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QUANTITATIVE HEAT LOSS ANALYSIS OF HEAT AND COOLANT DISTRIBUTION PIPES BY MEANS OF THERMOGRAPHY

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QUANTITATIVE HEAT LOSS ANALYSIS OF HEAT AND COOLANT DISTRIBUTION PIPES BY MEANS OF THERMOGRAPHY

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QUANTITATIVE HEAT LOSS ANALYSIS OF HEAT AND COOLANT DISTRIBUTION PIPES BY MEANS OF THERMOGRAPHY

SUMMARY

This project is based on an extension of earlier work at Studsvik within the field of thermography of district heating systems.

An interpretation model aimed at using thermography for determining the quantitative heat loss for district heating pipes is further developed and refined. The model is extended to include steam distribution systems.

Furthermore we have examined the possibility of extending the use of the model to include weather conditions other than those which are now necessary for a reliable result. An extensive sensitivity study regarding the influence of different climatic factors on the temperature profile has been performed. Under favorable circumstances, it is possible to use thermography even for periods with sunny days and clear nights.

The study of the influence of wet surfaces on the temperature profile has indicated that a uniformly very wet surface can be used for interpretation. However, a problem with the interpretation of wet surfaces is the latent heat transport during the drying process.

The possibility of extending the interpretation model for coolant distribution systems has been studied. Due to the relatively low temperature differences between the coolant pipes and the ground, it is not possible to quantify the heat gain in these systems.

Approved by:

PREFACE

The International Energy Agency (IEA) was established in 1974 within the framework of the OECD to implement an International Energy Program. A basic aim of the IEA is to strengthen the cooperation between the member countries in the energy field.

One element of this cooperative activities is to undertake energy research, development and demonstration (RD & D).

District Heating is seen by the IEA as a mean by which countries may reduce their dependence on oil and improve their energy efficiency. It involves increased use of indigenous or abundant fuels, the utilization of waste energy and combined heat- and power production.

IEAs "Program of Research", "Development and Demonstration on District Heating" was established at the end of 1983. Under Annex I ten countries did participate in the program: Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Italy, The Netherlands, Norway, Sweden and USA.

The National Energy Administration, Sweden was the Operating Agent for the program under Annex I, in which the following technical areas were assessed:

* Development of heat meters
* Cost efficient distribution and connection systems for areas of low heating density
* Small size coal-fired hot water boiler
* Medium size combined heat and power plants
* Low temperature applications in district heating systems

The results of these topics have been presented in printed reports published by the National Energy Administration, Sweden.

In 1987 is was decided by nine of the original ten participanting countries (ex Belgium) to continue the implementation of cooperative projects under an Annex II.

The Netherlands Agency for Energy and the Environment (NOVEM), was Operating Agent for Annex II, in which the following technical areas were assessed:

* Heat meters
* Consumer installations
* Piping
* Advanced fluids
* Advanced heat production technology
* Information exchange

The results of these topics have been presented in reports published by NOVEM.

In 1990 the cooperating countries decided to continue the planning and implementation of new cooperative projects under a new Annex III. During this annex United Kingdom joined the project.

NOVEM has been Operating Agent also for Annex III, in which the following technical areas have been assessed:

* District Heating and the Environment
* Supervision of District Heating Networks
* Advanced Fluids
* Piping
* District Energy Promotion Manual
* Consumer Heating System Simulation

This report belongs to the technical area Supervision of District Heating Networks.

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1. FOREWORD

This report is the final report of the IEA District Heating Project, Annex III: "Supervision of District Heating Networks".

The method investigated for **quantifying heat losses** from district heating pipes is based on the use of the temperature profile at the ground surface above the pipes to determine the heat loss.

In this project we have studied in detail the influence of different weather conditions (wind, rain, etc) on the temperature profile. We have also examined the possibility of extending the model for coolant and steam distribution systems and demonstrated the applicability of the model in a field test.

An expert group has supported the work and contributed important suggestions and advice during their meetings. Members of the expert panel have also contributed with important comments to the final report. Especially, we would like to thank Gary Phetteplace for an important linguistic review.

The expert group consists of the following members:

Benny Bøhm, Denmark
Jens Arne Melballe, Denmark
Egil Evensen, Norway
Bengt Jönsson, Sweden (Project Leader)
Lasse Koskelainen, Finland
Bertil Nilsson, Sweden
Gary Phetteplace, USA
Heimo Zinko, Sweden

2 BACKGROUND

In those countries which have a long tradition of district heating, a new concern has arisen recently: certain district heating networks are approaching the end of their technical lifetimes and the heat loss in older culvert networks is increasing significantly. In order to chart the requirements and resources for maintenance measures, it is important to be able to diagnose the conditions of the piping network.

One method increasingly used for heat loss detection is based on airborne and groundborne thermography. In this method the mapping of the ground temperature can be used to give qualitative information about the network conditions, mainly with the aim of finding leaks, ref. [1], [2], [3]. With the help of more refined analytical methods it is possible in the long run not only to trace leaking media pipes, but also to determine the condition of the insulation. In that way it will be possible to draw conclusions about any damage to the protective casing of the culvert by determining the amount of heat loss quantitatively, ref. [4], [5].

For the last couple of years Studsvik has been working on the development of a method for quantifying heat losses from district heating pipes by means of thermography, reference [4],[5]. Figure 2.1 shows an overview of different parts of the earlier and present projects which have led to the heat loss interpretation model.

The aim of this project was to verify a model for quantitative determination of heat losses using the temperature profile on the ground surface above a pair of hot water district heating pipes. In practical applications, this profile can be generated by means of thermographic methods.

A second aim of the project was to extend the model to include pipes for steam distribution and district cooling.

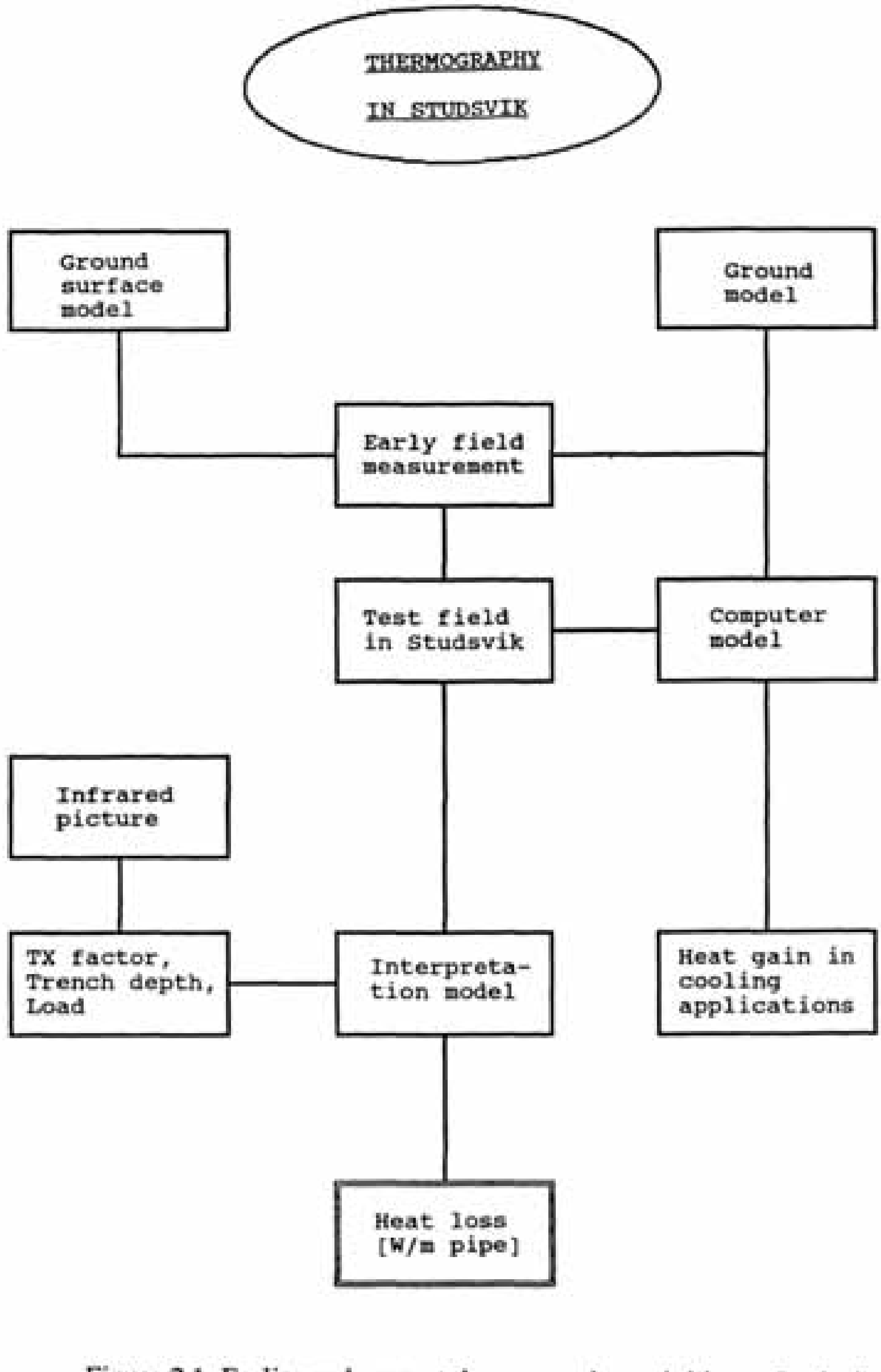


Figure 2.1. Earlier and present thermography activities at Studsvik.

The work to be carried out deals with the following problems:

- refining the model by systematic sensitivity studies including second order effects due to varying ground properties.
- modification of the model for steam pipes.
- development of model extension for coolant distribution pipes.
- experimental verification of the model on a test pipe with controlled heat supply, simulating hot water and steam pipes, respectively.
- application of the model to a thermographic evaluation system.

3 THE TX FACTOR PRINCIPLE

This method for quantifying the heat losses from district heating pipes is based on the temperature distribution at the ground surface above the pipes. A correlation between the temperature profile at the ground surface perpendicular to the pipes and the heat loss has been noticed in early experiments [4].

Figure 3.1 shows temperature profiles from Studsvik's test field (see chapter 5).

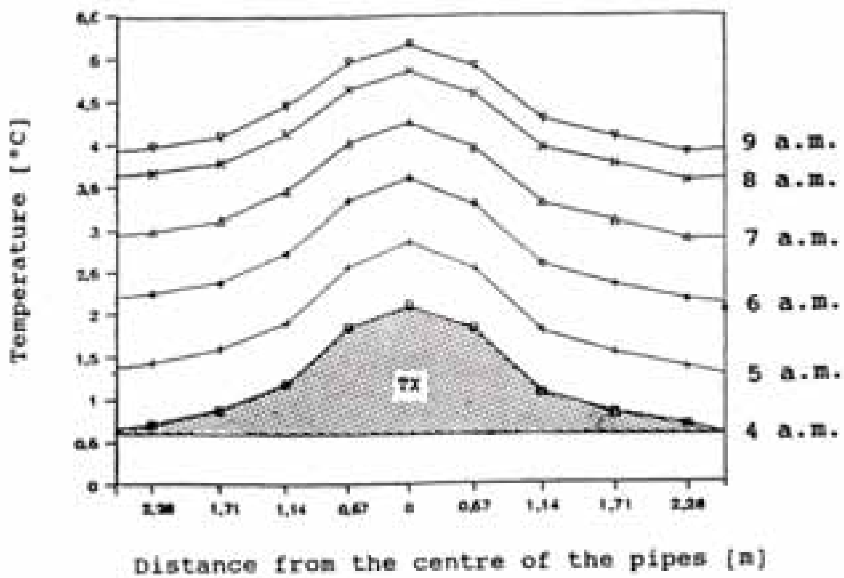


Figure 3.1. Temperature profiles at Studsvik's test field.

The area below the profile is the so called TX factor and is what we use to determine the heat loss. The TX factor can mathematically be expressed:

$$TX = \int_{-x_m}^{x_m} [T(x) - T(x)_{min}]\, dx \qquad [1]$$

Here:

x_m = Position at the ground surface across the pipes [m].

$T(x)$ = Local temperature [°C].

$T(x)_{min}$ = The lowest temperature at the ground surface within x_m metres from the centre of the pipes [°C].

By using the lowest temperature T_{min} in the profile as reference, the TX factor for all profiles in Figure 3.1 has about the same value (within ca. 10 %).

The measured TX factor is then used to calculate the heat loss by means of the interpretation model.

The interpretation model (explained in chapter 6) reads:

$$P_f = TX * [A + B*h_f + C*\lambda + D*(dT_m/dt) + E/x_m] + F*h_f + G*\lambda +$$
$$+ H*(dT_m/dt) + I/(x_m)^2 \qquad [2]$$

(For the definitions of the constants A, B.....I as well as the parameters see chapter 6).

The constants A – I are determined by a series of simulations with the simulation program where the variables included are systematically changed in order to fit the experimental results.

This method needs a very high precision in the temperature measurement. The resolution of the infrared camera is less than 1/10 of a °C for relative temperature measurements, and that is important for this method. This means that the precision in the measurements (and thus the TX factor calculation) depends on the difference between the highest and lowest value in the temperature profile. This difference can be as low as about 1°C, but with our method using relative temperatures the accuracy of the measurements can be kept high. This means also that the method is more reliable for higher heat losses.

4 THE SIMULATION PROGRAM

The simulation program, which for example is used to determine the values of the different factors in the interpretation model, will be explained in detail in this chapter. The program consists of two parts: **the ground model and the surface model**. The models are based on the finite difference method with different time intervals.

4.1 The ground model

The program works with a cross section of the ground according to Figure 4.1. The area included in the calculation must be large enough to get an undisturbed ground temperature field at the edges of the area. The thermal properties of the surface material (asphalt, grass, etc) must be specified in the input data.

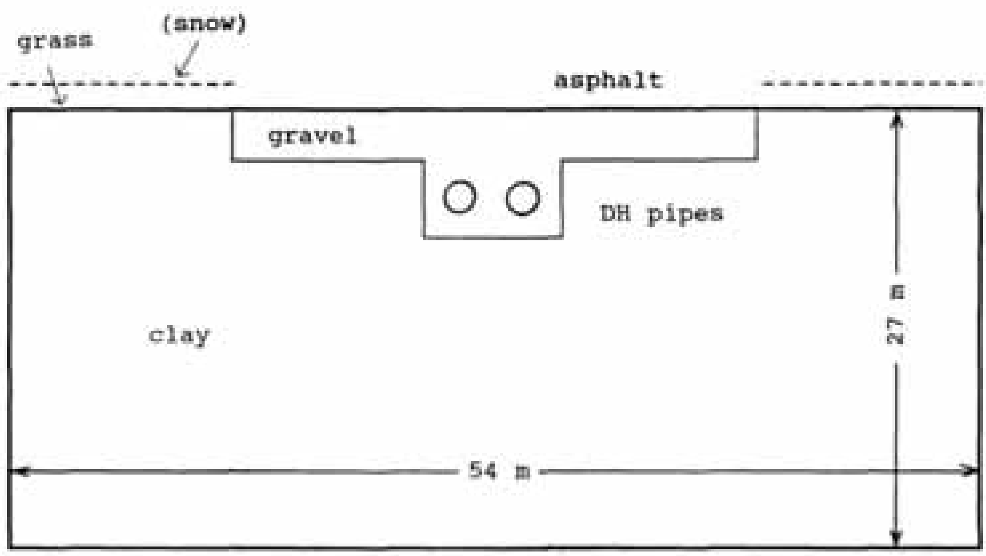


Figure 4.1. Model for the ground and the surface.

The calculation area is then divided into cells, see Figure 4.2. The heat flow between the cells is assumed to be two-dimensional, but for the calculations we assume a unit length of one meter in the direction of the pipes. Two of the cells represent the pipes.

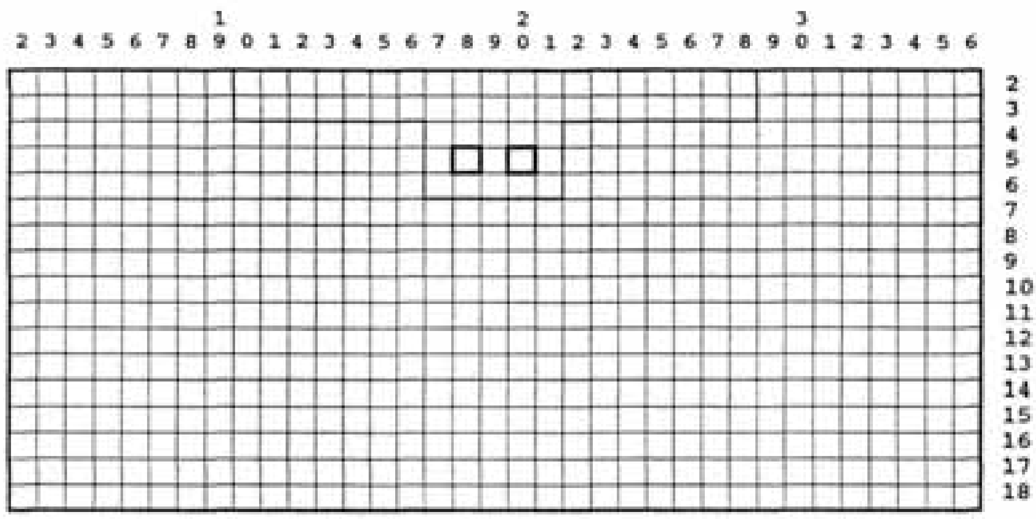


Figure 4.2. The thermal network of the ground with the two pipes.

Figure 4.3 shows two arbitrary cells from the pattern above. The properties which must be input to the program are:

λ: thermal conductivity [W/(m·K)]

C: volumetric heat capacity [J/(m^3·K)]

x: dimension of each cell [m]

T: initial temperature [°C]

R: thermal resistance at cell interface [$m^2 \cdot K/W$]

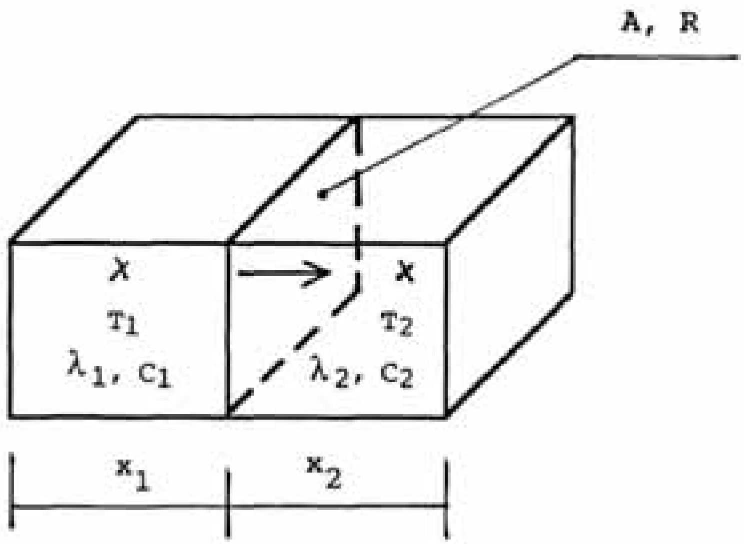


Figure 4.3. Two cells in the thermal network.

At the initial time $t=t_0$ the temperatures are T_1 and T_2 respectively. The heat flow q from cell 1 to cell 2 is then:

$$q = k \cdot A \cdot (T_1 - T_2) \qquad [3]$$

Where:

q: heat flow [W]

A: the area between the cells [m^2]

T_i: the temperature in cell i [°C]

The temperature in a cell represents the temperature in the centre of the cell. Therefore the heat transfer value k is calculated as

$$k = \frac{1}{\frac{x_1}{2\cdot\lambda} + \frac{x_2}{2\cdot\lambda} + R} \qquad [W/(m^2\cdot K)] \qquad [4]$$

Where:

x_i: dimension of cell [m]

λ: heat conductivity in cell i [W/(m*K)]

The heat flow is then determined as:

$$q = k \cdot A \cdot (T_1 - T_2) \qquad [W] \qquad [5]$$

The thermal conductance between two cells is:

$$L_{i,j} = \frac{q_{i,j}}{(T_i - T_j)} \qquad [W/K] \qquad [6]$$

The maximum time interval which the program uses is given by the heat flow dynamic between the cells with volumes V_i:

$$\Delta t_{max} = \min \frac{V_i \cdot C_i}{L_{i,j}} \qquad [7]$$

In most simulations, the time interval is determined by the layer of snow due to the low heat capacity in the snow.

Freezing

In order to consider all types of heat flows which can occur in the ground, a model for frost has also been developed following the "apparent heat capacity method" (see ref. 8).

Heat conductivity and volumetric heat capacity for each single cell in the area will be assigned given values.

Because the calculation area is considered as homogeneous, the parameters mentioned are dependent on the temperature alone. Likewise, both the stored heat in each single cell and the thermal conductivity are only dependent on the temperature. As a definition, the stored heat E_0 is zero at 0°C.

The freezing process is assumed to occur within the temperature interval: TFREEZ < T < 0, where the TFREEZ is also defined in the input data.

The computer program uses 3 different conditions: completely frozen, freezing and unfrozen.

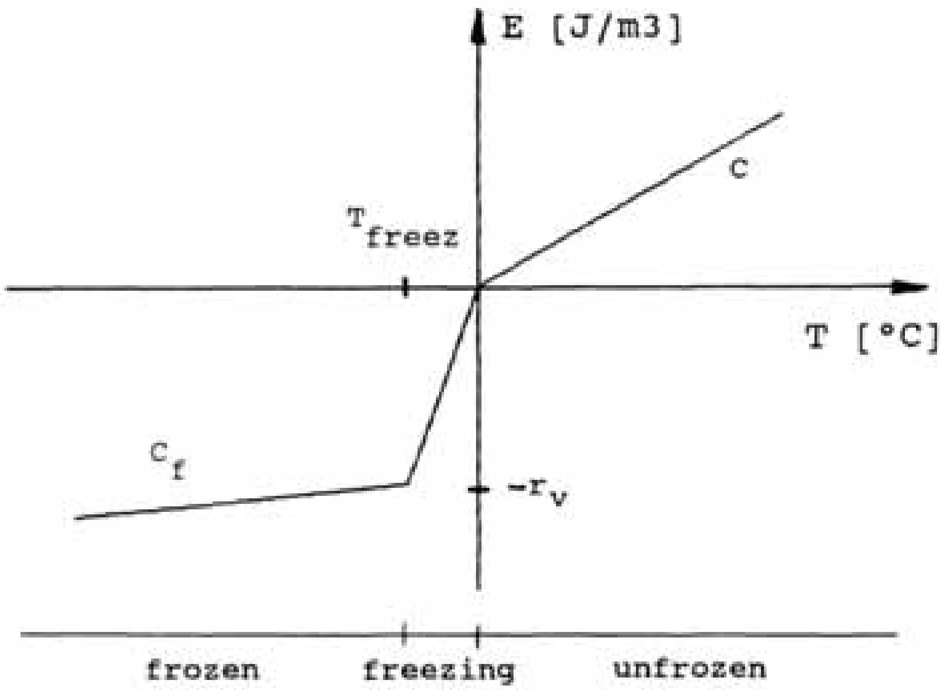


Figure 4.4. The freezing model for the ground.

To reach the completely frozen state from the unfrozen, the melting heat r_v (J/m^3) must be removed from each cell. The single cell has then decreased its stored heat to $-r_v$ when the temperature has reached the freezing point, TFREEZ, see Figure 4.4.

The slope at the different parts of the function represents the heat capacity for the respective conditions.

4.2 The surface model

The most important model for this application is the surface model. The heat flows at the ground surface which can occure due to the weather conditions can greatly affect the temperature profile. Therefore it is very important to take all heat flows into account in the model:

- Convection (natural and forced due to wind)
- Latent heat transport (evaporation, condensation, frost)
- Solar radiation (solar absorbance)
- Long wave radiation (calculated with regard to shielding from the horizon, cloudiness, surface material, moisture, frost and snow).
- A model for snow and water which takes into account the continuously varying layer at the ground surface.

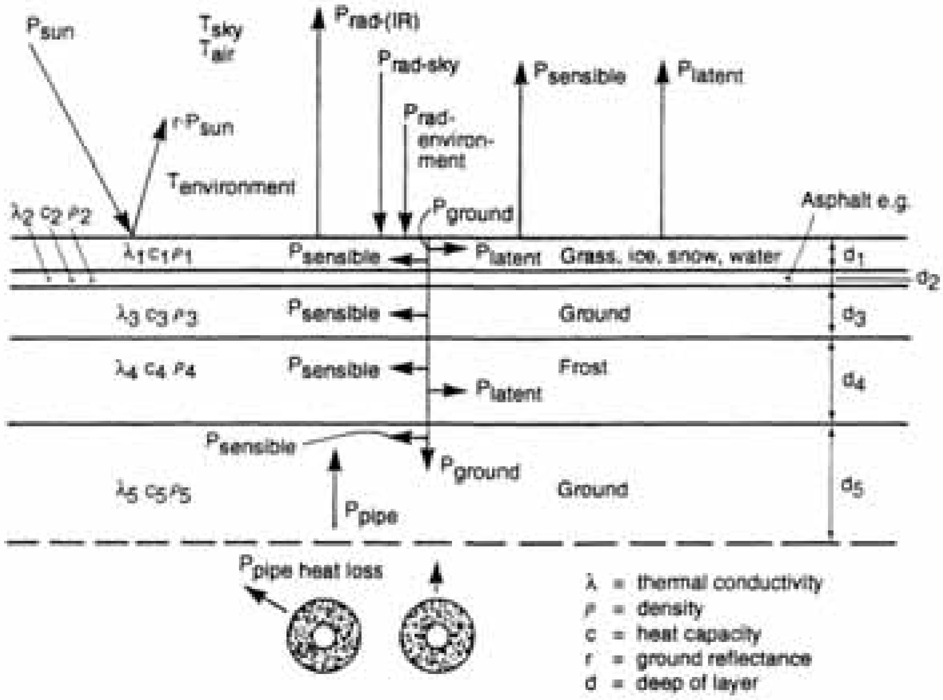


Figure 4.5. Energy balance model including heat flows between the surface and the ground.

The simulation program also needs climate conditions as they prevail on the ground surface:

- Wind speed [m/s]
- Ambient temperature [°C]
- Air humidity [%]
- Rain and snow [mm] (latent heat transport)

- Long wave radiation [W/m²]

- Global solar radiation [W/m²]
  sunrise, sunset time)

All these climatic data and the temperatures in the pipes are input as monthly mean values. The program then calculates instant mean values using idealized shape-formulae according to meteorological experience for the respective parameters. (In Studsvik we have a long series of climatic data from our experimental test field for solar collectors which has given us experience how to use climatic data for statistical evaluation).

According to this idealization, the wind speed varies in a sinusoidal form with the maximum value at 3 p.m. and minimum value at 3 a.m. The ambient temperature varies in the same way as the wind speed, but with one oscillation with the period one month and another oscillation period of 24 hours.

From the wind speed, the ambient temperature and the surface temperature, the convective heat loss can be determined.

As regards to the influence of rain, the input is the number of days with rain during the month and an assumption of the amount of water remaining after a shower of rain.

The latent heat transport due to the evaporation of the water is then calculated using the thermodynamic laws of evaporation and mass transfer.

In the winter, the surface temperature is greatly influenced by the occurrence of snow. The snow affects the surface both as an insulation layer and by its ability to store latent heat. The model works with two cases, with a constant layer and a melting layer of snow respectively. The number of snowfall periods during the winter and the amount of the fallen snow are stated in the input data.

The long wave radiation is determined by means of the Stefan-Bolzmann law. The sky temperature for a clear sky can be calculated by means of the air pressure and the temperature. The temperature of the cloudy sky is assumed to be 1°C less than the ambient temperature as it was derived from the evaluation of climatic measurements. The background and surface emissivity are defined in the input file.

The heat transfer due to solar radiation is determined by a simple model including the global solar radiation and the solar absorbance at the surface. The models for solar and long wave radiation also includes compensation for shading effects.

The initial conditions for the simulation are the climate and the temperatures in the pipes.

5 EXPERIMENTAL TEST FIELD IN STUDSVIK

At the beginning of the thermography project at Studsvik, we found it desirable to validate the method at a test field having a well known heat loss.

Using measurements with a constant heat loss, it is also possible to determine the influence of the weather conditions on the temperature profile.

At the test field at Studsvik, we have installed a double pipe which is electrically heated. The temperatures are measured continuously by temperature sensors and not by infrared equipment. In this way we have obtained a unique longterm base of measurements for different heat losses and weather conditions.

When constructing the test field at Studsvik, our aim has been to achieve conditions similiar to those in real district heating systems as regards material, dimensions etc.

The test field and all computer simulations, unless stated otherwise, are performed according to the so called reference case. This means a DN 100 double pipe covered by class 1 insulation (50 mm polyurethane). The trench depth is 0.5 meter.

The area of the test field is 9 m x 12 m and the surface is covered by asphalt. The test field is shown in Figure 5.1.

Temperature sensors have been placed in a line across the pipes according to Figure 5.2. Three heat flow meters have been placed at the surface. The temperature is also measured 0.2 and 1 m respectively below the surface at the centre of the pipes.

The space nearest the pipes is backfilled with gravel. The upper ground level consists of a layer of base gravel and above that a layer of asphalt with a thickness of 10 cm is applied.

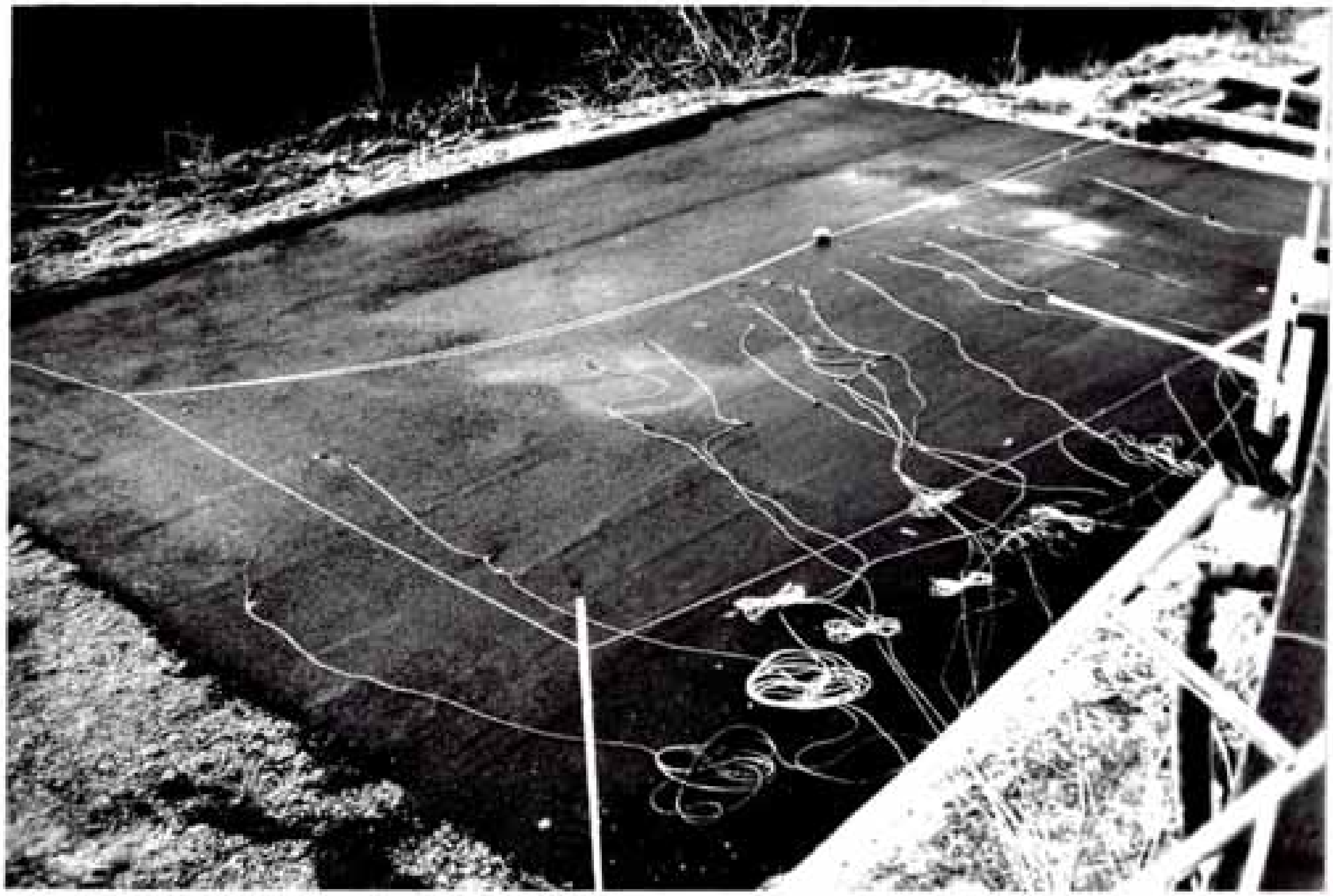


Figure 5.1. Studsvik's test field.

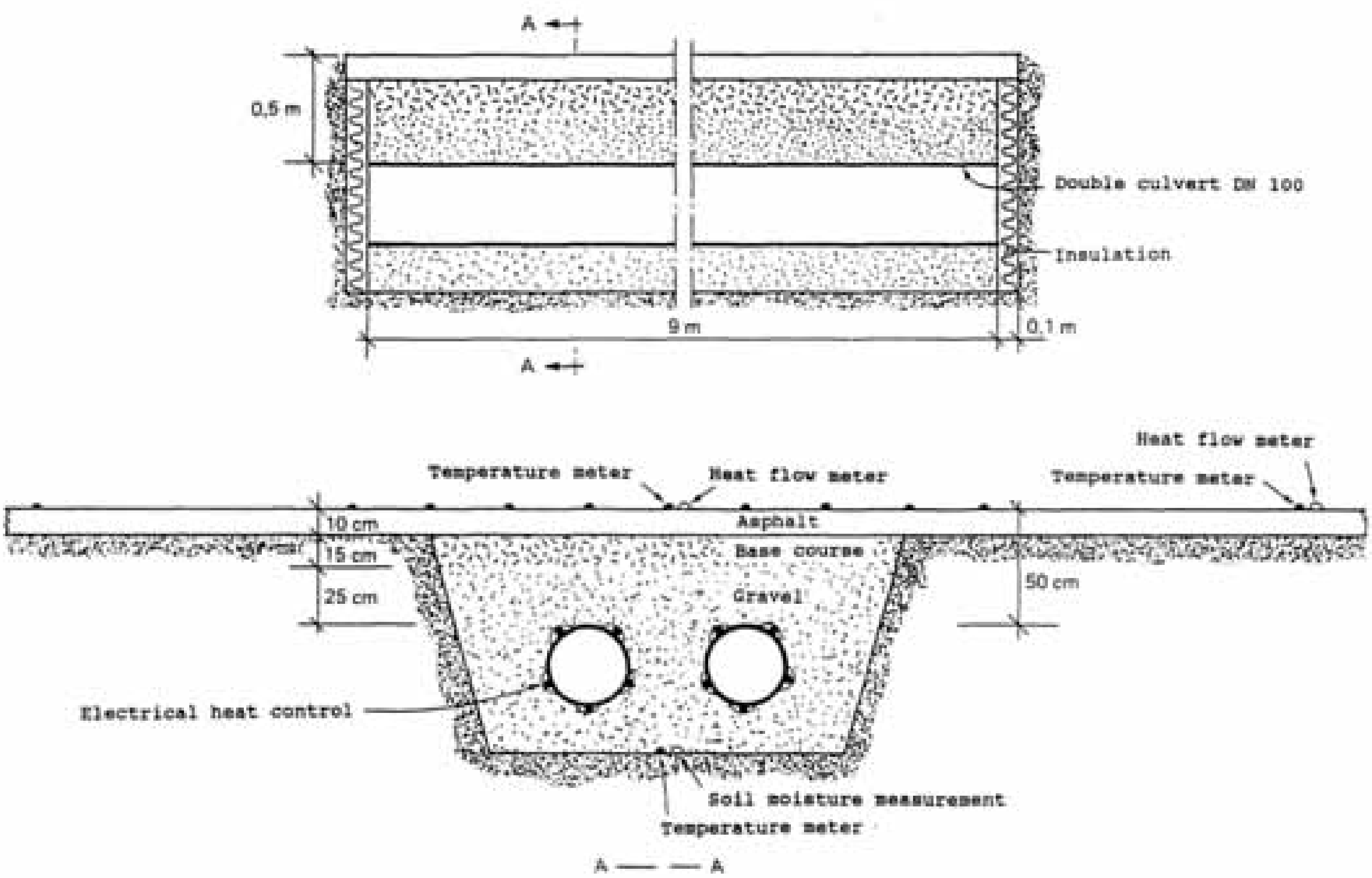


Figure 5.2. Cross section of the test field perpendicular to the pipes.

To be able to control the heat loss with a high accuracy, heating cables are mounted outside the pipes as shown in Figure 5.2 and 5.3. The outer pipe diameter is 200 mm which corresponds to the outer diameter of a DN 100 pipe with class 1 insulation. The thermal shield outside the cable guarantees that the heat supply from the pipe to the ground is uniform and simulates the heat loss from a real district heating pipe. The pipes are also filled with mineral wool to prevent convection in the air inside the pipes.

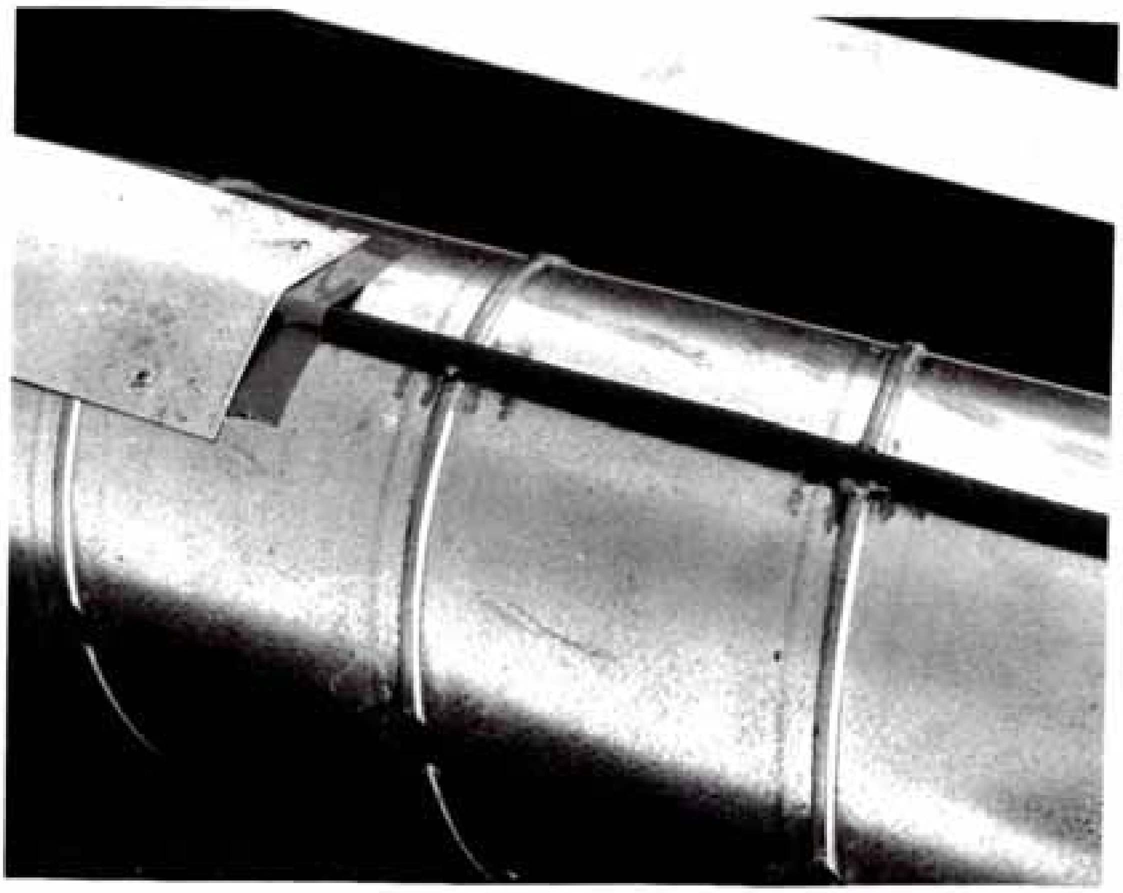


Figure 5.3. One of the pipes in detail with one of the heating cables and the thermal shield outside the cable.

At both ends of the pipes, two insulating layers are placed according to Figure 5.4. The reason is to prevent heat leakages along the pipes.

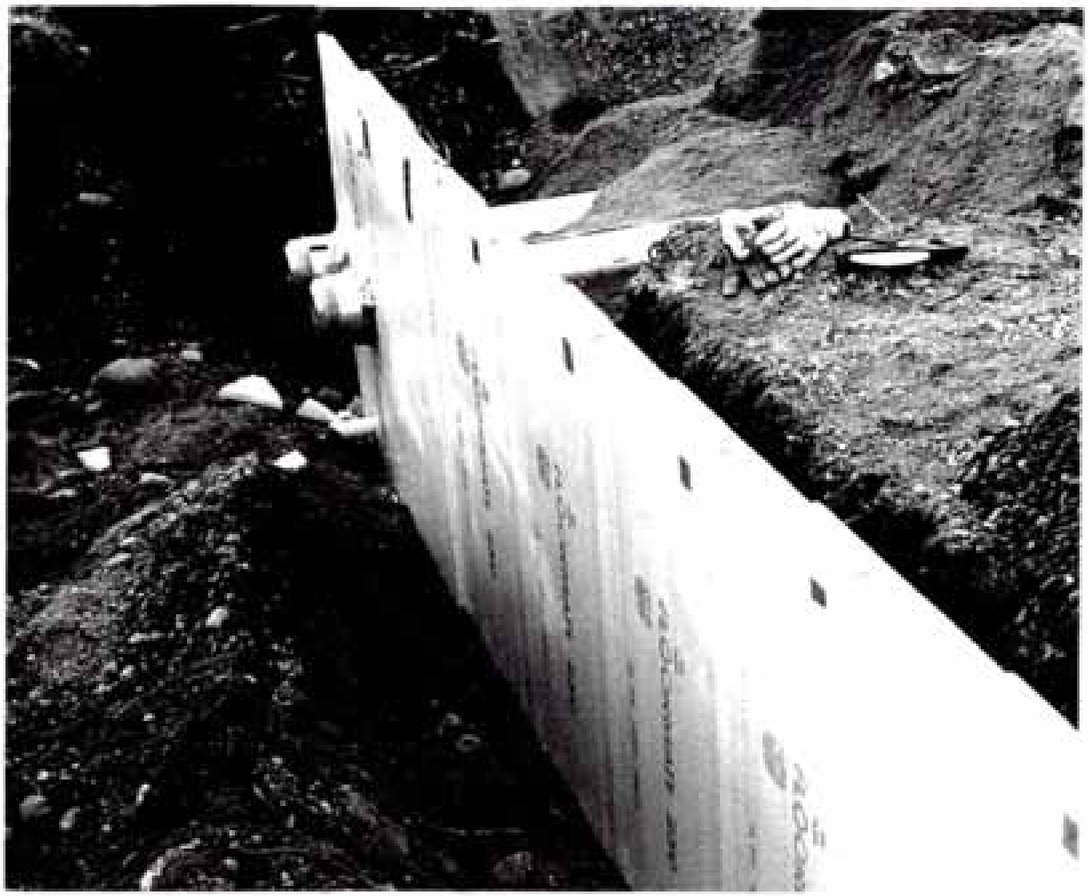


Figure 5.4. Insulation at one of the edges of the test field.

5.1 Measurements

The measurement equipment used consists of an HP-86 measurement computer and an HP-3497 evaluation computer. The parameters are measured every two minutes and stored as hourly mean values.

Besides the usual climate parameters (wind, ambient temperature etc), the heat flow at the surface and the temperatures at the surface and in the ground are also measured. All temperatures are measured using Pt-100 sensors.

Long wave radiation is measured by means of a pyrgeometer and the global solar radiation is measured using a pyranometer.

The parameters measured are:

- Ambient temperature
- Ground temperature below the pipes (1 meter below the surface)
- Ground temperature above the pipes (0.2 meter below the surface)
- Ground surface temperature profile (across the pipes)
- Temperature outside the pipes
- Relative humidity at the surface
- Long wave radiation emitted from the surface

  Absorbed solar radiation

- Reflected solar radiation
- Wind speed
- Heat flow at the surface (at the centre of the pipes and 5 meters from the centre)

Precipitation and supplied electrical power are also measured continuously.

The TX factor is calculated using the the surface temperature profile.

Measurements have also been performed using infrared video equipment. The results are presented in chapter 7.

6 THE INTERPRETATION MODEL

The interpretation model is a model which converts the temperature profile from a thermographic picture to an instantaneous heat loss from the district heating pipes. Our aim has been to determine the heat loss with an accuracy of better than ± 10 %.

As explained in Chapter 4, the ground model can be used as an interpretation model and gives very precise results for all types of pipes and for many different climate situations during the year, but it also requires a large amount of input information.

Our effort has instead been aimed at finding a correlation model between the temperature profile and the heat loss based on the ground model. This model only requires the temperature profile and some data from the district heating network such as the type of pipe, depth of trench, type of soil and temperature in the network during the last weeks before the investigation.

The main idea for the temperature profile is to use the ground temperature at a certain distance from the centre of the pipes as reference. In this way, most of the influence of the weather conditions can be ignored.

By means of simulations with the computer program where we systematically changed the variables which influence the heat loss and the temperature distribution at the ground surface, we have obtained an empirical model for quantifying the heat loss based on some simple field parameters. A justification for this approach is discribed in Appendix 1.1.

These parameters are:

h_f	= the depth of the pipe trench	[m]
λ	= the thermal conductivity in the ground	[W/(m·K)]
dT_m/dt	= change of mean distribution temperature during the last weeks	[K/24 hours]

x_m = the distance in each direction from the centre of the pipes to the end of the temperature profile [m]

The TX factor is defined in Chapter 3.

The advantage with these parameters are that all of them are quite easy to obtain for an investigated pipe section.

The results from the simulations can be interpreted by means of a linear regression analysis. This analysis gives the following formula for the heat loss P_f:

$$P_f = TX * [-13.6 + 19.6*h_f + 4.3\cdot\lambda + 12.8\cdot(dT_m/dt) + 40.1/x_m] +$$

$$+ 9.1\cdot h_f - 6.3\cdot\lambda + 18.8\cdot(dT_m/dt) + 24{,}7/(x_m)^2 \qquad [8]$$

By means of the simulations on which the linear regression is based, the parameters have been varied within the following limits, which also is the limit of validity for the approximation:

h_f : 0.5 – 1.0 m

λ : 0.5 – 2.0 W/(m·K)

x_m : 1.5 – 2.5 m

dT_m/dt : ± 0.16 °C/(24 hours) (= 5°C maximal change in one month)

The trench depth has the most influence on the TX–factor, but it does not have much effect on the heat loss. The influence of the heat conductivity in the ground is relatively small. The reason is that the thermal resistance is much higher in the insulation than in the ground.

Figure 6.1 shows the heat loss calculated by means of the interpretation model for different values of the soil thermal conductivity and the depth of trench. The TX factor has been kept constant at 2.5 K·m. By keeping the TX factor constant, the influence of the different parameters on the calculated heat loss can be determined.

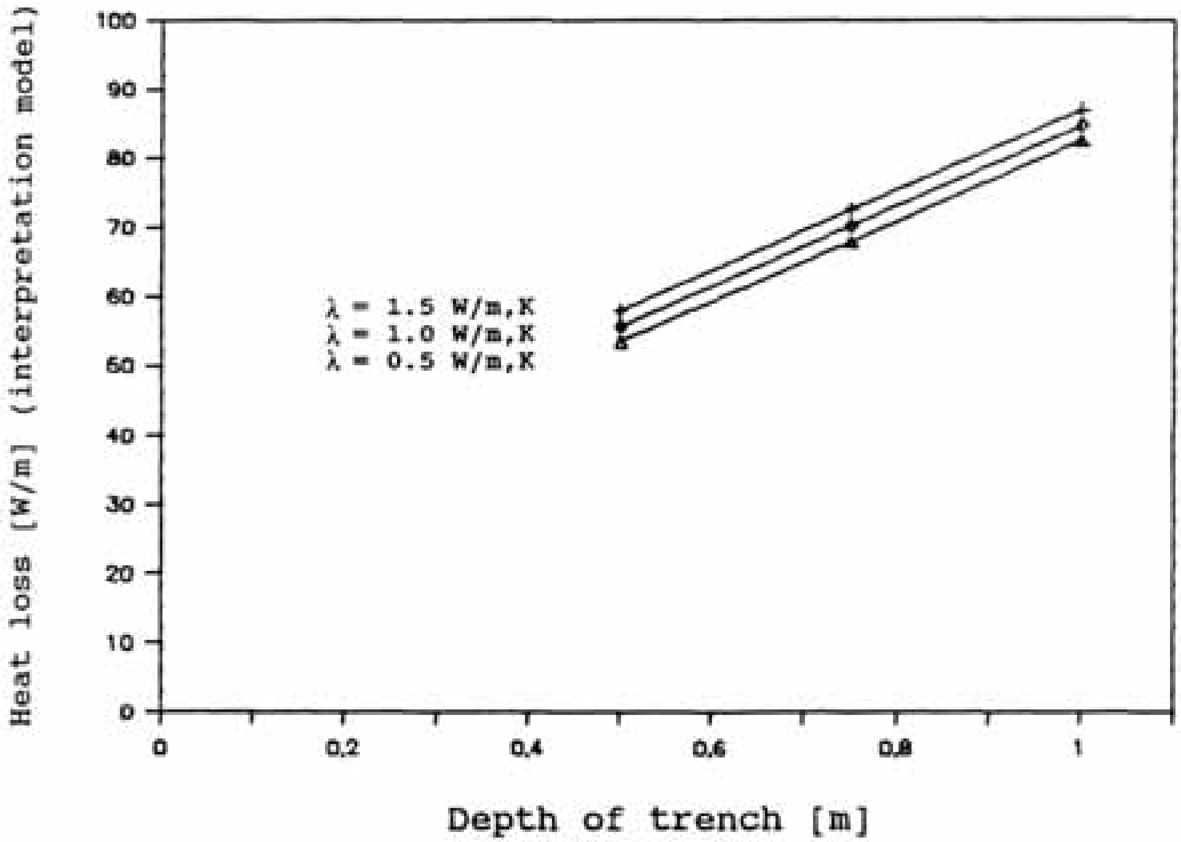


Figure 6.1. Influence of the different parameters in the interpretation model on the heat loss. (The reference case, see chpt. 5).

According to Figure 6.1, the depth of trench is the most important factor in the model. The heat conductivity has a relatively small influence on the heat loss. For example, by increasing the heat conductivity from 0.5 to 1.5 W/(m·K), the heat loss from the pipes increases only about 6 %.

The load situation during the last weeks before the thermography (dTm/dt) affects the relation between the heat loss and the TX factor due to the thermal mass in the ground, see Chapter 7.4. This implies that the TX factor measured in the spring when the load decreases is higher compared to a steady state situation. In the same way the TX factor measured in the fall is somewhat too low due to the rising load. This can be seen in Figure 6.2 where the TX factor is plotted versus the heat loss for different months during the year. The appearent hysteris reflects the thermal inertia of the ground. In order to correct for it, the dTm/dt – factor was included in the interpretation model (eq. [8]).

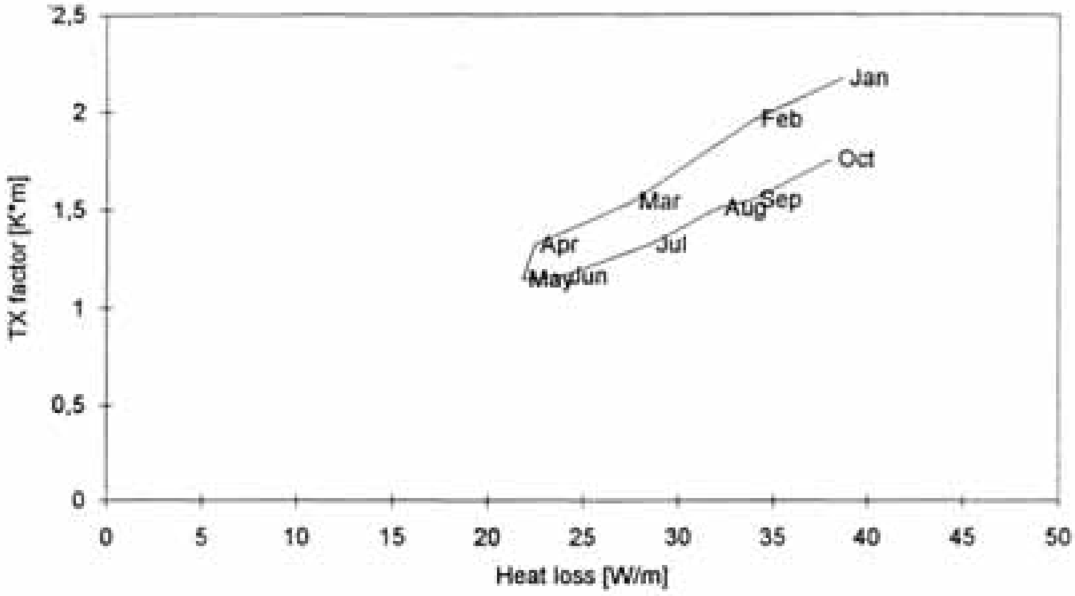


Figure 6.2. Hysteris in the relation between TX factor and heat loss due to the thermal inertia of the ground.

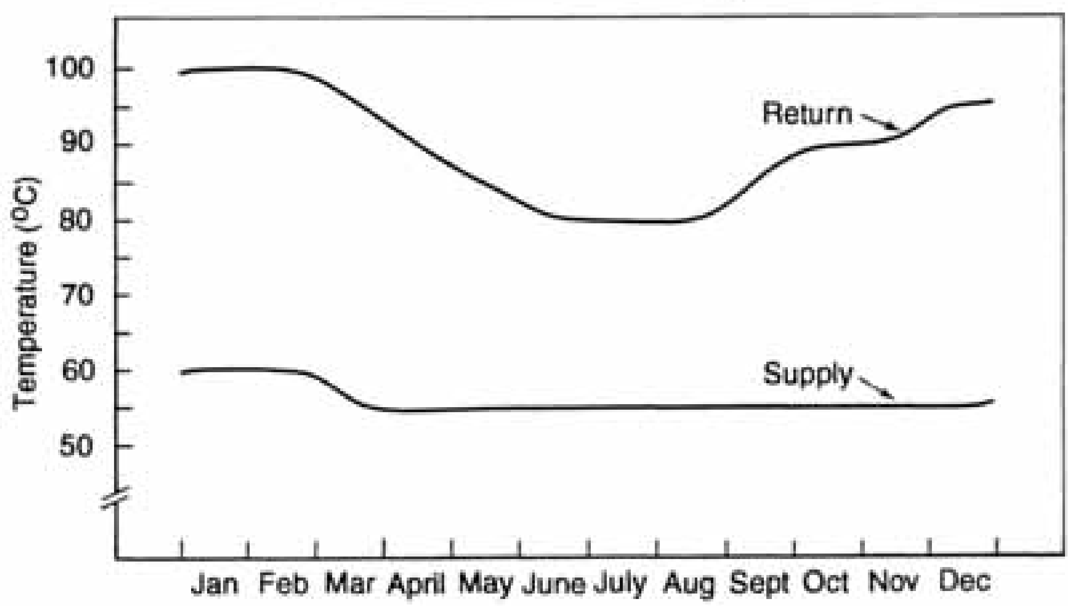


Figure 6.3. The monthly mean temperature distribution for an assumed district heating application

7 APPLICATIONS

This Chapter deals with the different types of systems for which the model can be applied. For each type of system (except coolant distribution) both measurement and simulation results are presented.

Section 7.4 describes dynamic simulations of instant changes due to insulation damage etc.

7.1 Heat distribution

In the first year at the test field we have simulated the heat loss for a normally insulated pipe as a reference. The *annual mean value* for this type of double pipe, DN 100 with class 1 insulation, is about 33 W/m.

Figure 7.1. shows temperature profiles from the test field for successive hours in the morning. The uniformity of the profiles indicates that the surface was dry. The figure indicates also that a TX width of 2 – 2.5 metres in each direction from the centre of the pipes is sufficient.

Figure 8.9 in section 8.3 shows the heat supplied electrically and the heat loss calculated by means of the interpretation model.

This case with intact pipes is the most difficult case to measure because of the relatively small heat losses. Higher heat losses due to poorer insulation properties are easier to determine with high accuracy due to the smaller influence of the climate conditions in those cases.

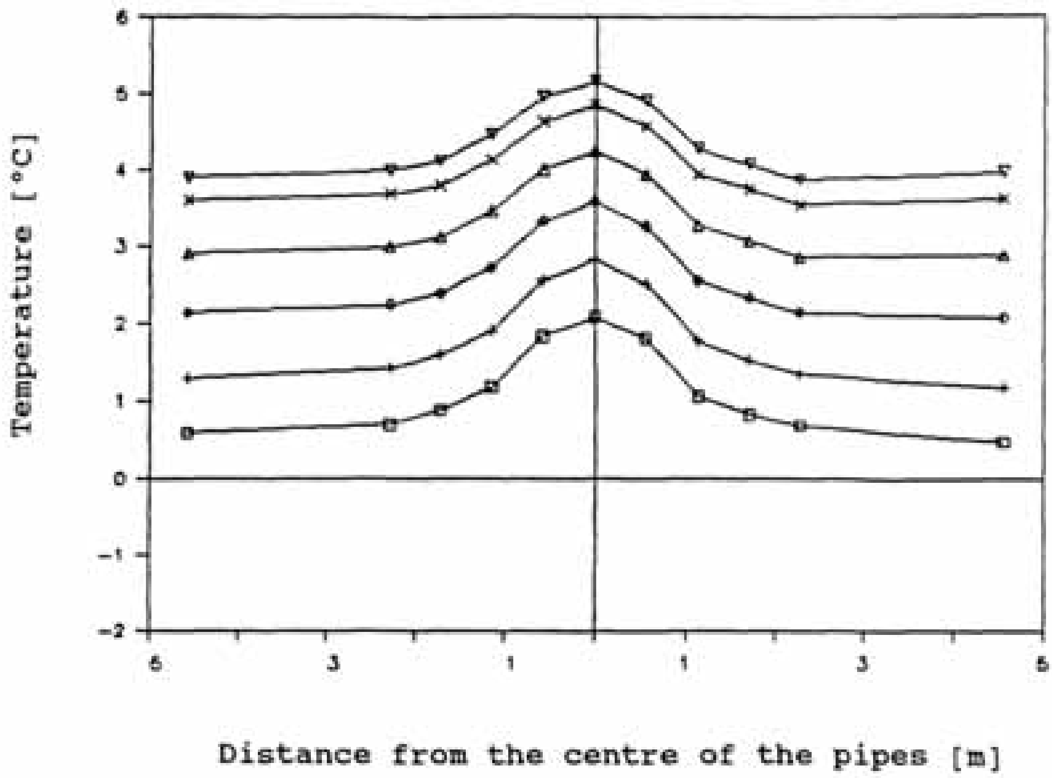


Figure 7.1. Temperature profiles from the test field at Studsvik simulating an intact system (the reference case, see chpt. 5).

7.2 Steam distribution

A steam distribution system has been simulated both at Studsvik's test field and by means of computer simulations. For simulations and measurements, the main difference between a hot water system and a steam system is the operating temperature and hence the amount of the heat loss.

7.2.1 Simulations

The steam distribution system simulated has the following properties which are typical for a steam system:

The supply pipe has an inside diameter of 200 mm and is insulated with 75 mm of PUR. The distribution temperature is 170 °C.

The return pipe for condensate has an inside diameter of 75 mm and is covered by 25 mm mineral wool. The condensate temperature is 90 °C.

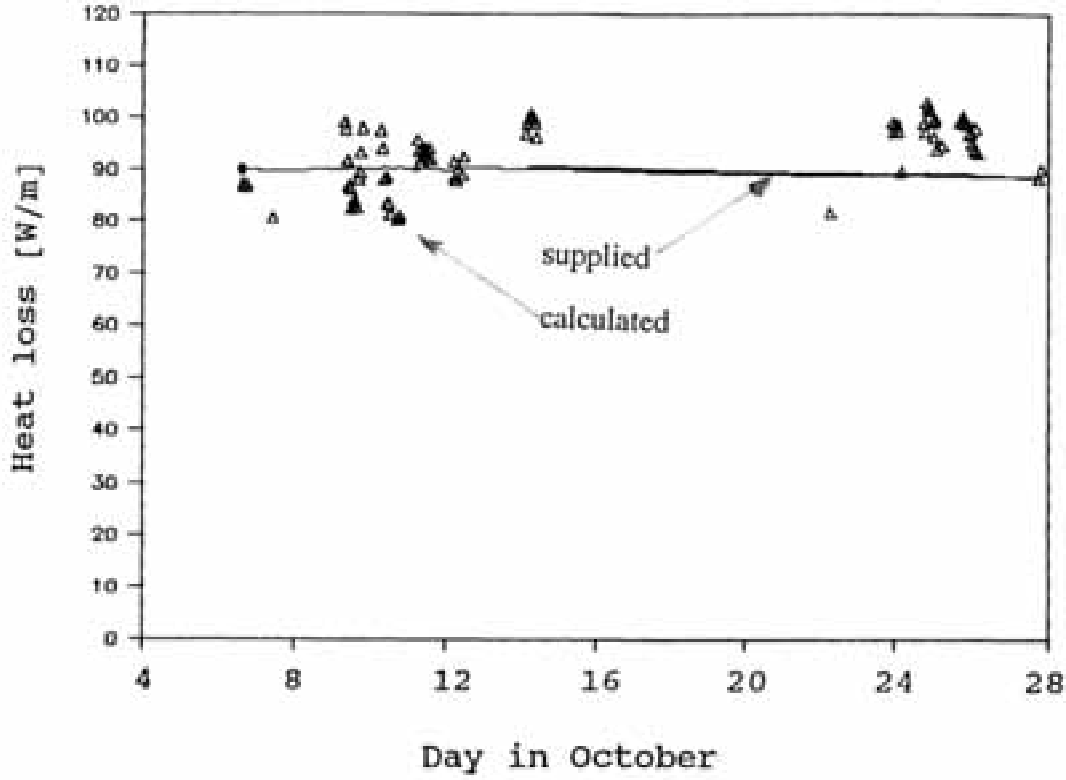
The trench depth in the simulations is 0.5 m (as in the test field) and 1.0 m respectively.

Simulations with the computer model yield about 75 W/m as annnual mean value of the heat loss for this steam distribution system. The weather conditions used are those of Stockholm.

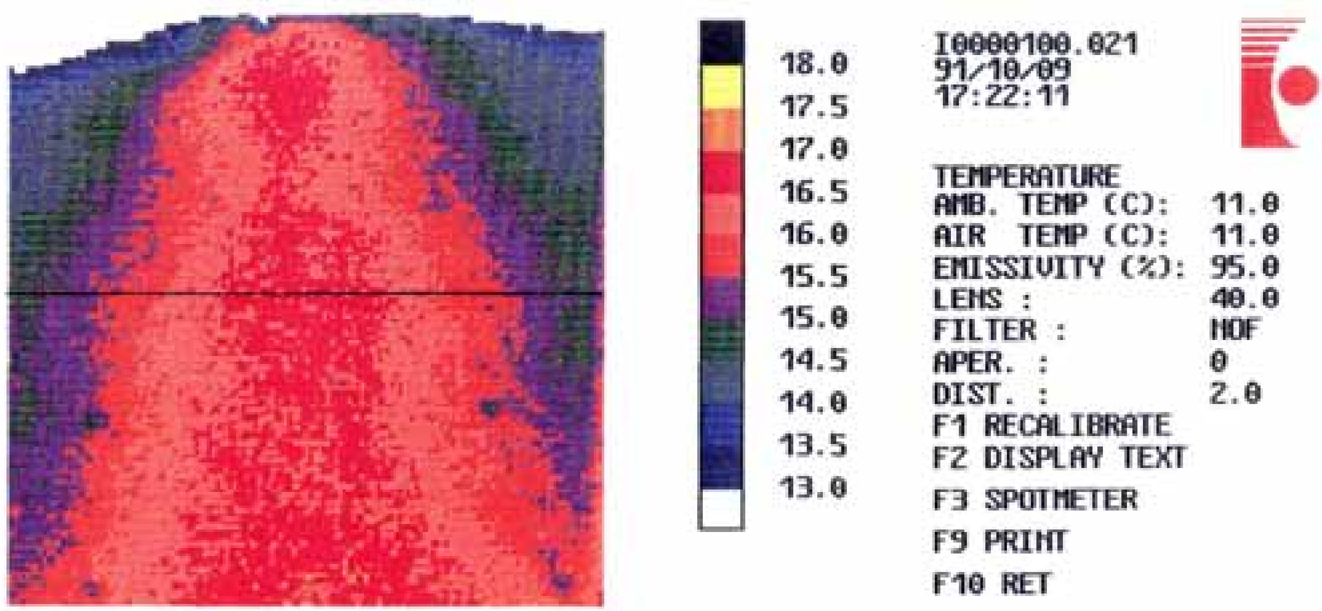
7.2.2 Measurements / comparison

The interpretation model has been applied on a case in which the pipe heat loss has been increased corresponding to heat losses of a steam distribution system. The total power supplied to both pipes is 90 W/m. Figure 7.2. shows the electric power supplied to the pipes and the heat loss derived by means of the interpretation model. According to the figure, the difference between the supplied and calculated heat loss is not more than 10 %.

The temperatures at the test field are also measured by means of infrared equipment. The temperature profile (thick line) in Figure 7.4. corresponds to the thermography picture in Figure 7.3. Figure 7.3 shows false colour thermograhphy pictures where red indicates the hotest and blue the coldest regions.



<u>Figure 7.2.</u> Supplied and calculated heat loss at Studsvik's test field when steam distribution is simulated.



<u>Figure 7.3.</u> False colour thermography picture from the test field.

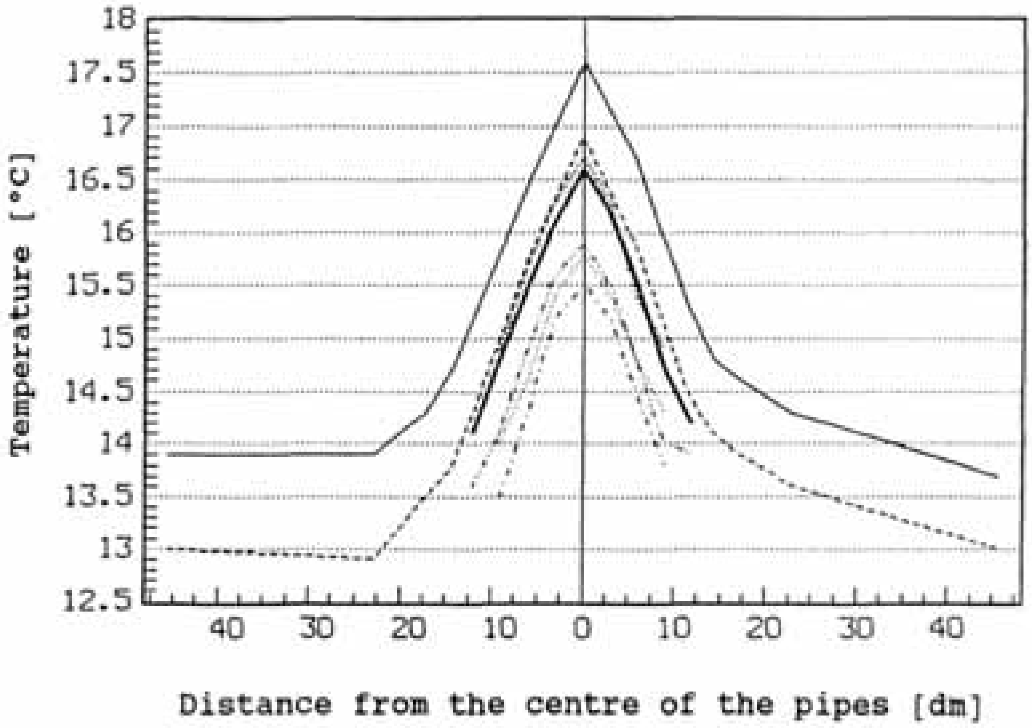


Figure 7.4. Temperature profiles from the test field, steam distribution. The thick curve corresponds to the false colour picture of Figure 7.3.

7.3 Coolant distribution

Computer simulations have been performed for analyzing the use of the TX model for different cooling applications. As can be seen from Figures 7.5. and 7.6., the temperature differences at the surface of the ground are too small in most cooling applications to be quantitiatively analysed. It should be possible to analyse the profile above a coolant pipe without insulation if the trench depth is small, Figure 7.5. However, this particular case does not require analysis since there is no damaged insulation to be detected. In the case of insulated pipes as shown in Figure 7.6. however, the temperature difference along the profile is less than 0.1 °C, which is is too small to be used for quantitative interpretation.

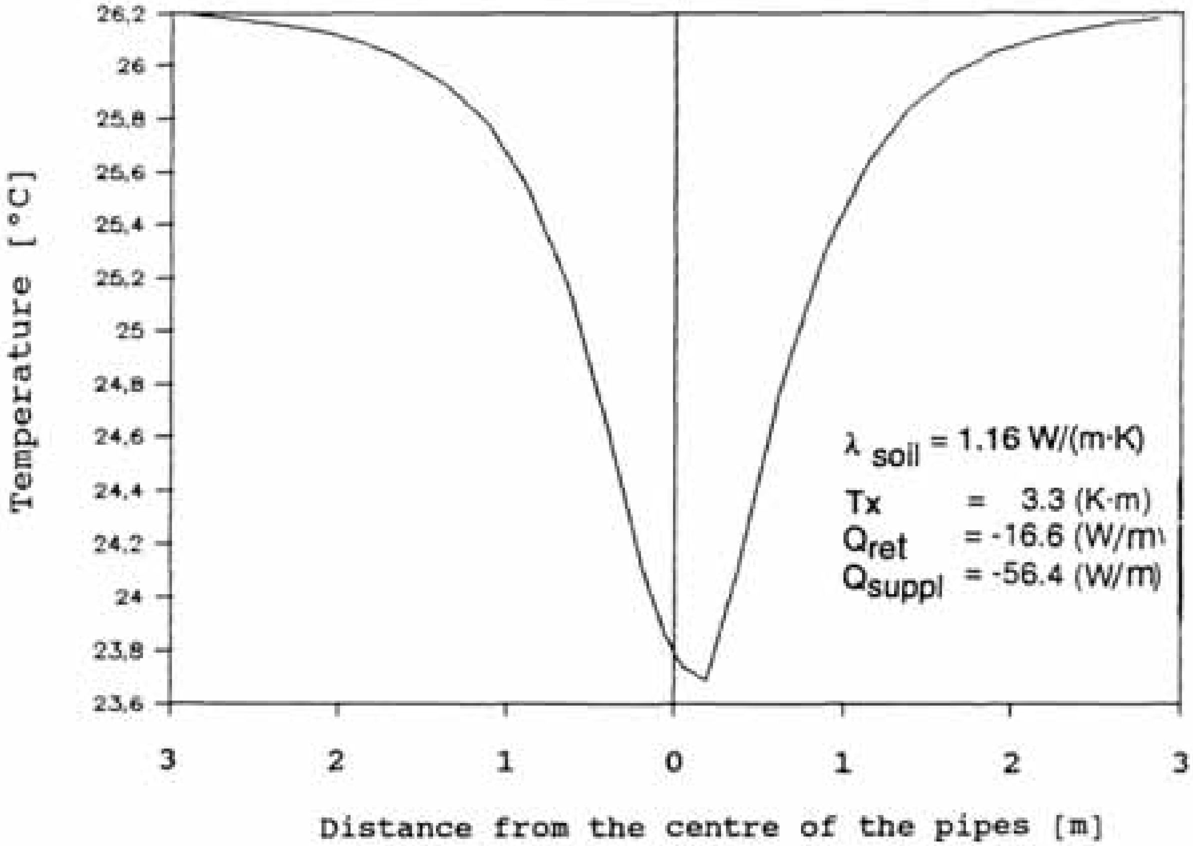


Figure 7.5. Temperature profile above two uninsulated coolant distribution pipes (4 and 12 °C respectively) with 0.5 m trench depth. Computer simulation.

Another reason of performing thermography on coolant distribution pipes is to find water leakages. In that case it is sufficient to interpret the thermographic pictures qualitatively, and then compare the temperature profiles of different pipe sections. Even if only small leaks exist for more than one week, they should certainly be detectable. The interpretation of water leakage from a coolant pipe in the ground by means of thermographic methods should therefore be analysed in more detail in the future.

Consequently, there is no possibility to develop an interpretation model with sufficient accuracy for quantifying the heat gain in coolant distribution systems, but thermography is still applicable for the purpose of network survey.

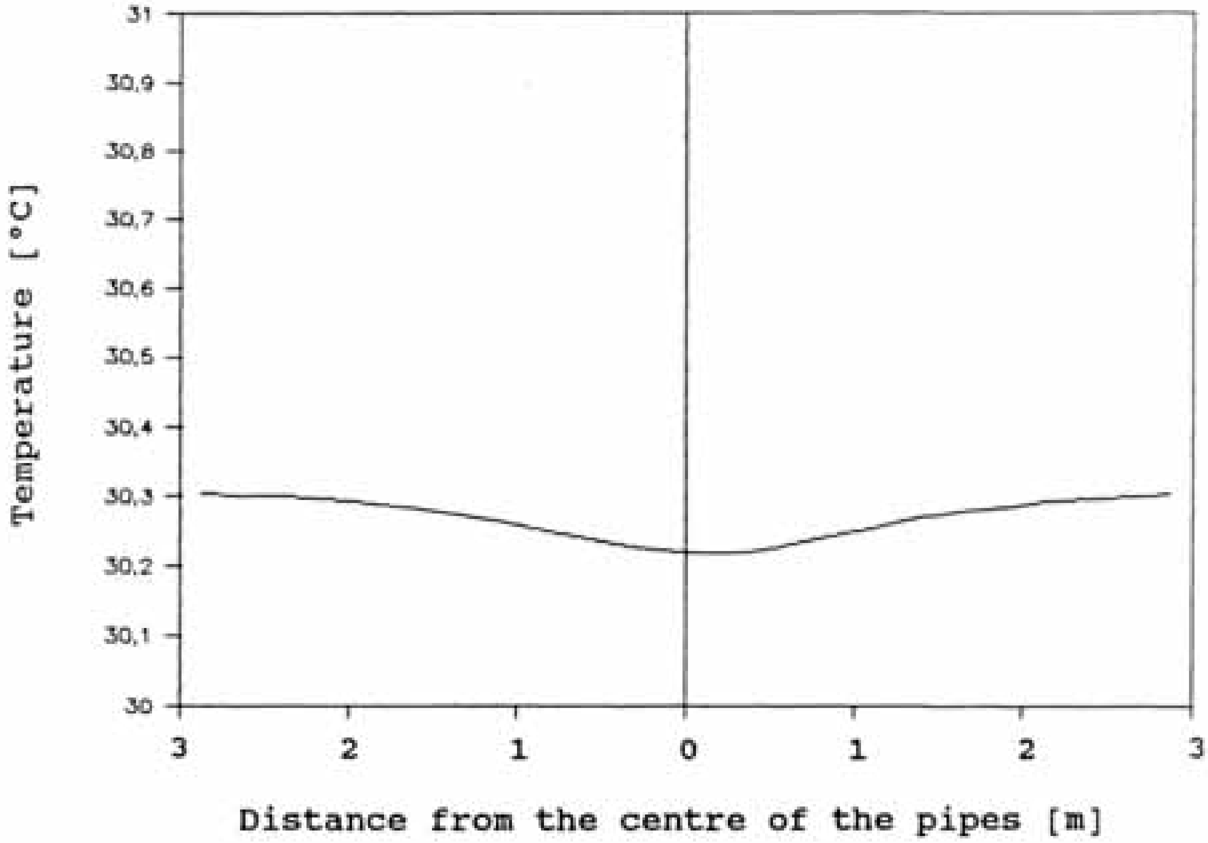


Figure 7.6. Temperature profile above two insulated coolant distribution pipes (4 and 12 °C respectively, class 1 insulation).

Another important possible application for using the simulation program for coolant distribution concerns the problem with freezing in uninsulated pipes, which are not operated during the winter. Because the simulation program includes phase transition between water and ice, it is possible to use it for calculating the expected temperatures in coolant distribution pipes during the off-duty season in the winter time.

Still another application of the model is its use for determining whether it is economically justifable to insulate the coolant distribution pipes. This is performed by calculating the heat gain during the summer for both insulated and uninsulated coolant distribution pipes. However, this analysis can also be performed analytically.

For these two applications it is sufficient to apply the simulation program with the climate valid for the particular place, an interpretation model would not be needed.

7.4 Temperature changes in the ground

Because of the thermal mass in the ground, it is of interest to study how changes of the pipe surface temperature caused either by impaired insulation or by increased distribution temperature affect the temperature profile at the ground surface.

In order to verify the models for dynamic effects, we have performed simulations with an instant change in the insulating properties and studied the changes in the TX factor during the following days. This case with instantaneous damage in the insulation will rarely occur in reality, but in order to be able to study the dynamic response at the ground surface, it is meaningfull to simulate such an instantaneous change of properties.

The calculations have been verified with measurements at Studsvik's test field.

7.4.1 Simulations

By means of an instant change in the insulation property with all other parameters equal, a wet insulation has been simulated. The influence of the damaged pipe on the surface temperature has then been studied.

The following relation is valid for the thermal conductivity of wet polyurethane (PUR) insulation, according to reference [6]:

$$\lambda_{wet} = \lambda_{dry} + 0{,}0005 \cdot U + 0{,}00003 \cdot U^2 \quad [W/(m \cdot K)] \qquad [9]$$

U = percentage by volume of water in the insulation.

In the simulations, we have assumed that the insulation becomes soaked by 60 vol% of water instantaneously. This means that the heat conductivity increases from 0.027 W/(m·K) to 0.165 W/(m·K).

The process which is most interesting for this study concerns the changes in the TX factor during the weeks following the damage.

The computer simulations for the case of damage give an annual average value of 95 W/m for the heat loss. We have assumed that the forward pipe is damaged. This can be seen in Figure 7.7. with the peak in the profile some what to the left of the centre of the pipes.

Figure 7.7. shows temperature profiles from a system with one damaged pipe and from a system with intact pipes. In this Figure it is interesting to note that the profile for the damaged system is higher but not much wider. This implies that larger heat losses can also be described with the same TX evaluation width x_m as normal heat losses.

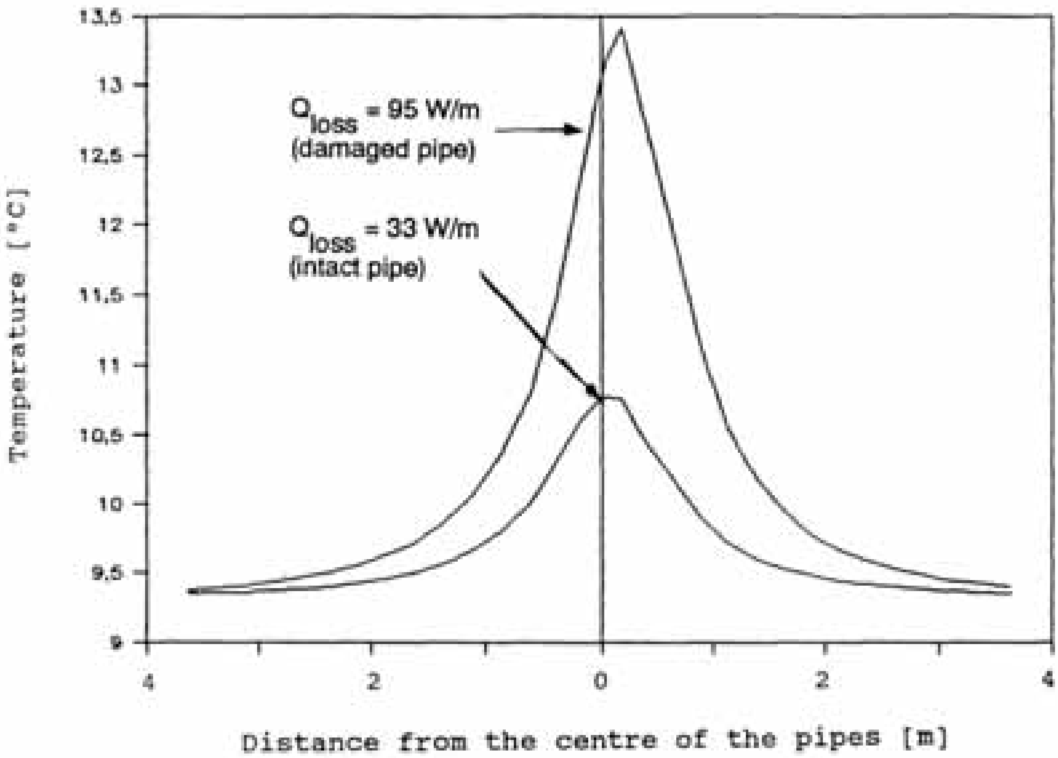


Figure 7.7. Temperature profiles for an intact system and for a system with one pipe damaged.

The following Figures 7.8. – 7.10. show the changes of the heat loss and the TX factor when a pipe is damaged. Figure 7.8. implies that the TX factor rises relatively fast in the beginning and than stabilizes in about two weeks. This means that thermography for qualitative purposes (leakage detection) can not produce reliable results before 3–4 days after damage has occured.

If the aim is to quantify the heat loss by thermography, the relation between the TX factor and the real heat loss is of the most interest. Figure 7.9. shows that the heat loss is stabilized 5 – 10 days after the damage. The peak in the heat loss at the occasion of the damage is due to sensible heat absorption in the soil close to the pipe during a transition time. Figure 7.10 shows that the relation between the heat loss and the TX factor can be as much as three times higher than for a normal pipe. This means that the TX factor cannot be used to quantify the heat losses in the first two weeks after a damage occurs.

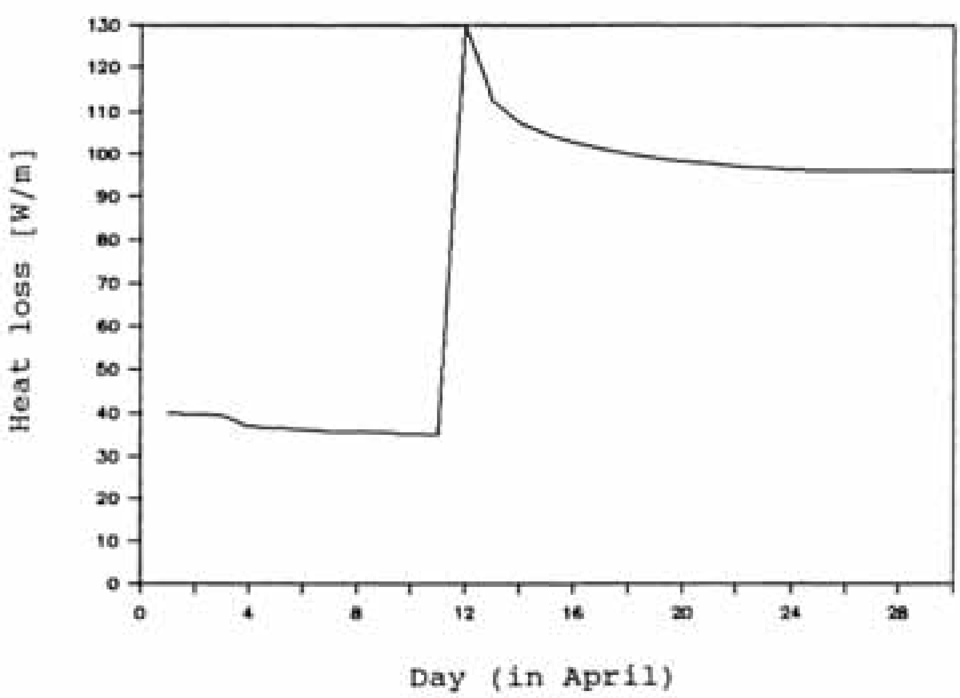


Figure 7.8. Heat loss from a pipe with a damage occurring at April, 11.

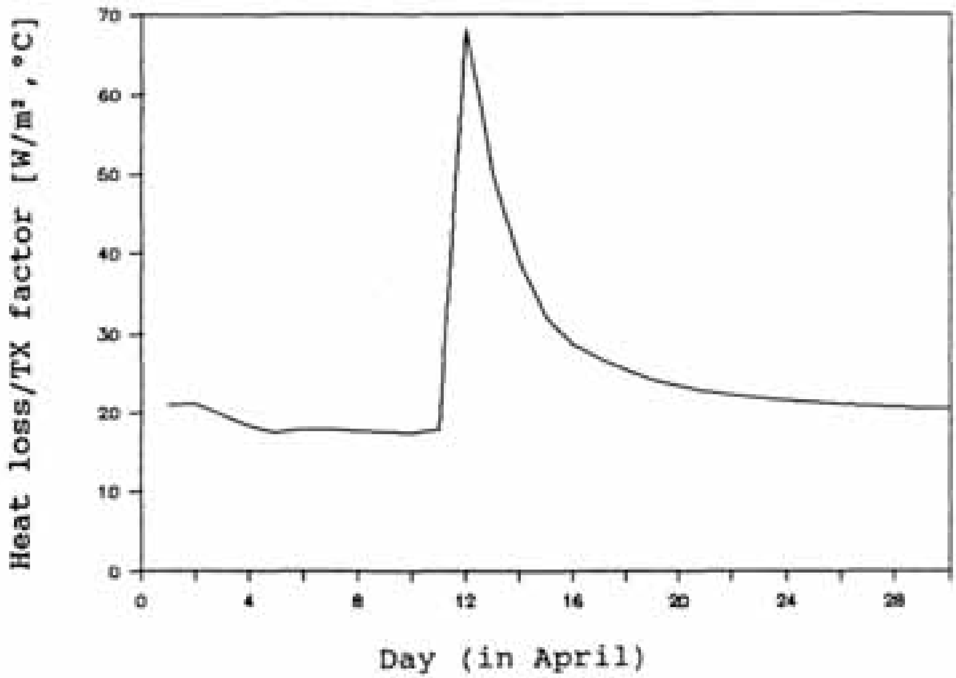


Figure 7.9. Heat loss in relation to the TX factor at the days around the occurrence of a damage in the pipe.

7.4.2 Measurements at the test field

In May 1991 the electrical power was increased to simulate a damaged pipe. The power supplied was increased from about 45 W/m to about 90 W/m. According to the computer simulations, this corresponds to the heat loss from a pipe soaked by 60 vol% of water in the insulation.

Figure 7.10 shows the effect of the increase of the heat loss by 7 May 1991 on the TX factor. After about 5 days the TX factor approached the new value.

The Figures 7.11 and 7.12 show the temperature profiles from the test field before and after the rise of the heating power when the conditions have been stabilized. The TX factor is almost doubled as well as the heat loss. In these measurements as well as obtained in the simulations, the temperature profile shows a larger temperature difference, but not a larger width for the case of increased heat loss when compared with the reference case.

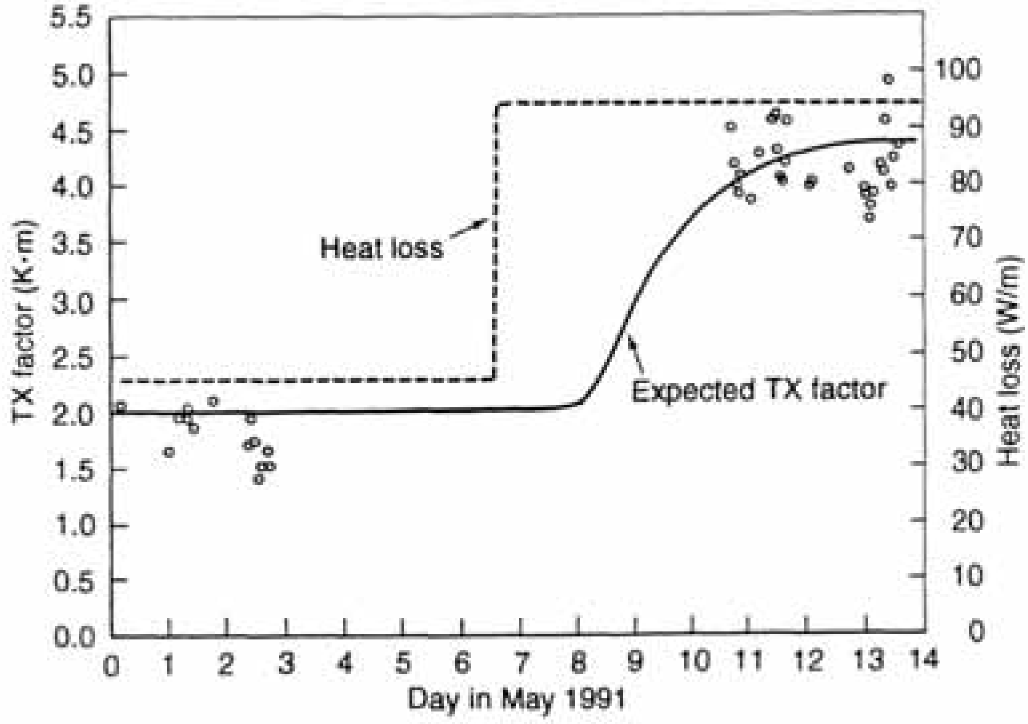


Figure 7.10. Effect of the heat loss on the TX factor at Studsvik's test field in May 1991.

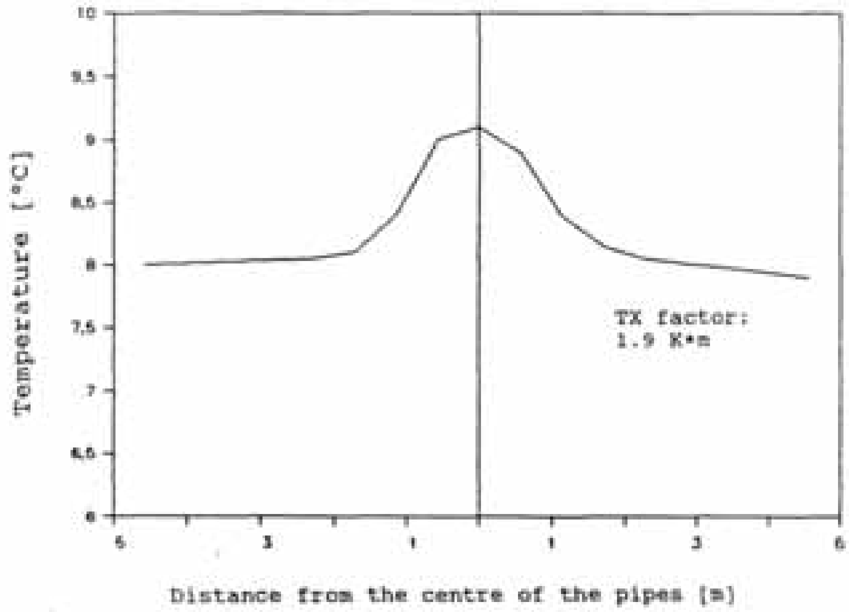


Figure 7.11. Temperature profile before the rise of the heat loss.

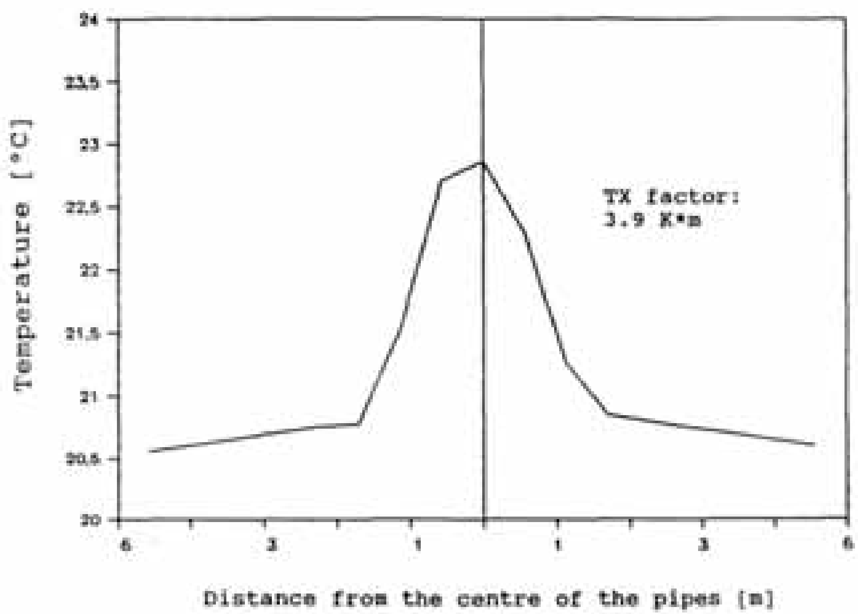


Figure 7.12. Temperature profile after the rise of the heat loss, when the temperatures are stabilized.

The conclusion from simulations and measurements is that the instant TX factor as measured represents the insulation status (and load situation) about 1 week previously. Hence, changes in the insulation status which are more recent than this, will not be correctly analysed. However abrupt changes in the insulation status are normally caused by water leakages which also will soak the surrounding of the pipes and hence will very easily be detected in the course of a thermograpy survey.

7.5 Field application

Our method for quantifying the heat loss from district heating pipes has also been applied in practice on some sections totaling 300 m of the district heating network in Västerås, Sweden. The investigated pipes have outer jackets made of asbestos cement or concrete and are insulated with mineral wool.

When choosing measuring points it was important to avoid places with disturbing elements such as grass or areas where the asphalt had been repaired, because of the inhomogenous emission at the ground surface. Curbstones and bushes, as well as shadows covering the measurement area in the case of sunshine, will also influence the accuracy of the results.

Because of rain in the days before the measurement, moisture remained in some cracks in the asphalt which affected the temperature profile.

After selection of the proper measurement places however, the method has worked as anticipated in spite of a sunny day and clear sky at night. Partially shaded areas could also be corrected for when the TX factor was calculated.

The table in Figure 7.13 shows the summary of all the points investigated from a thermography survey on a 300 m long district heating section in Västerås. The district heating pipes where placed in culverts made of concrete or asbestos cement. One third of the points could not be evaluated. For most of the points the insulation was in good shape. However in some cases (3 out of 8), damaged insulation was detected.

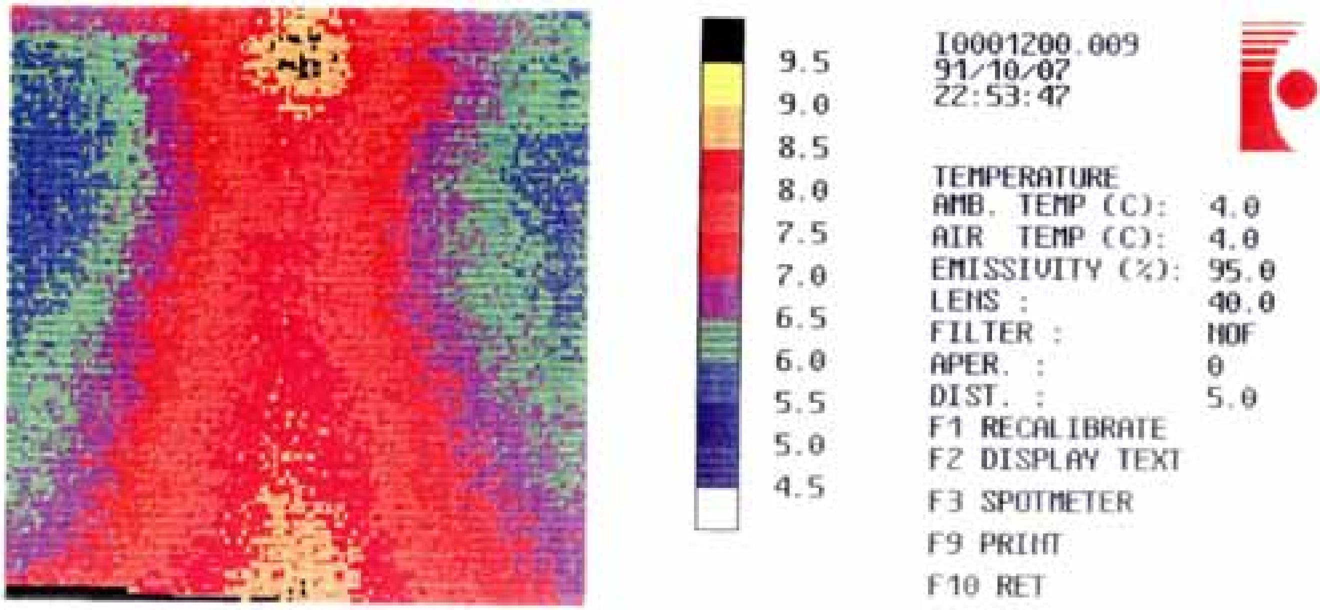
Type of pipes	Position	$P_{thermogr}$	P_{calc}
		Watt/meter	
asbestos	1.1	87	63
asbestos	1.3	131	65
asbestos	2.1	109	67
asbestos	2.2	105	67
asbestos	2.3	99	71
concrete	3.1	86	84
concrete	3.3	65	86
concrete	4.1	73	81

Figure 7.13. Summary of quantitative heat loss analysis in Västerås

In the interpretation model, see Chapter 8, an important parameter is the trench depth. It is normally derived from municipal drawings which might date back as far as the 1960s, and hence the information is often uncertain because of later road constructions etc. Hence in uncertain cases the trench depth should be measured separately with electronic devices [7].

Figure 7.14 (point 2.2) shows one of the sites which was evaluated. The temperature profiles show that the surface was been partly shaded from the sun during the afternoon and hence the profile became asymmetrical but recovered in the evening. The TX analysis of the temperature profile results in a TX value of 4.2 K·m, which corresponds according to the interpretation model to a heat loss of 105 W/m. The theoretical heat loss for this type of culvert was calculated to be 67 W/m. Thus our measurement indicate that now the insulation is damaged and has higher thermal conductivity.

Figure 7.15 (point 3.2) shows a measurement on a grass surface. Due to moisture in the grass this picture is impossible to evaluate. However, the location of the pipes can be seen in the middle of the picture.



Example of
Thermography at point 2.2

Temperature profile
point 2.2

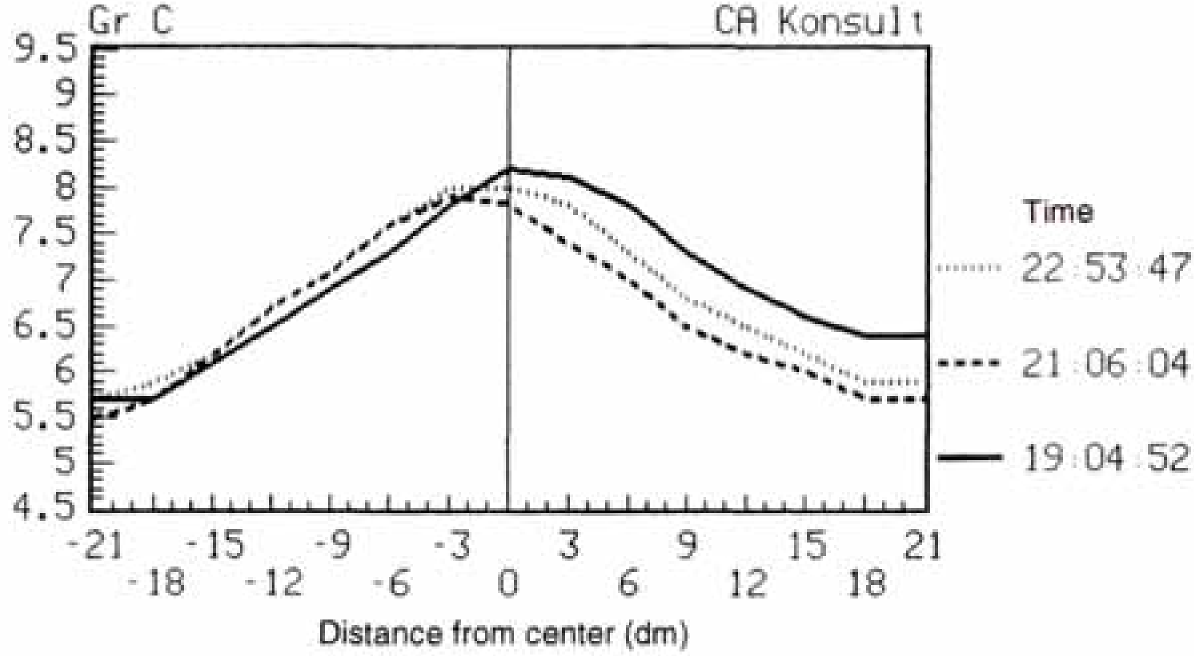
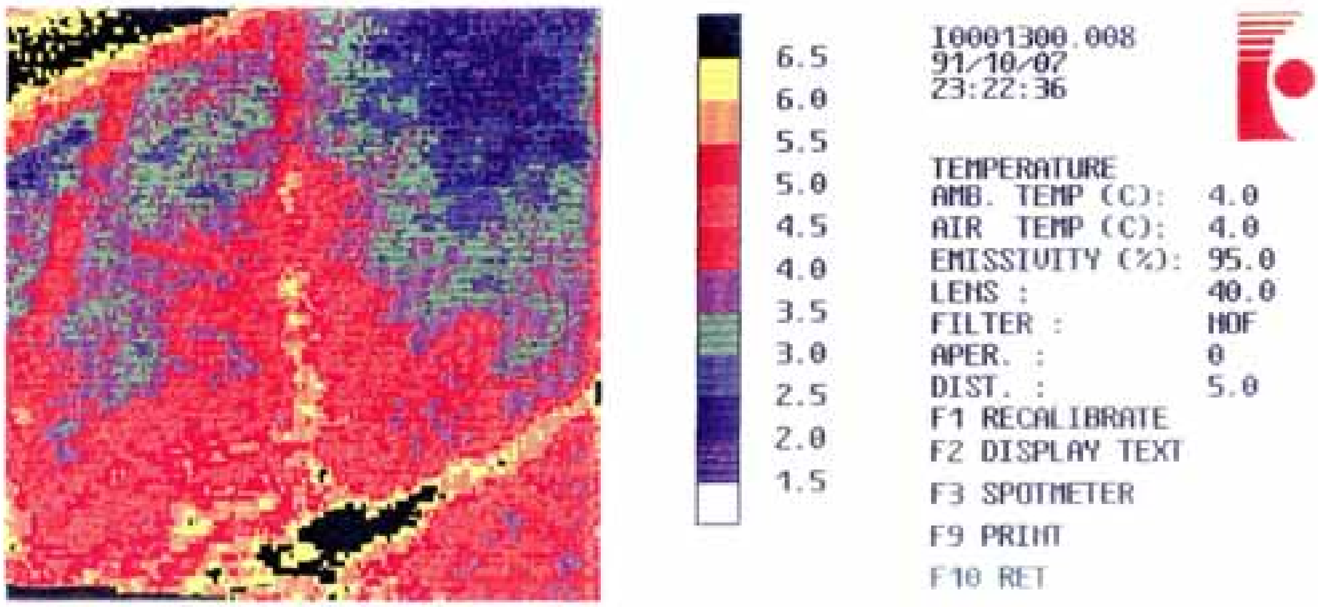


Figure 7.14. False colour thermography picture for Västerås; point 2.2., area partially shaded in the afternoon.



Thermography example from place 3.2.
Pipe center is shown along the centerline of the picture.
No Tx profile can be determined due to wet grass surface.

Figure 7.15. False colour thermography picture for Västerås; point 3.2., grass area.

8 SENSITIVITY STUDIES

One of the tasks in this project is to validate the model and extend it so as to include other weather conditions than those which at present are necessary for reliable thermography results. The aim is to make thermography usable under a greater variety of weather situations during the year.

The weather conditions which at present are considered to be necessary for a reliable thermography result are according to reference [2] any of these:

- a cloudless night after a cloudy day

- a cloudy night

- a cloudy day with uniform temperature conditions

Furthermore, according to reference [2], the following conditions should apply during the thermographic survey:

- ground temperature > 3 °C

- wind speed < 3 m/s at the ground surface

- air temperature < 15 °C

- low relative humidity

- ground surfaces without precipitation.

The main problem is the influence of precipitation, frost, wind etc. on the temperature profile. Erratic results can be obtained if the measured profile is used without caution.

The method for heat loss determination by using the temperature profile can **never be used in the winter** with snow at the surface and frost in the ground.

This is due to the fact that the latent heat transport during phase changes can "fade out" the temperature profile. This behaviour can be seen in Figure 8.1. from the test site at Studsvik. The location of the pipes can be easily seen due to the melting snow.

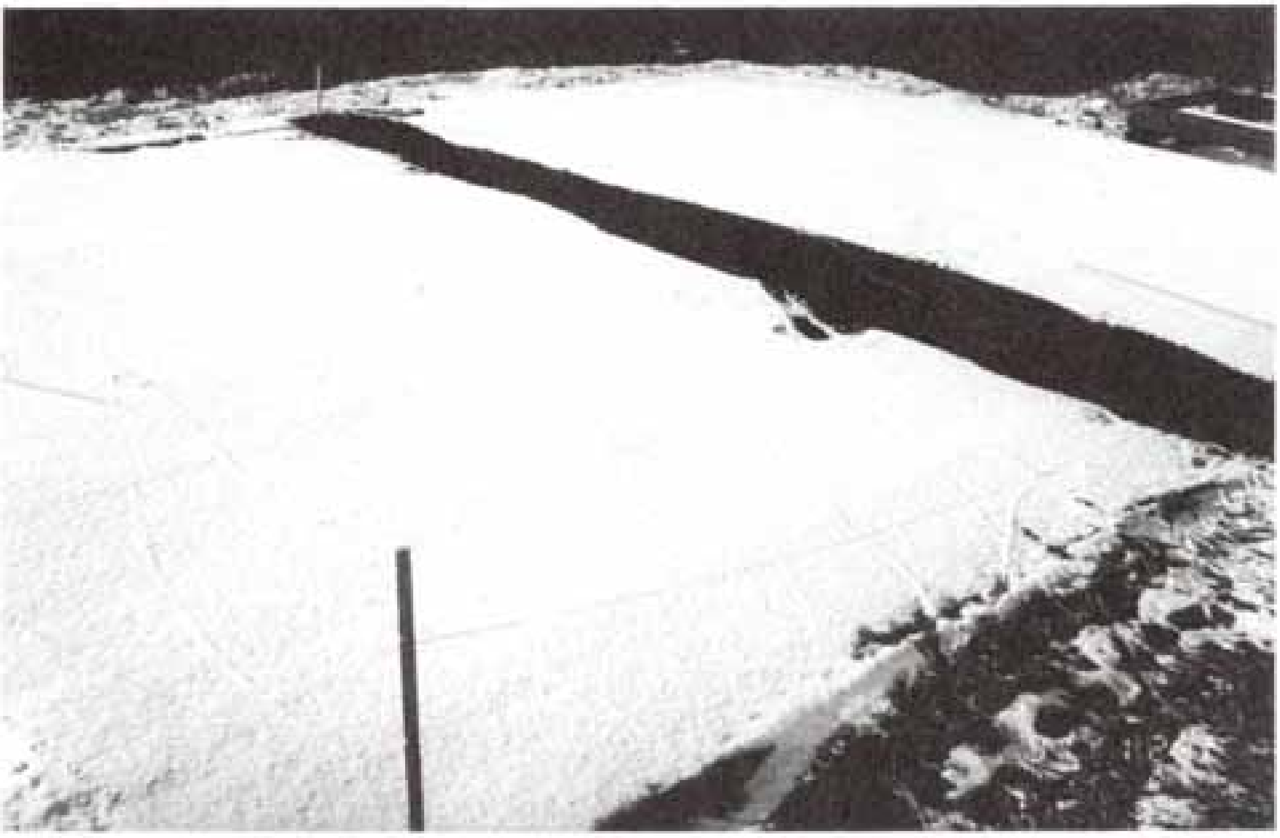


Figure 8.1. Studsvik's test site in the winter.

In the case of wet surfaces, we have found that there also exists a detectable temperature profile, but at a lower level than for a dry surface. A more detailed study of this effect is described later.

The influence of wind, wet surfaces and solar and long wave radiation on the temperature profile has been studied in detail by several computer simulations.

The system simulated in this Chapter is the reference case described in Chapter 5, but with a thermal conductivity for the insulation which is about 4 times that in the reference case. The reason for assuming such a high thermal conductivity is that the influence of the weather conditions on the TX factor is easier to detect with a higher value of the TX factor. The heat loss is about 110 W/m for this case.

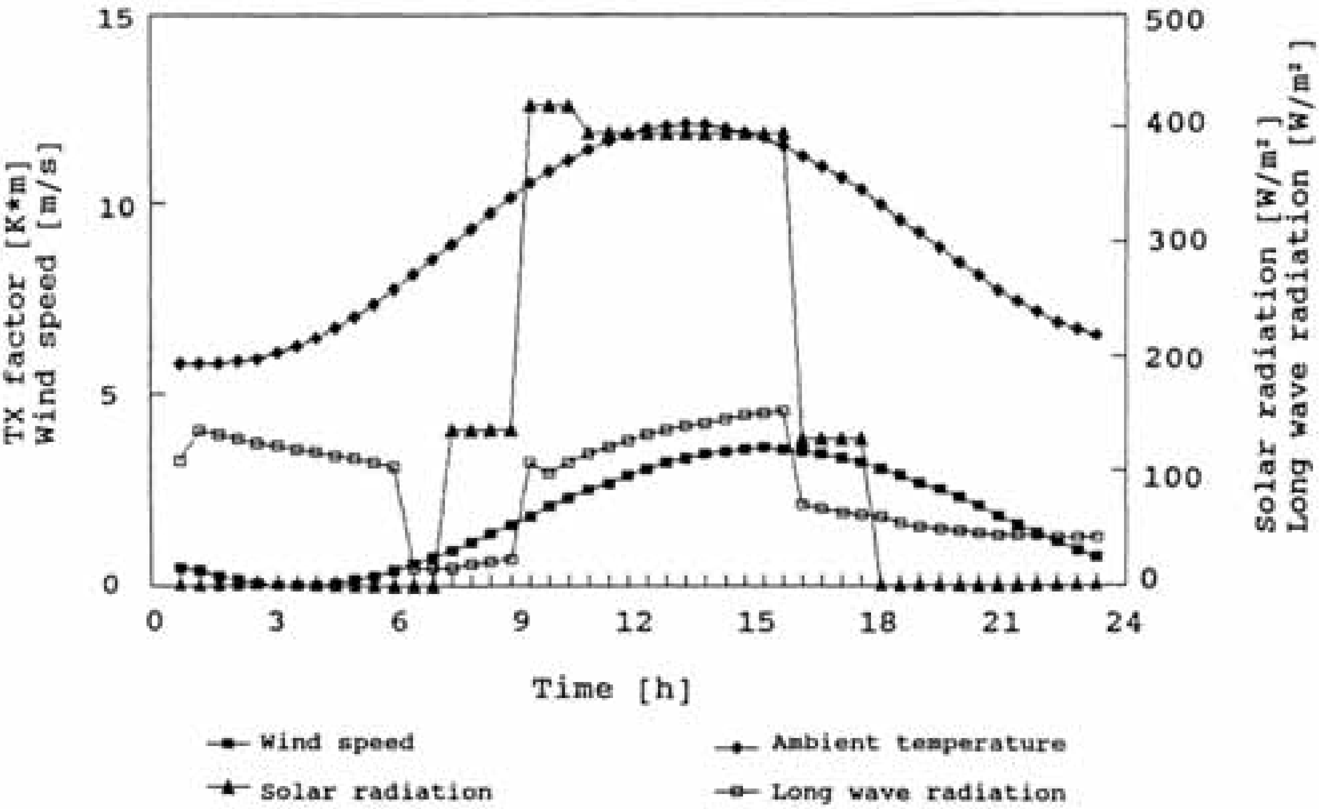


Figure 8.2. The weather conditions for the September model day.

In these simulations, we have studied a typical but idealized day in September based on long term September mean values for Stockholm. The model day is shown in Figure 8.2.

As regards the measurements at the test field, most of the effects established in the simulations have been verified in broad outline.

8.1 Wind speed

The influence of wind on the temperature profile has been studied both by simulations and at the test site.

The heat loss from the surface is partly dependent on convection in the air, which is caused by the temperature difference between the surface and the air. Convection can be of two kinds, natural and forced. Forced convection is here the dominant mode and caused by the wind.

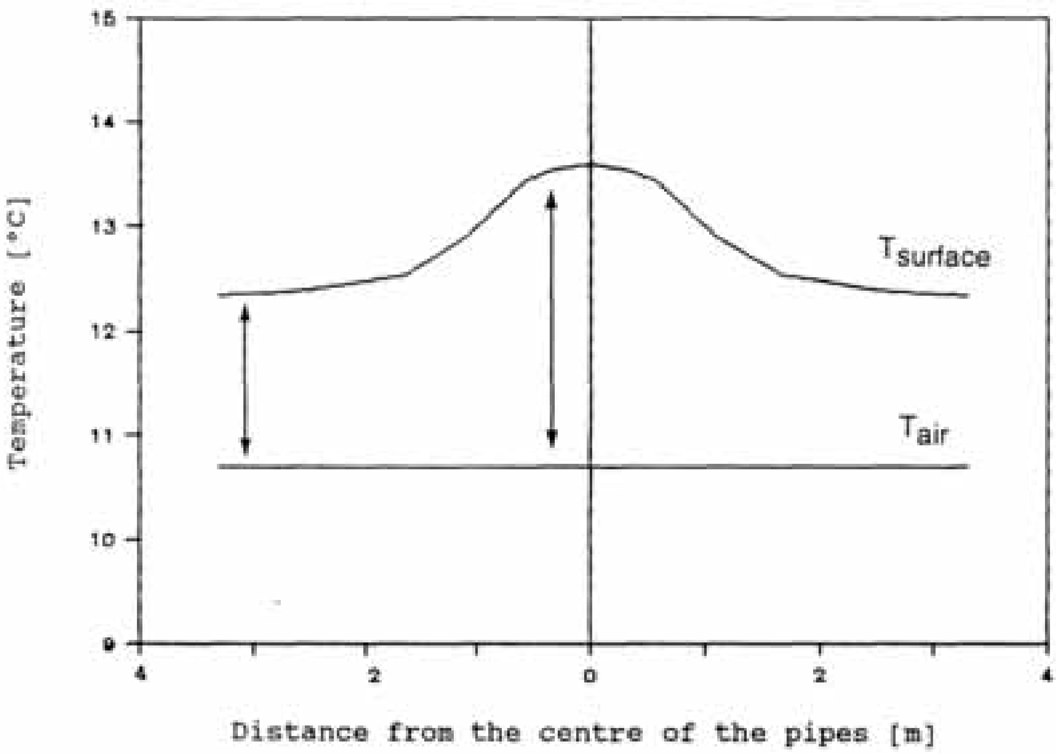


Figure 8.3. An example of temperature differences between the ground surface and the air.

Because of the temperature profile at the surface, the temperature difference between the surface and the air is different just above the pipes compared to the undisturbed ground, see Figure 8.3. This means that the convection flattens the temperature profile and hence reduces the TX factor.

The influence of the wind speed on the TX factor in the simulations can be seen in Figure 8.4. The wind speed has been kept constant at 7 m/s, and at 12 noon changed to 0 m/s. The opposite case is also studied. According to the Figure, it takes more than 10 hours from the point when the wind speed is changed until the TX factor is stabilized at a new level.

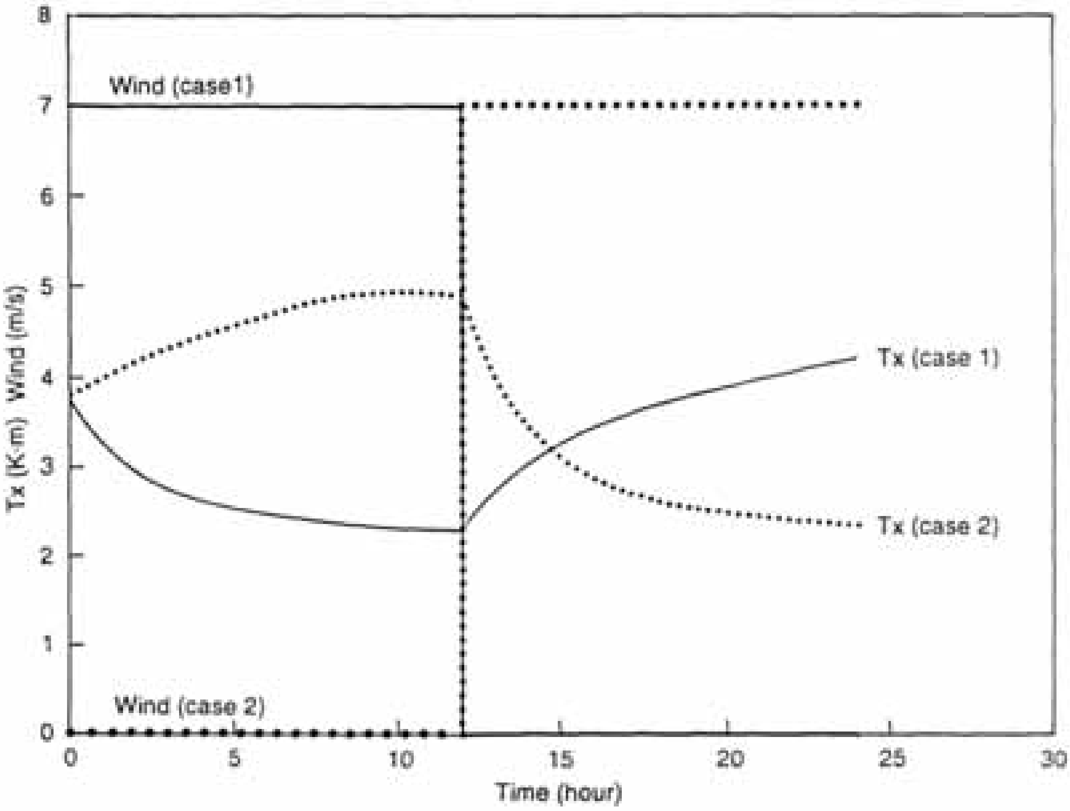


Figure 8.4. Influence of wind on the TX factor.

Figures 8.5 and 8.6 show the influence of the wind speed on the temperature profile and the TX factor respectively derived from the measurements at the test site. These values are hourly mean values.

The decrease of the TX factor at October, 17 can be caused by factors other than the wind speed (such as a temporarily clear sky, etc), but the wind is probably the main reason.

Including the wind speed into the interpretation model complicates the measurements because the wind speed must then be measured for several hours before the thermography measurement. Thus, quantitative thermography should for the present be performed when the wind speed is low.

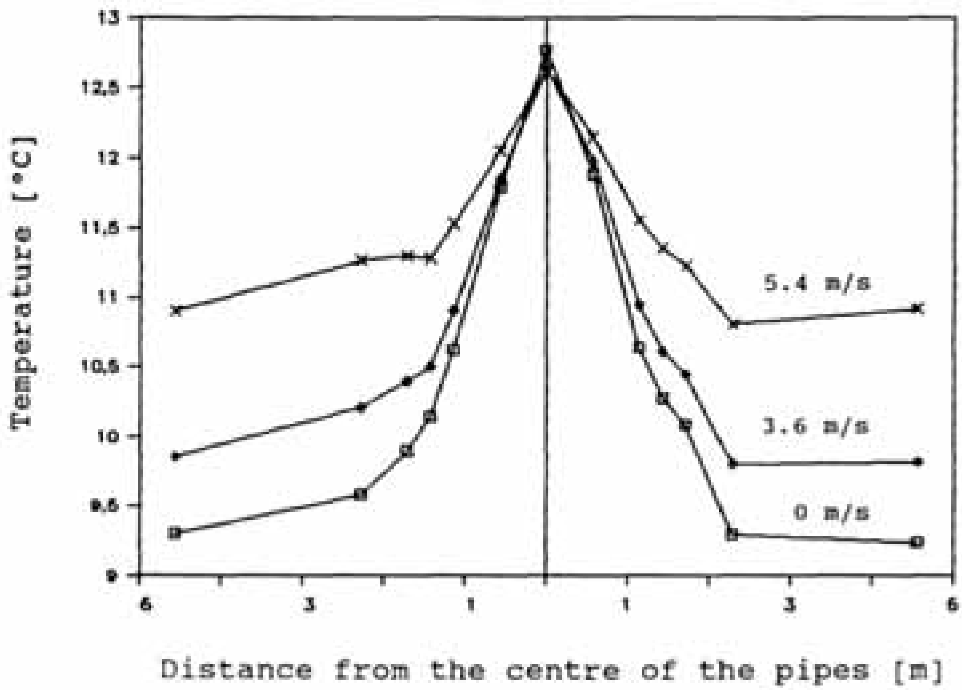


Figure 8.5. Temperature profiles when the surface is exposed to wind.

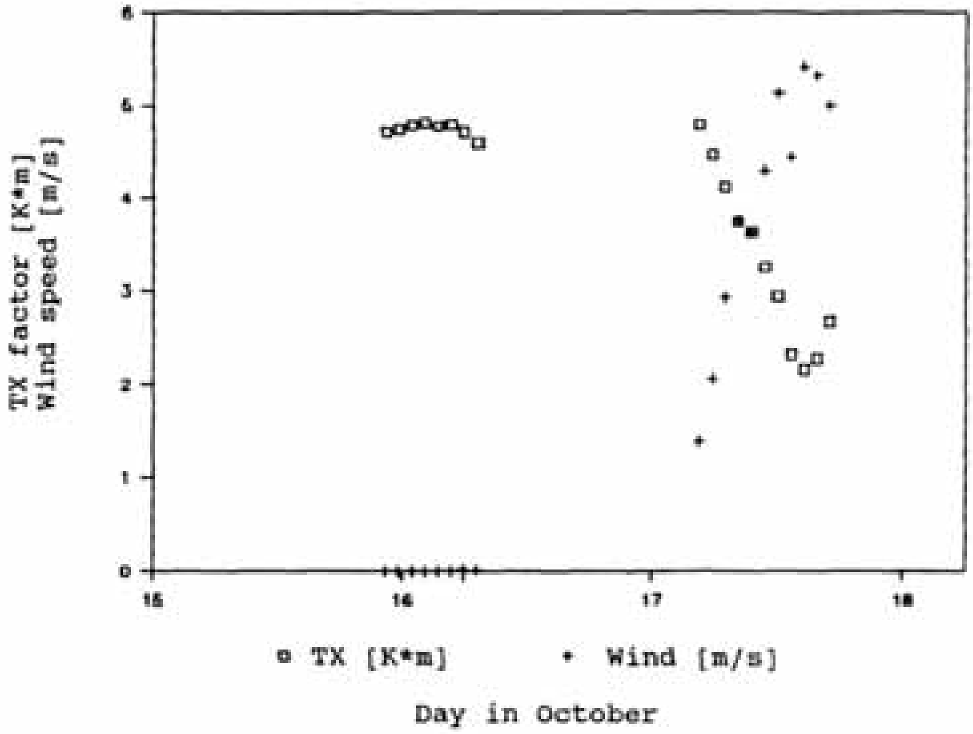


Figure 8.6. Wind influence on the TX factor as measured at the test field.

8.2 Solar and long wave radiation

As was expected, the simulations have shown that the effects of solar and long wave radiation do not have any great influence on the temperature profile as long as the whole surface is exposed uniformly.

A risk when interpreting temperature profiles that are influenced by radiation occurs if the surface is subjected to intermittent shading due to buildings etc. This can cause anomalous results in the interpretation. However, in some cases it is possible to correct the temperature profile for this shading effects when determining the TX factor, f. i. by correcting deviations from the "normal curve" in the temperature profile.

Another problem when radiation affects the surface arises if the surface contains parts with different emissivities. Figures 8.7 and 8.8 show temperature profiles from a simulation when the ground surface includes a assumes the physical conditions for street asphalt). At the surface, a 18 cm wide part has lower emittance for long wave radiation and lower absorptance for solar radiation (absorptance 0.85 and 0.7 respectively, emiittance 0.95 and 0.80 respectively).

The difference between the figures is that Figure 8.7 is valid for a clear sky while Figure 8.8 represents a cloudy sky.

From these simulations it can be seen that the emission and absorbtance coefficients of the surface should be homogeneous for the ground area under investigation, especially when the surface is exposed to solar radiation.

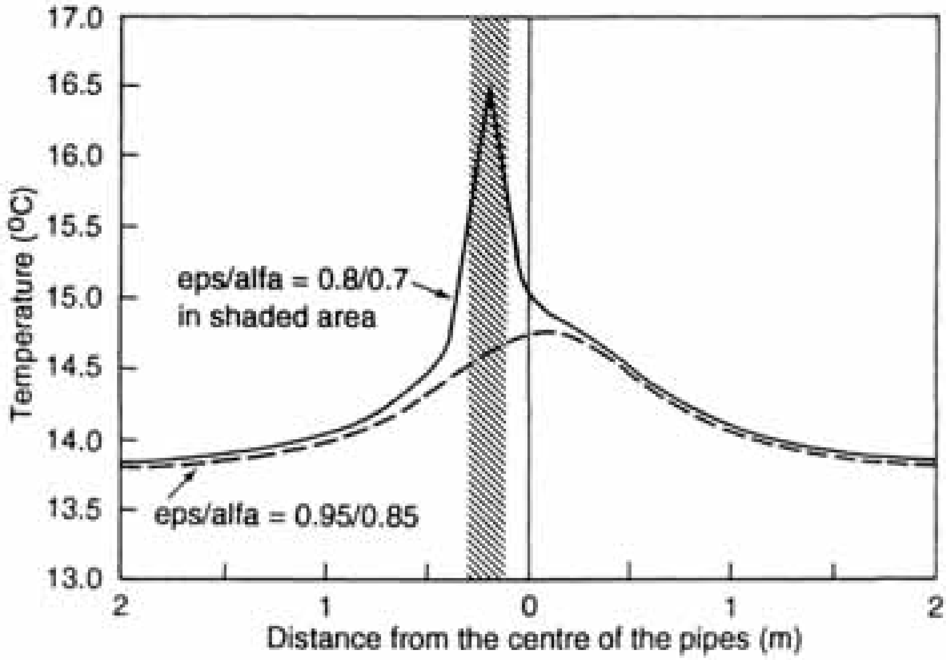


Figure 8.7. Temperature profile from a simulation with different emissivity and absorbtance on one part of the surface (clear sky).

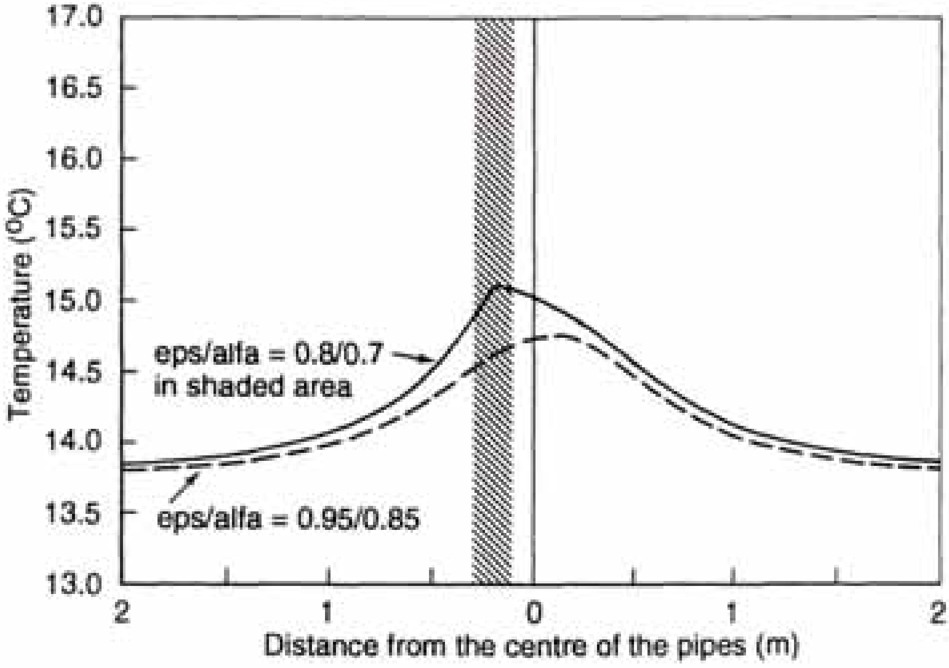


Figure 8.8. Same case as in Figure 8.7 but with a cloudy sky.

One condition, which must be fulfilled when an irradiated surface is used for interpretation, is that the surface and the ground should be dry. Otherwise, for example, the ground below cracks in the asphalt can store water which is evaporated for a long time after a shower of rain, and hence would affect the temperature profile. This can be difficult to discover visually but can be detected by the infrared equipment (see next section).

8.3 Precipitation

At the test field at Studsvik, we have found a TX factor even when the surface was wet. Figure 8.9 shows the heat loss from the pipes and the heat loss calculated by the interpretation model. There is a good agreement when the surface is dry but a lower TX value when the surface is wet. The transient situation when the surface is drying can also be seen in the figure. We have therefore studied the situation with wet and drying surfaces by computer simulations.

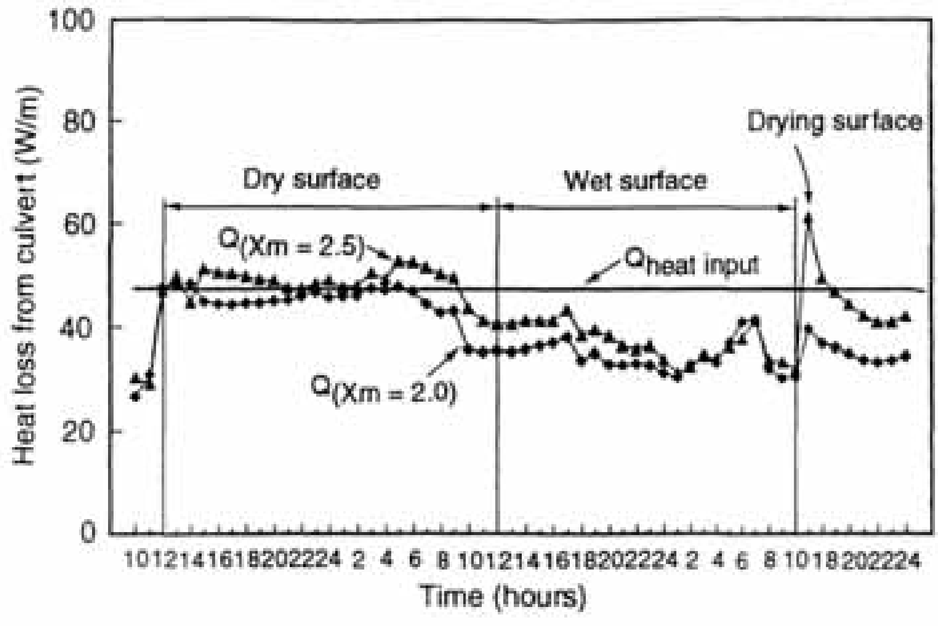


Figure 8.9. Measurements of the heat loss at Studsvik's test field with wet and dry surface.

In the computer simulations, the surface becomes wetted by rain during certain nights. When rain occurs, it is assumed that 1 mm water remains at the ground surface. This water is then evaporated in the morning due to wind and solar radiation as described in Section 4.2. Figure 8.10 shows the development of the water layer at the surface for successive hours in the morning. The accelerated disappearence of the layer just above the district heating pipes is caused by augmented evaporation due to higher driving temperature above the pipes.

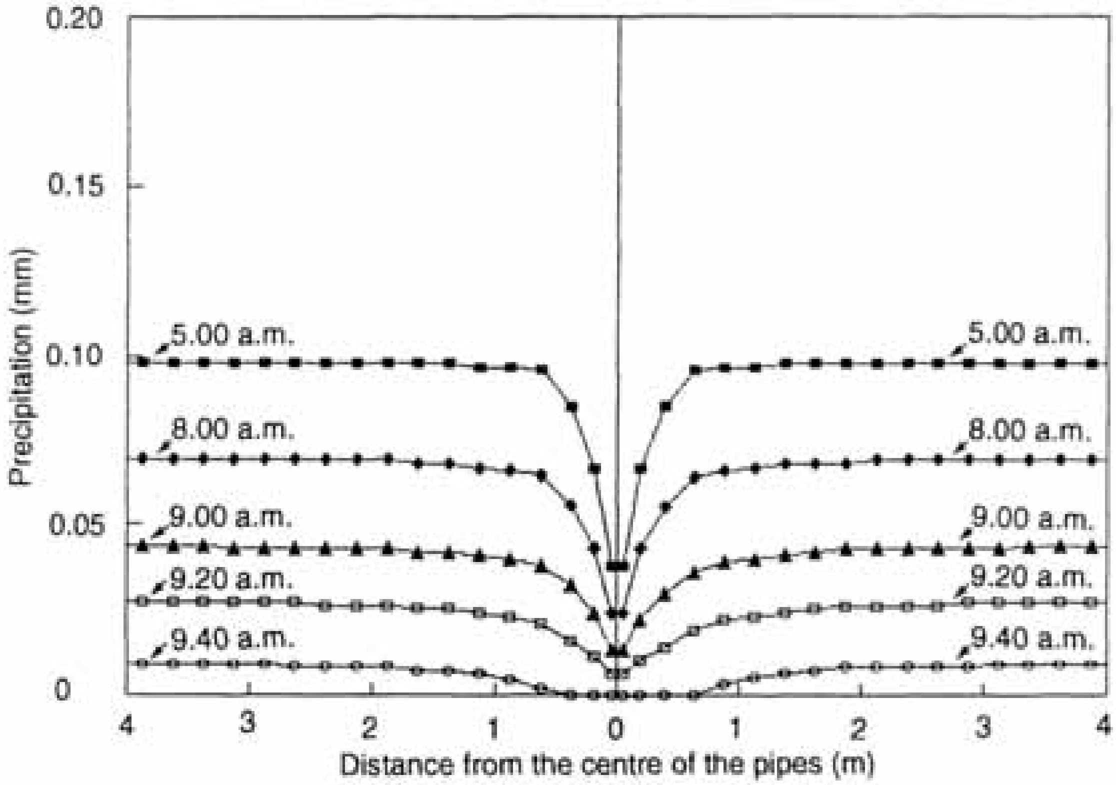


Figure 8.10. The thickness of the water layer during the evaporation process in the morning.

The transient behaviour of the TX factor under the drying process can easily be seen from the simulations summarized in Figure 8.11. The lower level of the TX factor when the surface is uniformly wet and the reduction of the TX factor during the drying process from 9.00 a.m. onwards are both caused by the fact that the evaporation process cools the ground surface.

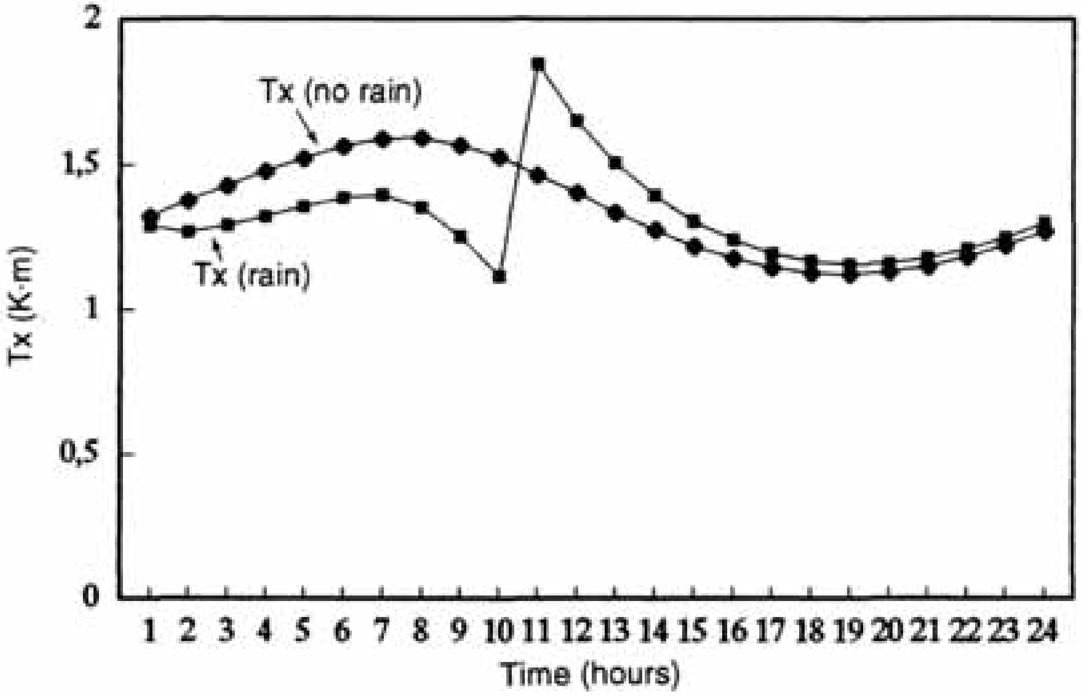


Figure 8.11. The TX factor during a day with and without rain in the night.

The increase of the TX factor in Figure 8.11 when the surface is drying is further explained by Figure 8.12, which shows both temperature profiles and the thickness of the wet layer. The temperature increases at the dry part of the surface, but as long as the outer parts of the area included in the TX factor calculation are wet, the TX factor will remain higher than if the whole surface were dry. The drying process can be easily seen under field conditions, as illustrated in Figure 8.13 from Studsviks test site. The surface reflectance differs for wet and dry areas and hence the dry part above the experimental pipes is visualized.

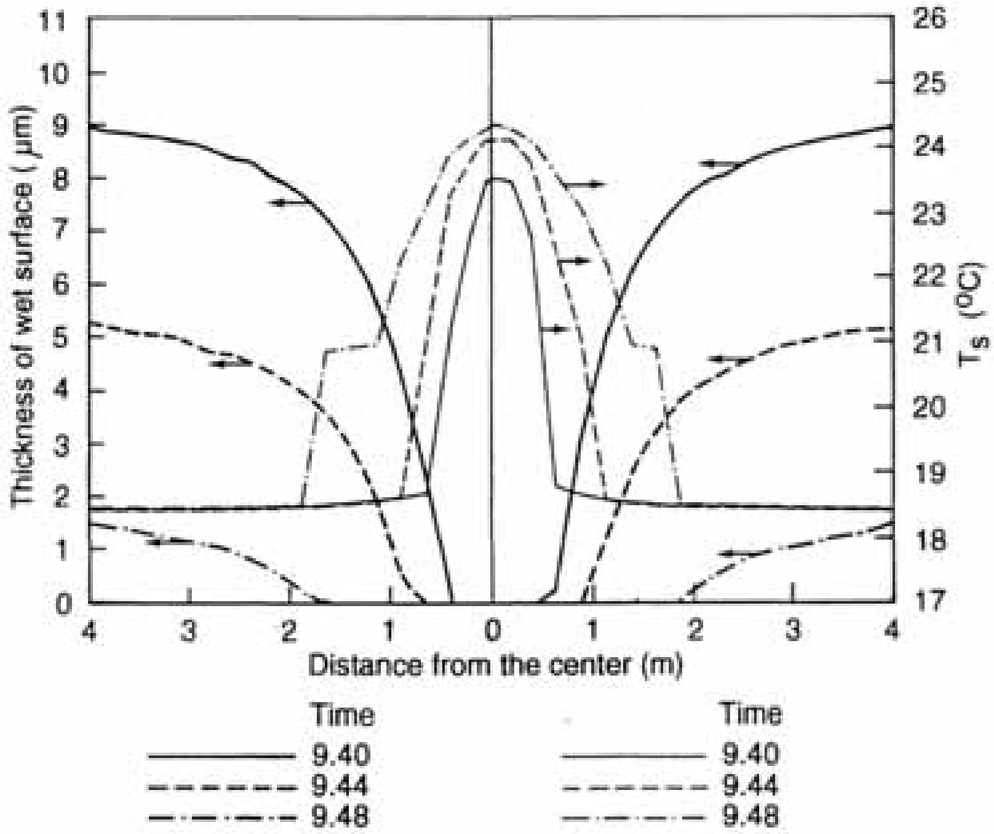


Figure 8.12. Temperature profiles and the layer of water at the surface at 3 different consecutive times.

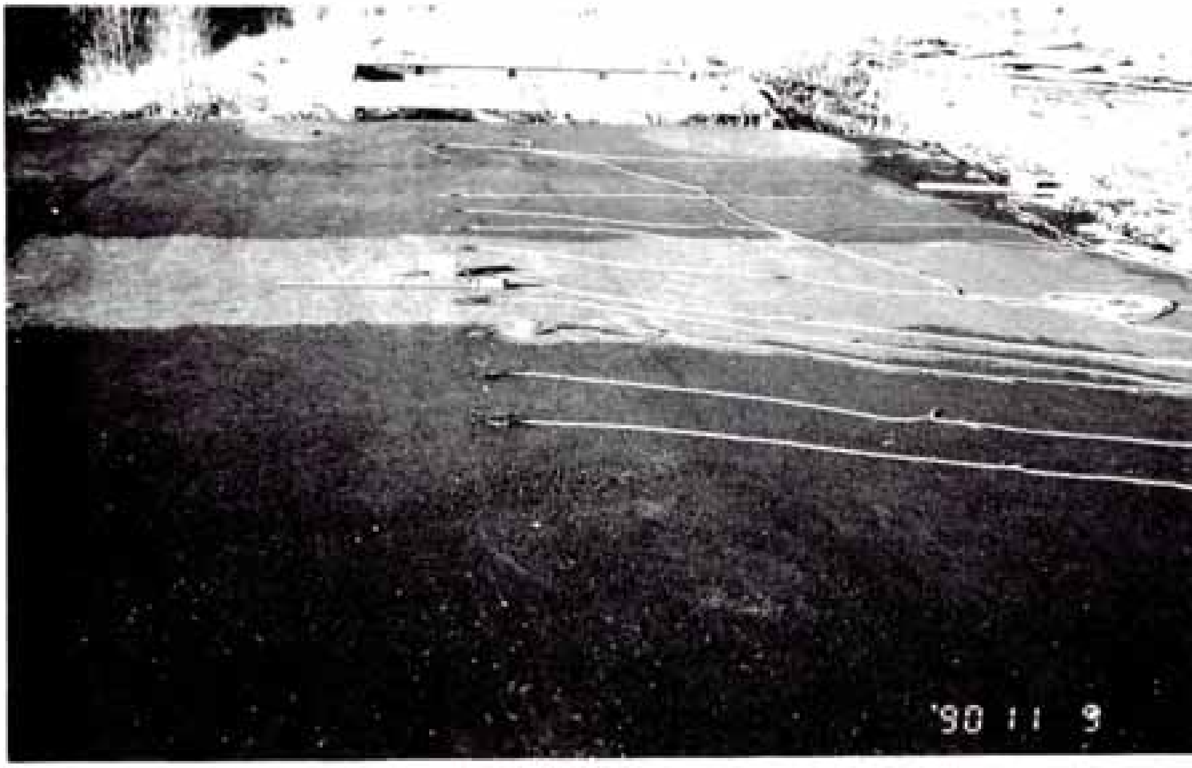


Figure 8.13. Studsviks test field when the surface is drying.

The measurements at the test field when the surface is wet show that there is a profile even in this case, but with a lower level compared to a dry surface. Figure 8.14 shows temperature profiles for wet surfaces. The TX factor is about 2 K·m for these profiles. When the surface is dry, the TX factor should instead be 4 – 5 K·m for the corresponding heat loss.

The change in the TX factor from about 4 – 5 to about 2 K·m when the surface is wet does not correspond to the computer simulations in Figure 8.11, where the TX factor decreases only about 20 % when the surface is wet. This reflects the uncertainy when interpreting temperature profiles of wet surfaces, probably due to missing information about the amount of humidity stored in the ground.

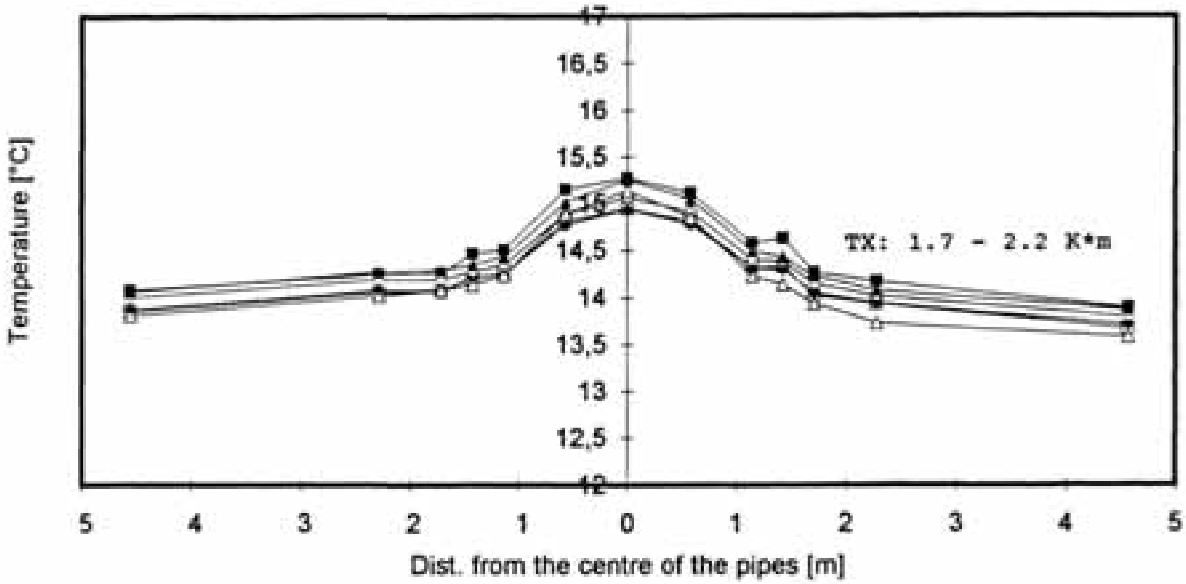


Figure 8.14. Temperature profiles from the test field when the surface is wet.

9 CONCLUSIONS

- The model for *quantitative termography analyses* has shown to enlarge the range of applicability compared with conventional thermography evaluation. Under ideal conditions the heat loss from district heating pipes can be analysed within an accuracy of ± 10%.

- The *interpretation model* was applied in a field experiment in Västerås showing its usefulness in the further analysis of questionable sections as detected in the course of a general thermography survey.

- The interpretation model needs an input value of the *trench depth* with a higher accuracy than often available from drawings. In this case the use of electronic sensor techniques for pipe detections might be a possibility.

- The *thermal conductivity of the soil* has – in contrast to a common opinion – only a relative *small influence* on the heat loss.

- The *ground must be dry*, otherwise evaporation of water on the ground will affect the temperature profile. However, well wetted surfaces can, under some circumstances, also be used for qualitative evaluation of the pipe standard.

- A *drying surface* will cause misleading results due to latent heat transport.

- *Thermography during exposure to long wave and solar radiation is possible* if the surface is uniformly exposed to the radiation and if it has a homogeneous emissivity within the surface area to be analysed.

- The prevailing *wind conditions* affects the temperature profile for several hours. This effect can be included in the interpretation model with further analysis.

- *The TX factor measured at a certain moment represents the insulation status (and temperature condition) from a period starting about one week prior*. Hence, changes in the insulation status which are more recent than this, can not be correctly analysed. Similiar, if the distribution temperature changed drastically within the preceding week or so, one must be careful in interpreting the thermography results.

- The interpretation model can also be used with high accuracy for *steam distribution systems*. Its higher temperature level compared to hot water distribution systems facilitates the evaluation of the thermography picture.

- It is *difficult to quantify the heat gain in district cooling applications* by means of quantitative thermography analysis due to the small temperature differences at the ground surface.

- Quantitative thermography analysis can be used for *leakage detection in district cooling systems*. However, the process of leaking water soaking the ground must be further analysed.

10 REFERENCE LIST

1 BARTSCH, D
Search for Leaks in District Heating Systems
(Fernvärmeversorgung Niederrhein, Dinslagen, Germany)
Fernvärme Int, Feb 1979
ISSN: 0340-2572

2 LJUNGBERG, S. Å.
Termografering av fjärrvärmenät, Västeråsprojektet, en metodstudie.
(Thermography of District Heating Networks, the Västerås project, a method study).
Värmeverksföreningen och Statens Institut för Byggnadsforkning, Dec 1987.

3 HANSEN, K-E
Fjernvarme 32. Termografering av fjernvarmeledninger
(District heating 32. Thermography of district heating culverts).
Danske fjernvarmevaerkers forening, April 1987.

4 PERERS, B, SCHMELING, P
Bestämning av värmeförluster i fjärrvärmenät med termografi.
Simuleringsmodell för noggrannare bildanalys.
(Determination of heat leaks in District Heating Systems by means of thermography).
Studsvik AB, Sweden 1989. Studsvik/ED-89/5

5 PERERS, B, JÖNSSON, B
Värmeförluster i fjärrvärmenät med termografi.
(Heat loss measurements in district heating networks by means of thermography).
Studsvik AB, Sweden 1990. Studsvik/ED-90/28

6 JARFELT, U
Chalmers University of Technology, Sweden.
(Internal communication, December 1990)

7 BIGL, S R, HENRY, K S, and ARCONE S A
Dedection of buried utlities.
Review of available methods and comparative field study
CRREL Report 84–31, Dec 1984

8 SJÖBERG, P
Anävndarmanual för Kulvertförlust – Simuleringsprogram.
(User manual for a program for the simulation of pipe losses, part of master thesis).
University Västerås, October 1988.

9 BøHM, B
Enkle metoder til bestemmelse af varmetab fra fjernvarmeledninger under normal drift (Simple methods for evaluation of heat losses of district heating pipes under normal operation).
Laboratoriet for Varme- og Klimateknik, Danmarks Tekniske Højskole
July 1990.

APPENDIX 1.1

There are different ways for the analysis of the simulation results which relate the TX factor and the overall heat losses. One would be to find the physically most significant analytical model, another to use a mathematically more straight forward approach by developing a power series. We have chosen the latter one for the reason of simplicity and the possibility to include the time derivative of the distribution temperature in a simple manner.

In a comment to our results Benny Bøhm showed that the general findings are consistent with our approach. He showed that the heat flux q from a single, buried pipe can, according to ref.[9], be found as following:

$$q = \frac{2\pi \cdot \lambda_s \cdot \triangle T_s}{\ln(1 + 2/(\alpha \cdot h_f))} \approx (\pi \cdot \alpha \cdot h_f) \cdot \triangle T_s \qquad [W/m]$$

$\triangle T_s$ = temperature difference between ground surface and pipe surface.

This simple analysis of the pipe heat loss means that

- the pipe depth h_f is important as well as the heat transfer coefficient α which includes also the wind speed.
- the thermal conductivity of the soil λ_s is not included in the simple solution which means that it is not expected to have strong influence on the heat loss.

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