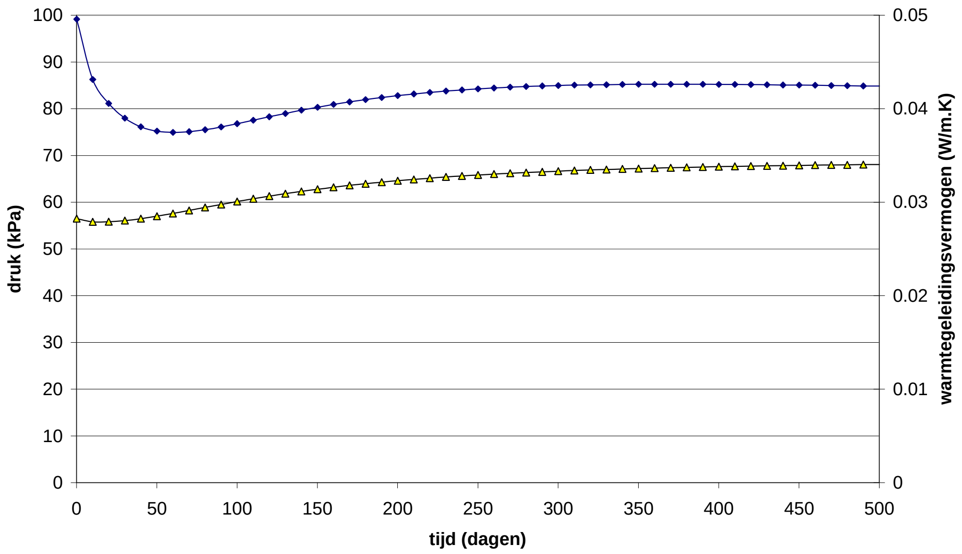


Figure A.10: Calculated isobutane pressure in 19 mm thick PE foam layer at 20ºC in the corrugated PE jacket as a function of the position in thickness direction



FigureA.11: Calculated total pressure change and heat conductivity (lower curve) in the foam cells versus time for 19 mm PE foam at 20ºC ; free exchange with atmosphere. An average was calculated over the thickness of the foam.

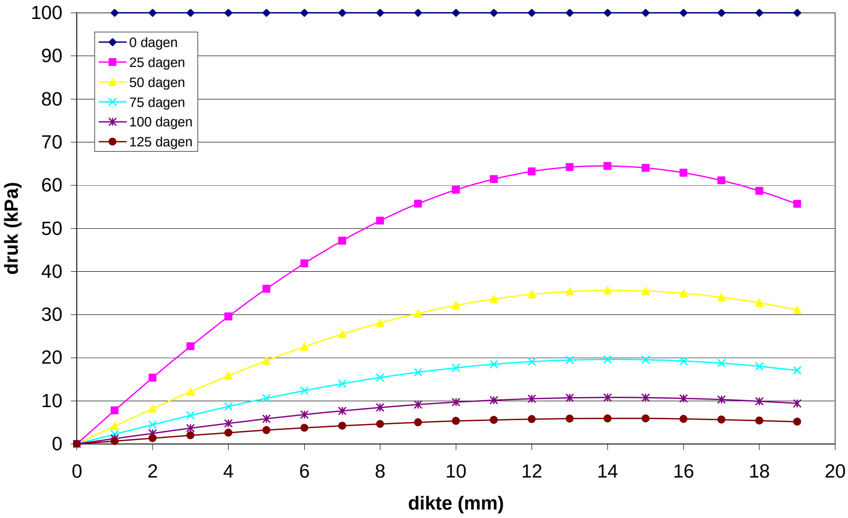
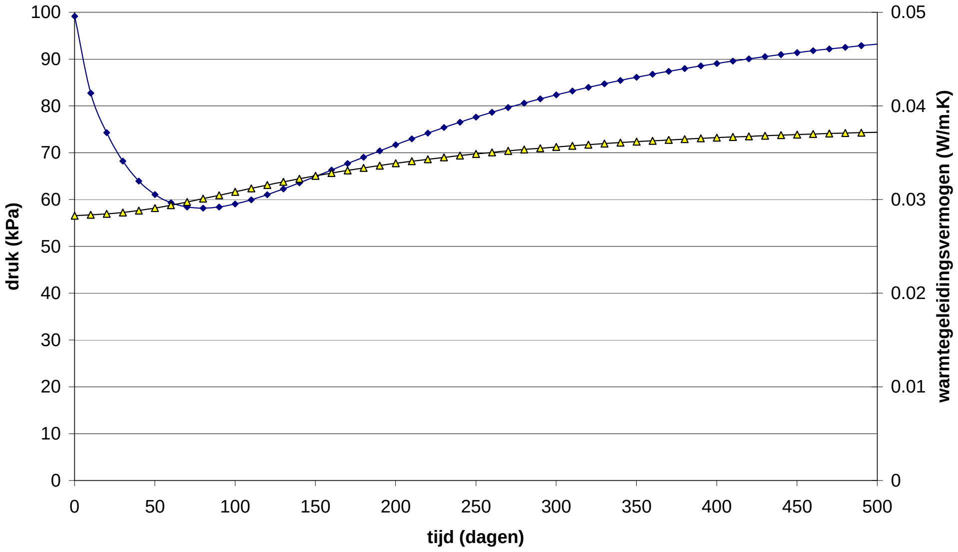


Figure A.12: Calculated isobutane pressure in 19 mm thick PE foam layer at 20ºC at the end parts of the corrugated PE jacket as a function of the position in thickness direction.



FigureA.13: Calculated total pressure change and heat conductivity (lower curve) in the foam cells versus time for 19 mm PE foam at 20ºC ; free exchange with atmosphere. An average was calculated over the thickness of the foam

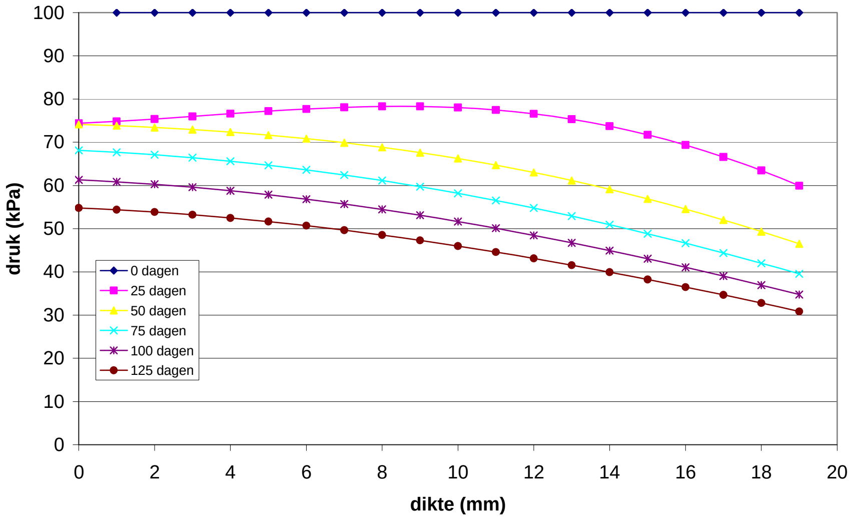


Figure A.14: Calculated iso-butane pressure in 19 mm thick PE foam layer at 20ºC in an infinitely long corrugated PE jacket as a function of the position in thickness direction.

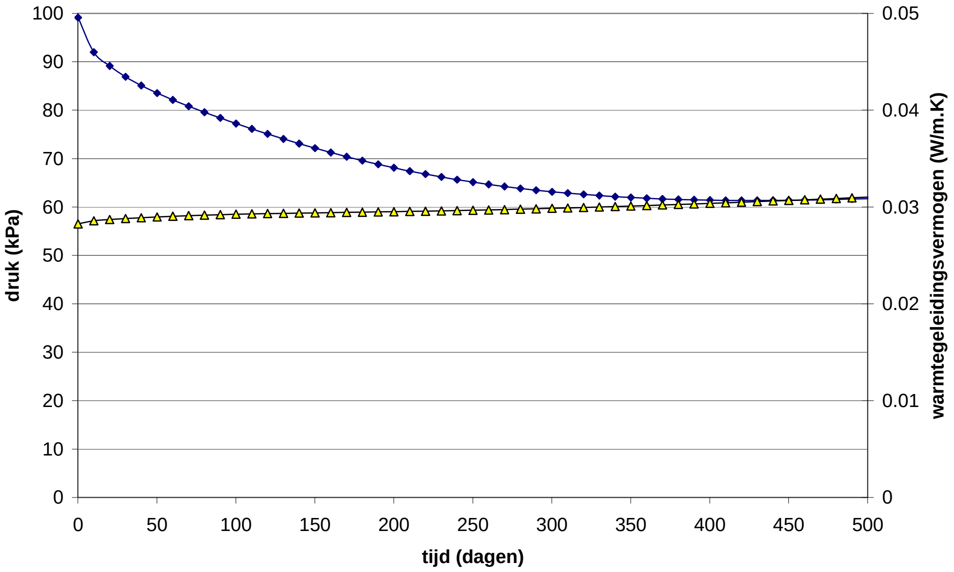


Figure A.15: Calculated total pressure change and heat conductivity (lower curve) in the foam cells versus time for 19 mm PE foam at 20ºC ; free exchange with atmosphere. An average was calculated over the thickness of the foam

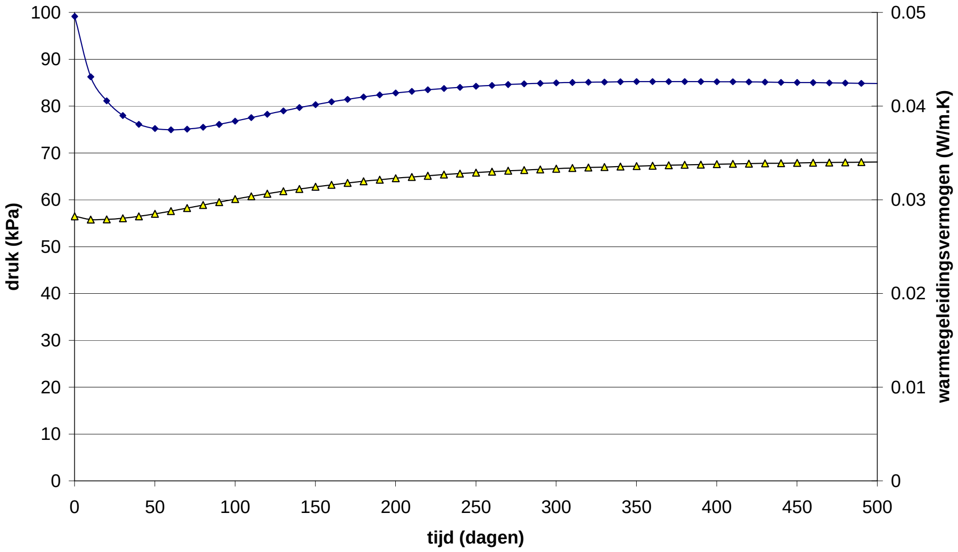


Figure A.16: Calculated total pressure change and heat conductivity (lower curve) in the foam cells versus time for 19 mm PE foam at 20ºC ; free exchange with atmosphere. An average was calculated over the thickness of the foam.

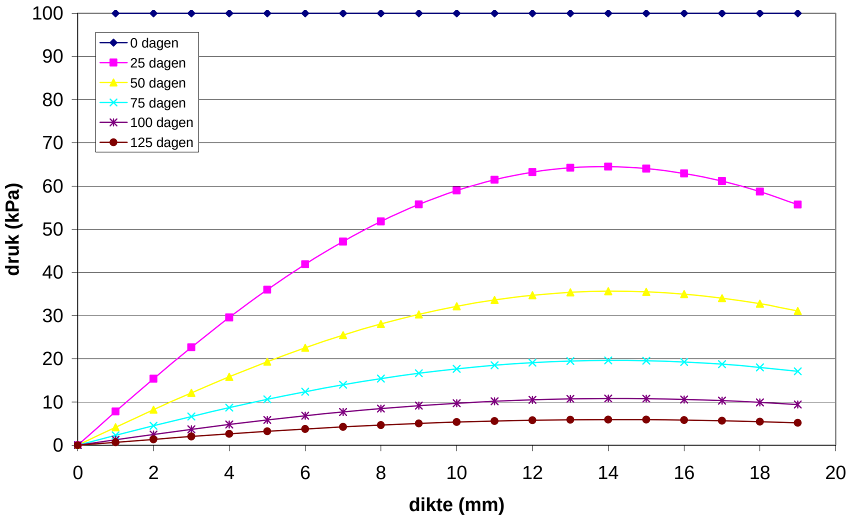


Figure A.17: Calculated iso-butane pressure in 19 mm thick PE foam layer at 20ºC at the end parts of the corrugated PE jacket as a function of the position in thickness direction.

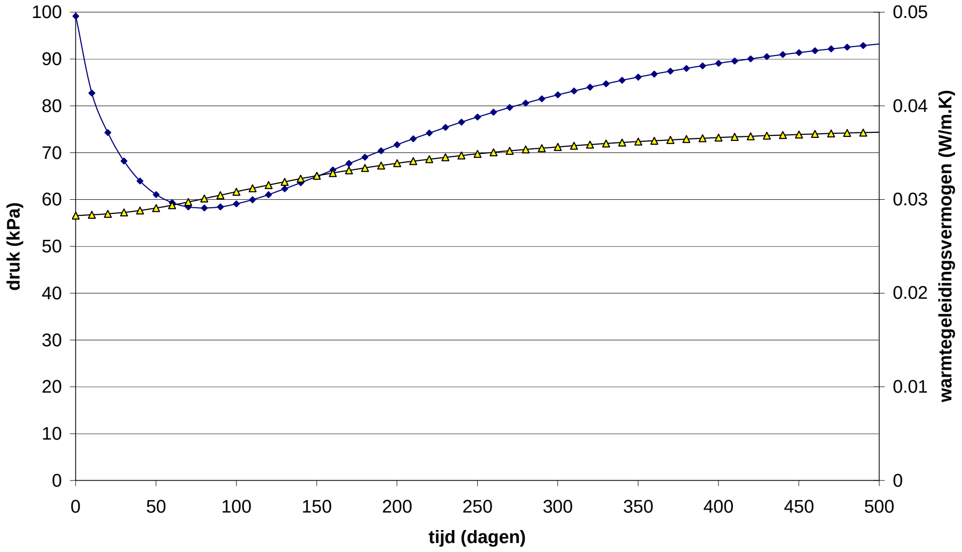


Figure A.18: Calculated total pressure change and heat conductivity (lower curve) in the foam cells versus time for 19 mm PE foam at 20ºC ; free exchange with atmosphere. An average was calculated over the thickness of the foam