Project B

The Effect of Surfactants on Domestic Heat Exchangers for Hot Water Supply and Heat Flow Meters in D/H Systems

EV-1670

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1. Introduction

In the electricity supply system in the Netherlands, combined heat and power generation is becoming increasingly important. More and more units are decentralized, and this creates new opportunities for district heating.

An important feature of district heating systems is that the heat needs to be transported over relatively long distances. Research has been under way for many years now, especially in Germany, the U.S.A. and Canada, to develop suitable additives for reducing friction losses in pipelines.

These efforts have been successful in that additives are now available that reduce friction losses by up to 70 %.

The amount of friction in the transport system dictates the pipe diameters and the pump power the be installed for heat circulation. The pipelines and the pumps, together with the pump energy, form a major cost item and any reduction achieved here will add to the profitability of district heating. In existing systems, the use of suitable additives allows the flow rate, and so the maximum load, to be increased without any further investment. In addition, such additives can reduce pump losses.

The International Energy Agency (IEA) coordinates an international research and development programme aimed at developing improved additives. It has assigned NOVEM to act as operating agent for the Netherlands.

Habon-G is an additive specially designed for use in the water mains of district heating systems. Since Habon-G reduces turbulence, it reduces not only friction losses but also the heat transfer. These effects can only determined through experiment, as no models are as yet available for theoretical determination. Up until now, only the effect of Habon-G on friction losses and heat transfer has been assessed in large industrial systems and in demonstration projects.

Extensive fundamental research into the effects of additives has been carried out in a doctoral research project at the University of Dortmund, Germany [1]. Chapter 2 of this report is largely based on the results of that project.

Going on where the German work leaves off, the present investigation aims to assess the performance of Habon-G, through measurements, in small district heating systems and the heat exchangers and heat flow meters for the domestic water supply in homes. This investigation was ordered by NOVEM.

2. Fluid flow and friction

The flow condition in a pipe is normally described by means of the Reynolds number Re:

$$Re \equiv \frac{v \cdot D}{\nu}. \qquad \text{eq. (2.1)}$$

Depending on the value of Re, the flow is either laminar or turbulent. If conditions in the entry flow region are ignored, a laminar flow is characterized by the absence of fluid exchange perpendicularly to the direction of flow. Turbulence, on the other hand, is characterized by complete mixing in the fluid flow, with the velocity varying in both magnitude and direction. The occurrence of eddies is another remarkable feature.

The resistance to flow in a pipe can be expressed as the pressure difference per unit pipe length using the dimensionless friction factor ξ

$$\xi \equiv \Delta p \cdot \frac{2 \cdot D}{L \cdot \rho \cdot v^2}. \qquad \text{eq. (2.2)}$$

For laminar flow, at Reynolds numbers not exceeding 2320, the friction factor is independent of the roughness of the pipe wall and equals:

$$\xi = \frac{64}{Re}. \qquad \text{eq. (2.3)}$$

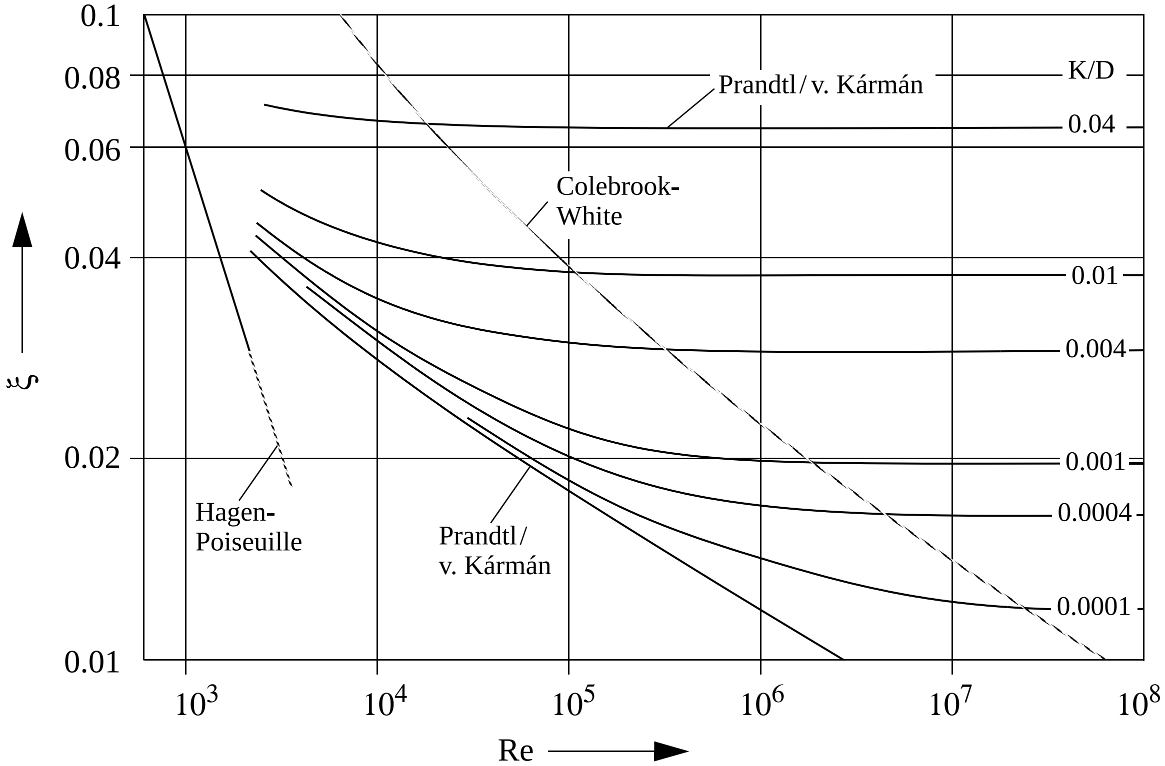


Fig. 2.1: Friction factor for hydraulically smooth and technically rough pipes

At high Reynolds numbers the flow is turbulent, in which case it is no longer possible to theoretically determine the friction factor. If the flow passes the transition region between laminar and turbulent, the friction factor obeys the following formula, which was derived by Prandtl and improved by Nikuradse through experiment. This formula is valid only for smooth pipe walls.

$$\frac{1}{\sqrt{\xi}} = 2 \cdot \log(Re \cdot \sqrt{\xi}) - 0.8 \; . \qquad \text{eq. (2.4)}$$

Both formulas are graphically represented in **figure 2.1**.

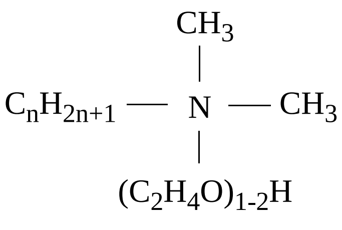
2.1 Possible additives

For many years now, efforts have been made to reduce friction losses in pipelines. Apart from using smooth-wall pipes, two options are available, i.e. wall dampening and the use of additives.

In wall dampening, the pipe is lined with either a smooth, elastic and dampening coating or a highly elastic liner.

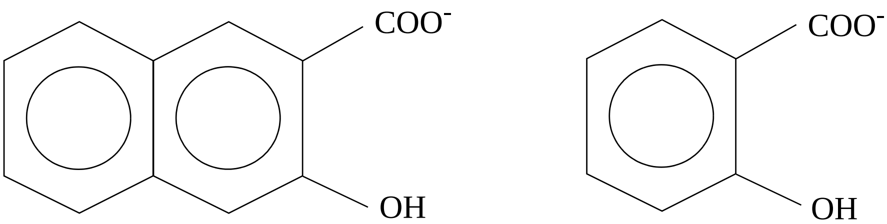
A wide variety of products, mostly polymer-based, are available or under development for reducing the friction losses. Polymers, however, because of their high thermal sensitivity, generally are less suitable for use in district heating systems.

Another class of additive are surfactants. These are surfactants, such as soap, with a relatively low molecular weight. Under certain conditions, surfactants form micelles (small clusters) that have a friction-reducing effect. They differ from polymers in that the micelles, but not the surfactants, degrade under heavy mechanical loads. This degradation mechanism is reversible - the micelles are restored on relief of the load.



n = 16: Habon-G
n = 18: Obon-G
n = 22: Dobon-G

n-Alcyldimethylpolyoxethylammonium-Cations



3-hydroxy-2-naphthoate and Salicylate

Fig. 2.2: Chemical structure of surfactants

A number of surfactants developed under the auspices of IEA exhibit increased corrosiveness to metals, for which reason they are less suitable. Three surfactants developed by Hoechst AG neither exhibit such corrosiveness nor degrade to any appreciable extent.

These three surfactants (Habon, Obon, Dobon) were specially developed by Hoechst for district heating service. They have different temperature ranges and, so, different areas of application. Depending on their chemical structure, the upper limit of the temperature range is between 90 and 140 °C at flow velocities up to about 4 m/s. The temperature range of Habon extends to 95 °C. Accordingly, for the purposes of the present investigation, Habon would seem to be most suitable.

The Hoechst surfactants are surfactants comprising a hydrophilic head and a hydrophobic tail consisting of carbon chains. Their chemical structure is shown in **figure 2.2**.

Friction losses are reduced by preventing turbulent flow from occurring. In this way, friction loss can be reduced by about 80 %. As well as friction loss, the heat transfer is reduced also. Both effects are advantageous in district heating systems except that a lower heat transfer is a disadvantage for the heat exchangers included in such systems.

2.2 Operating principle of Habon

A turbulent flow can be broken down into a laminar boundary layer, an intermediate buffer layer and a turbulent main stream flow. The laminar layer is adjacent to the wall and is very thin. It is followed by the buffer layer, where most of the irreversible energy dissipation takes place as a result of the vehement exchange of impulses. The layer at the centre, the turbulent main stream flow, is characterised by strong eddies but accounts for only a small portion of the overall energy dissipation.

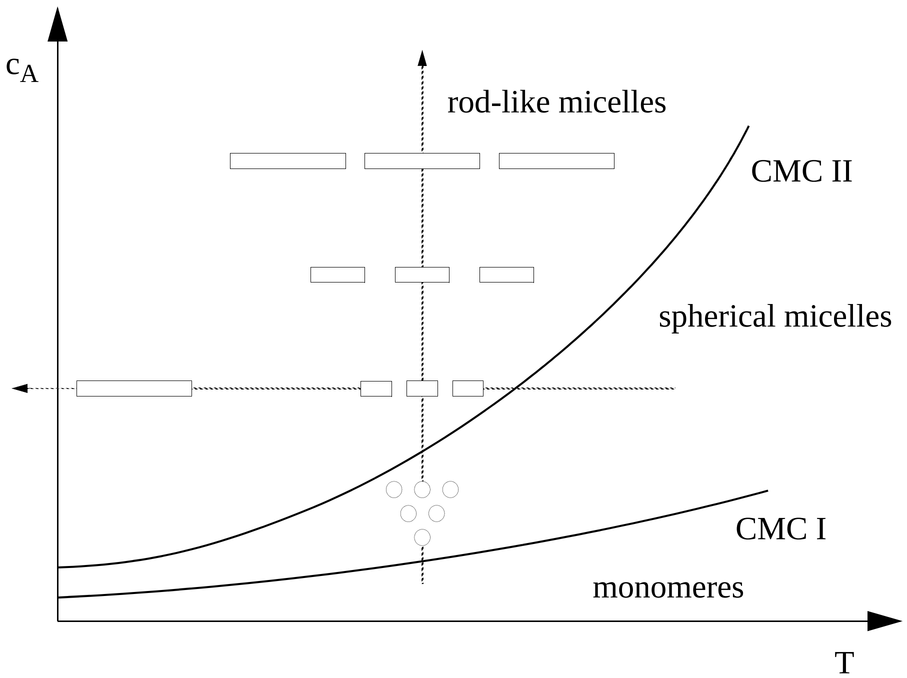


Fig. 2.3: Critical micelle concentrations I and II

The friction-reducing effect of surfactants in aqueous solutions depends on the formation and the shape of micelles. Micelles are clusters of surfactant molecules, which can take any of a variety of shapes, such as spheres, bars or disks. Their hydrophilic heads form the boundary layer relative to the water whilst the tails combine to fill the micelle volume. Bar-shaped micelles should be used for reducing the friction loss.

If a given concentration is exceeded, the critical micelle concentration (CMC_I), the surfactants will form spherical micelles. This concentration is hardly temperature-dependent. If the concentration is increased still further, the number of surfactant molecules per micelle will increase until the micelle volume is completely filled with carbon chains. When another critical concentration (CMC_{II}) is exceeded, some surfactants, including Habon, produce other micelle shapes, such as bars, because these boundary faces are more favourable energy-wise. The CMC_I concentration is strongly temperature dependent (see **figure 2.3**).

Surfactant solutions that form spherical micelles behave in the same way as the solvent, in this case water, even at high concentrations and the viscosity becomes somewhat higher than that of the water.

At Habon concentrations that are only little higher than CMC_{II}, the surfactant solutions in which bar-shaped micelles have formed exhibit a favourable viscoelastic behaviour. Such cells become oriented by the pulse loads of turbulent flow and form a viscoelastic network which expands the buffer layer and reduces the layer of the turbulent main stream flow (**figure 2.4**).

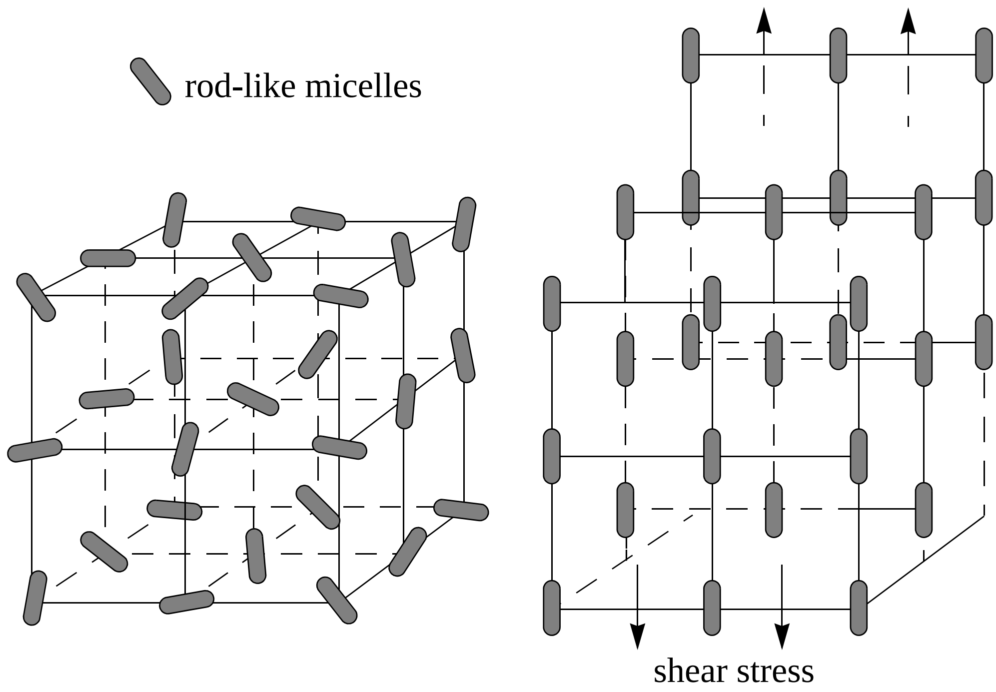


Fig. 2.4: Viscoelastic network, shear induced structure

2.3 Operating range of surfactants

At the maximum reduction in friction loss that can be attained with polymers or surfactants - in other words, when the laminar buffer layer extends to the centre of the flow - the friction factor may be determined using Virk's equation [1]:

$$\frac{1}{\sqrt{\xi}} = -16.2 + 9.5 \cdot \log\left(\frac{Re \cdot \sqrt{\xi}}{2}\right). \qquad \text{eq. (2.5)}$$

If the flow is within the operating range of the surfactant, the friction loss of the (aqueous) surfactant solution is almost independent of temperature and concentration. In that case, the friction loss of a solution of Habon in water approaches this theoretical minimum resistance according to Virk's equation. This flow condition is also known as pseudolaminar flow. The figure below shows the range in which the friction factor may vary on addition of Habon. The possible behaviour of such a fluid is given by way of example.

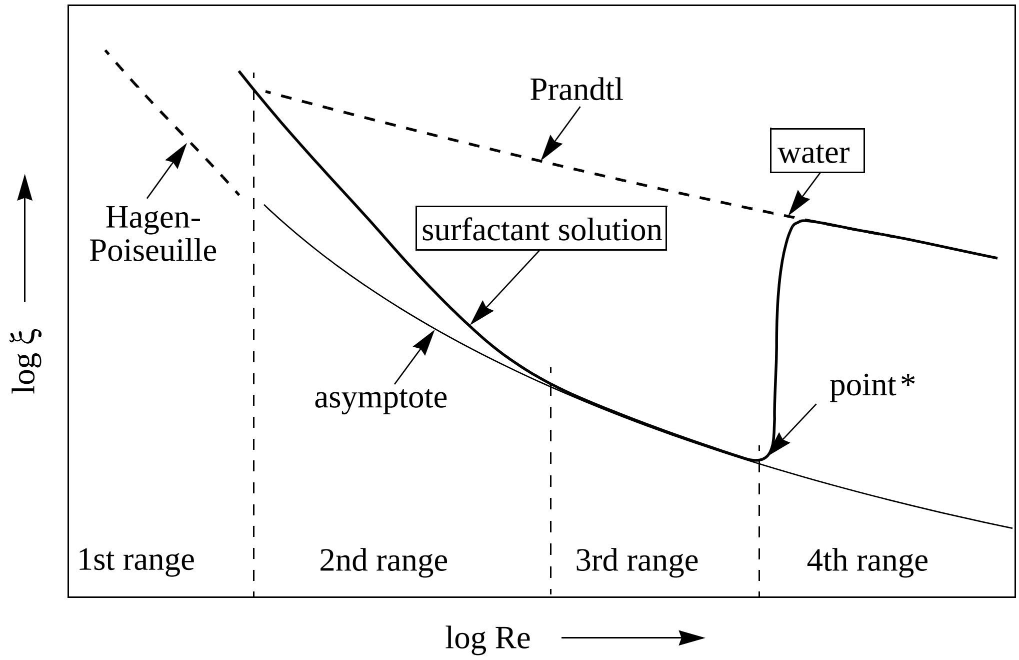


Fig. 2.5: Behaviour of a surfactant solution

Both the upper limit and the lower limit are dependent on the Habon concentration, the temperature, the flow velocity and the geometry.

2.3.1 Lower limit of operating range

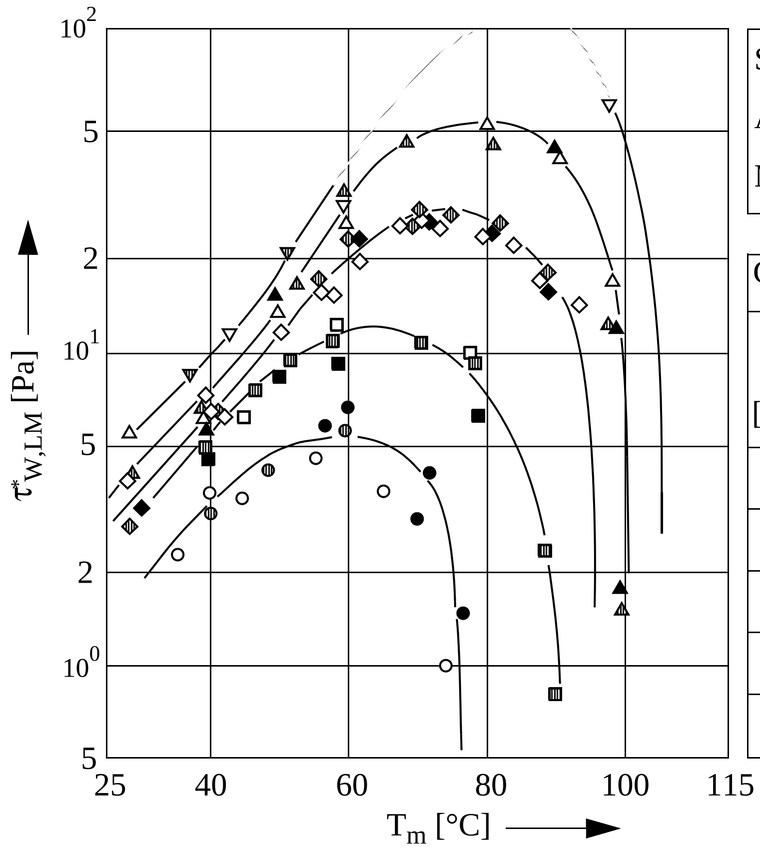
First of all, if bar-shaped micelles are to be produced, it is necessary that a certain limit concentration, CMC_{II}, be exceeded. The flow will not be completely viscous but rather slightly viscoelastic. This viscoelasticity ensures that the bar-shaped micelles will become oriented on exposure to pulse loads. When the Reynolds number is increased, the pulse load from turbulence will become so high as to cause the bar-shaped micelles to form permanently oriented networks. These dampen the turbulence and eventually prevent the main stream flow.

If the concentration is only just above CMC_{II}, only few, relatively large micelles will be formed. These are not well capable of forming an oriented network, which is why their friction-reducing effect is only small.

2.3.2 Upper limit of operating range

The networks are destroyed when a given flow velocity and temperature are exceeded. The upper limit is determined by the mechanical load resulting from friction. These frictional forces exert a shear stress on the networks. When the maximum shear stress of the networks is exceeded they disappear and the flow becomes viscous again.

The maximum shear stress is a function of the temperature and the concentration.



Solvent: demin. water, pH 7

Additive: Habon

Method of operation: isothermal

Course of $\tau^*_{W,LM}$ (T_m)			
c_A [wppm]	Symbol D_i [mm]		
	8	15	25
62,5	○	◍	●
125	□	▥	■
250	◇	◈	◆
500	△	◬	▲
1000	▽	⛛	▼

Fig. 2.6: Critical shear stress as a function of temperature

It is also possible that on a temperature rise, CMC_{II} rises to exceed the concentration used. When that happens the bar-shaped micelles are replaced by spherical ones and the flow turns viscous again.

2.4 Effects of temperature and concentration

To each flow velocity belongs a lower temperature limit at which the solution begins to be effective. It has been shown that the upper temperature limit is dependent on the micelle concentration CMC_{II} and that the effectiveness of Habon rapidly diminishes above this temperature limit.

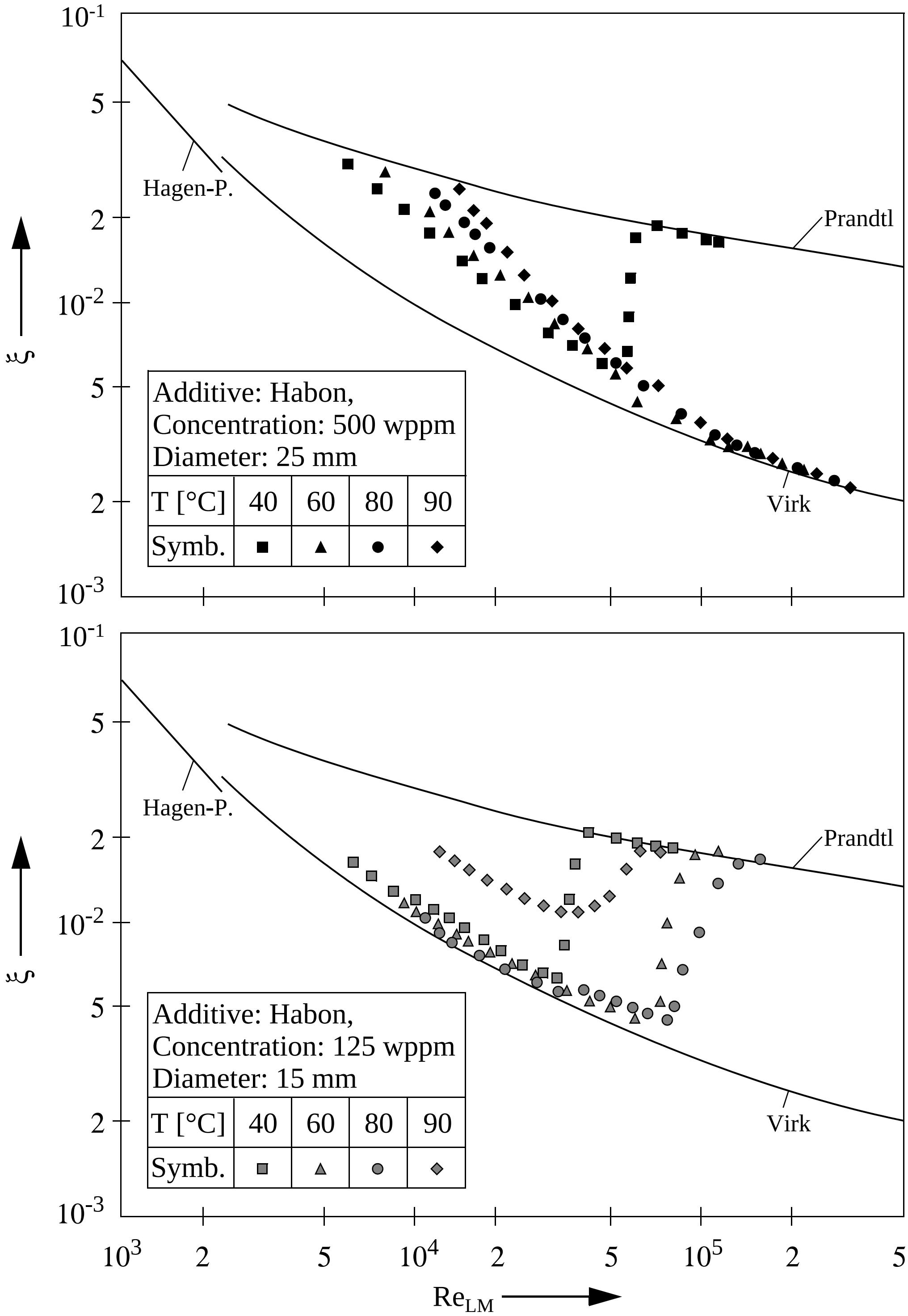


Fig. 2.7: Effect of temperature on flow behaviour

The length of bar-shaped micelles increases, but their number decreases, with decreasing temperature. When the lower temperature limit is exceeded, the solution is no longer able to build a proper micelle structure from the few large micelles that are available, so that the friction-reducing effect ceases. When the velocity, and, so, the mechanical load, is increased the lower temperature limit becomes higher and the upper temperature limit becomes lower.

Figure 2.7 shows how the micelle structure, and so the friction-reducing effect, eventually collapses under the mechanical load.

When the temperature is increased the upper limit rises from the operating range to a maximum value. When the temperature is increased still further the upper limit drops to a lower value. At the same time, the friction-reducing effect diminishes, that is, the flow changes from pseudolaminar to attenuated turbulent.

As the figure shows, at low flow loads and high Habon concentrations, an increase in temperature causes the effectiveness in the attenuated turbulent flow range to diminish. Eventually, pseudolaminar flow is attained at higher Reynolds numbers, with significantly lower friction (**figure 2.8**).

An increase in concentration ensures that formation of the effective micelle structure remains possible, so extending the operating range.

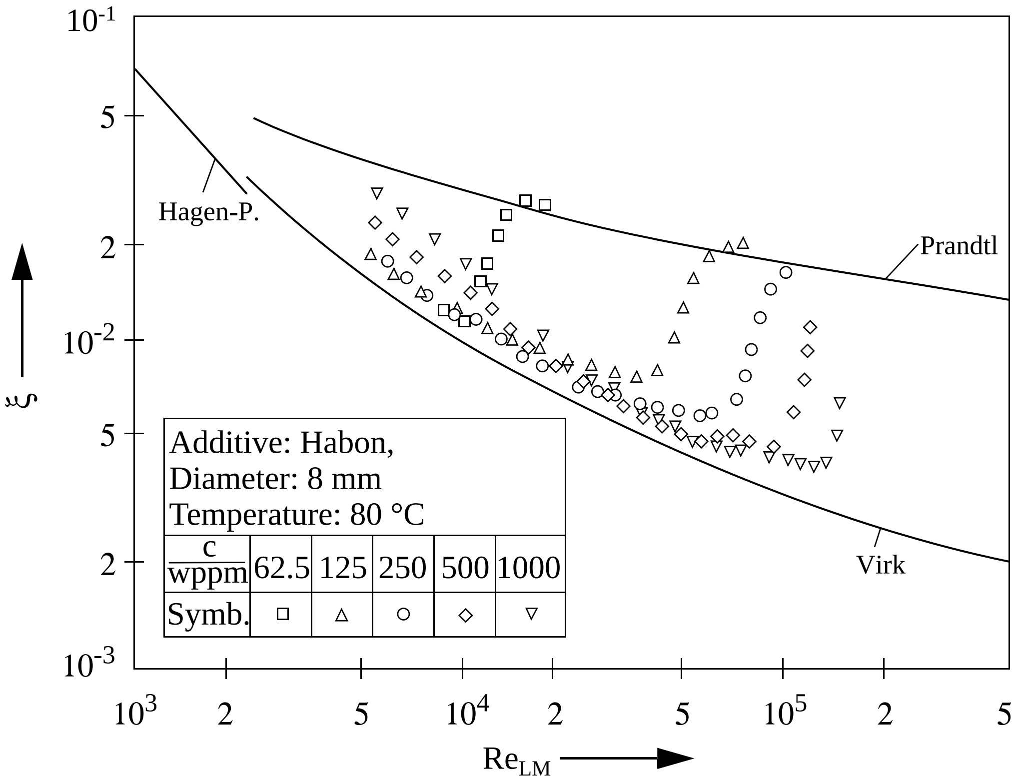


Fig. 2.8: Effect of Habon concentration on flow behaviour

2.5 Effects of hydraulic diameter and flow velocity

The Reynolds number is not a suitable means of designating the mechanical limit load. All other conditions being equal, different critical Reynolds numbers are found for different hydraulic diameters (whereupon the flow becomes turbulent again).

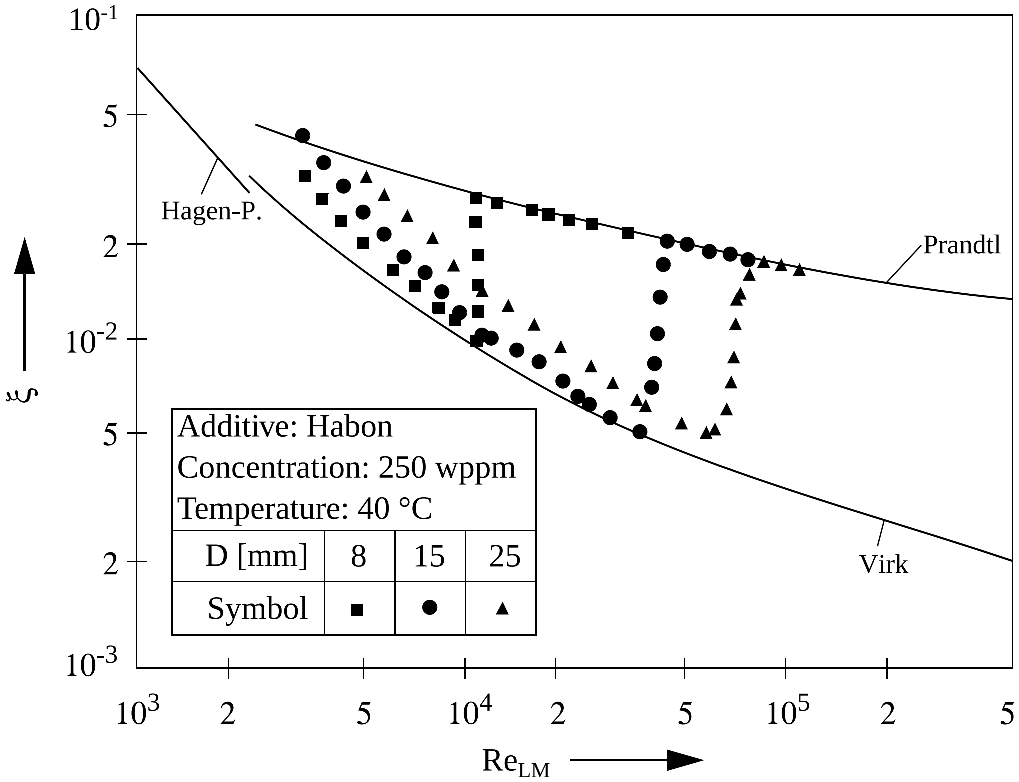


Fig. 2.9: Effect of pipe diameter on flow behaviour

The critical Reynolds number increases with increasing hydraulic diameter. At the same time, at lower flow velocities (within the attenuated turbulence area), the turbulence-dampening effect decreases with increasing hydraulic diameter.

2.6 Effect of wall shear stress

In the earlier investigation it was found that the wall shear stress can be used for determining the turning point to designate the thermal and mechanical load limits. **Figure 2.10** shows the wall shear stresses for the three friction curves indicated in **figure 2.9** as a function of the Reynolds number.

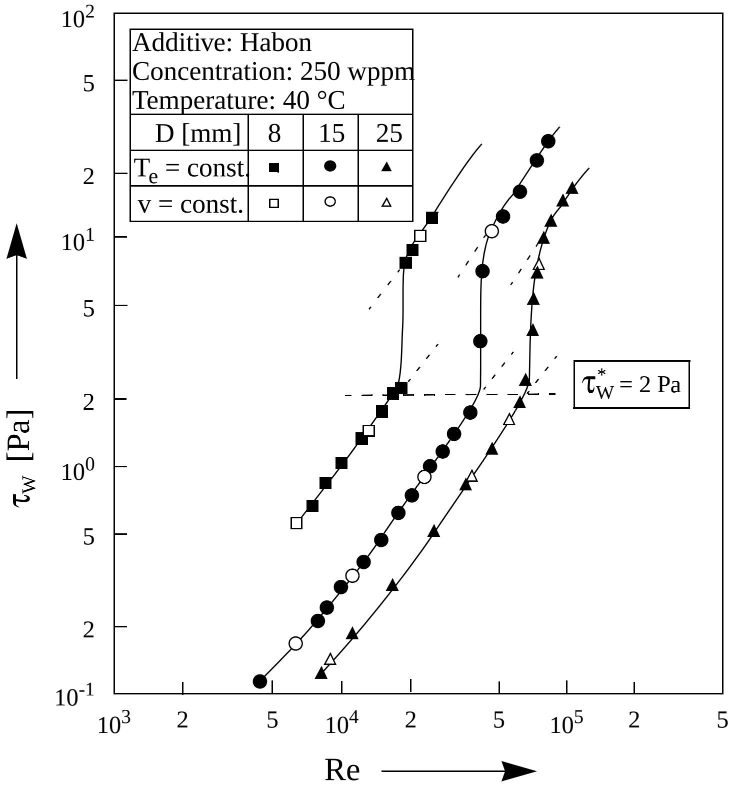


Fig. 2.10: Wall shear stress vs Reynolds number

The turning point can be identified as a sudden change in shear stress. Both the limit shear stress and the turning point are about the same for all pipe diameters.

2.7 Outlook for present investigation

In the light of the theoretical backgrounds described in the preceding sections an attempt may be made to predict some results. The heat exchangers under test are relatively small in diameter and contain many tube bends. Thus, the internal friction and the flow velocity will be large. Also, the Reynolds number will be high, with completely turbulent flow.

If the internal diameter is known, it is possible to determine with [1] what concentration of Habon G needs to be added in order to change the flow regime in a heat exchanger from turbulent to pseudolaminar. It is also possible, then, to predict by calculation the reduction in friction loss and in heat transfer (see Appendix A).

The following should be noted here.

1. The investigation referred to in [1] largely dealt with isothermal flow whilst the present investigation deals with flow regimes involving a radial and an axial temperature gradient. The radial temperature gradient is especially important in as much as the effective bar-shaped micelles need to be built up from the wall if they want to have any friction-reducing effect. The effect of such a gradient is unknown but may be significant.
2. Some of the measurements in [1] were made on bench-scale systems with all flows fully developed and the hydraulic entry effect specially eliminated in the interest of accuracy. Others were made on district heating systems some kilometers long, which presumably were designed and constructed in such a way as to minimize the entry effect. The present investigation covers four small and compact heat exchangers with thin-wall tubes and a large number of bends. In such heat exchangers, the hydraulic entry effect has a major impact.
   This being so, it will probably be necessary to add more Habon-G than the calculations in Appendix A suggest in order for pseudolaminar flow to develop within the heat exchangers.

3. Description of test facility

As far as their heat demand is concerned, district heating systems are dependent on weather conditions and the user's need for comfort. This dependence generally changes with the seasons and is manifested by varying water temperatures. In the present investigation, this variation has been compensated for by assuming two particular temperatures that are representative of summer and winter conditions.

The domestic water supply must always be as hot as the user pleases, regardless of the season. The lower temperature limit should be high enough to kill bacteria and dissolve fat whilst the upper temperature limit should not cause excessive scaling or skin burns. In practice, this is accomplished by varying the flow rate of the system water.

In the present investigation, the flow rates of both the domestic water supply and the transport lines in the district heating system were varied in a realistic way.

This is because flow rate variations over as wide as practicable a range yield more results from which to determine the effectiveness of Habon-G.

Domestic water supplies operating in conjunction with a district heating system must meet the following requirements:

- The temperature of the domestic water supply should be between 50 and 60 °C.
- At a flow rate of 5 l/min and an inlet temperature of 10 °C, the domestic water must be able to be heated at least 45 K.
- The return temperature of the system water must be as low as possible, certainly lower than 50 °C.

Given the wide variations in the flow rates of both the domestic water supply and the system water, these requirements have been ignored in the measurements, but they are taken account of in interpreting the measuring results.

The heat exchangers used for domestic water supply come in all sorts of design and are supplied by many different vendors. The same applies to the heat flow meters. Therefore, in consultation with NOVEM, four heat exchangers and heat flow meters of different design were chosen. The vendors are felt to be immaterial and no further details of them are given here.

In order to be able to assess the effect of adding Habon-G, a reference measurement (without addition to the system water) was carried before and after the Habon-G measurements.

An essential parameter, apart from temperature and flow rate, is the concentration of Habon-G. Earlier work [1][2][4] has shown that the effects of Habon-G depend on many factors such as the size and shape of the heat exchanger, temperatures and flow rates. Theoretical considerations cannot be made without making a large number of assumptions and simplifications. As opposed to the other three heat exchangers, the internal dimensions of unit C were known, so enabling broad theoretical calculations (Appendix A). From those calculations and the results of earlier work, a concentration range for Habon-G of 100 -1000 wppm (eight parts per million) was chosen.

3.1 Automatic control

In keeping with general laboratory practice and given the large number of measurements that had to be taken, the test facility was automated wherever practicable. Instruments with analogue 4 - 20 mA inputs and outputs were used where appropriate and linked to a process computer. For data acquisition, the methods of data storage and processing available in the laboratory were opted for.

As a result of these departure points, the inlet temperature of the primary system, the primary flow rate and the secondary flow rate were controlled by a programmable logical controller. A PC was used for controlling the PLC, for sampling the points of measurement and for data acquisition.

3.2 Test circuit

A facility was assembled at the Technical University of Delft enabling the domestic water supply with heat input from a district heating system to be simulated. The flow diagram is shown below. Further details and a photo are given in Appendix B.

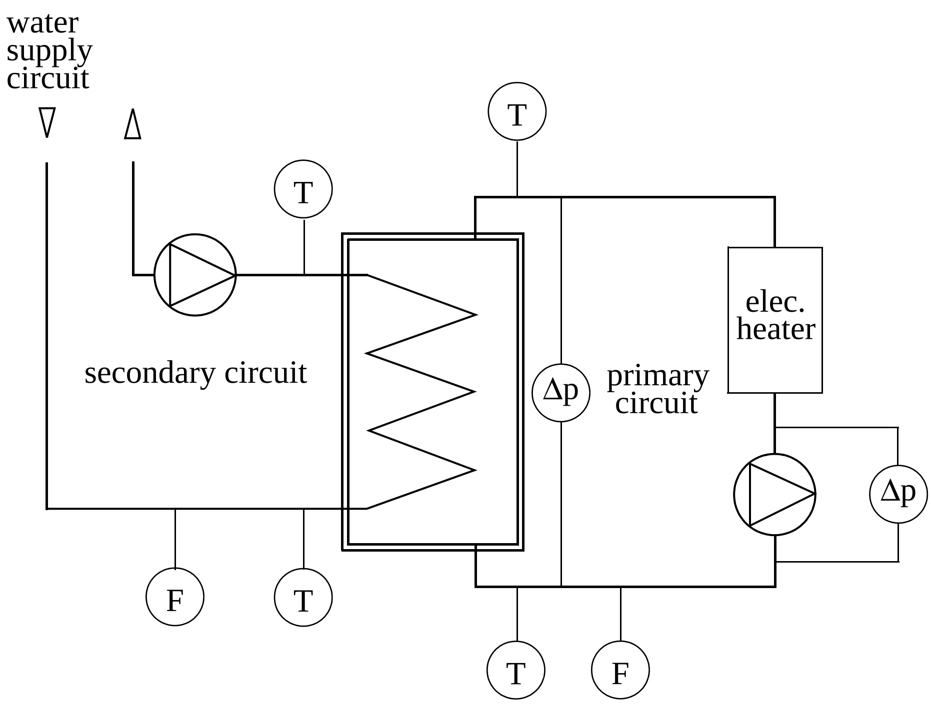


Fig. 3.1: Flow diagram of test circuit

The heat exchangers are connected to headers having a larger diameter than the mains. This makes it easier to connect or replace any number of heat exchangers and reduces the number of instruments needed. The temperature in, and the pressure difference between, the headers are representative of all heat exchangers inserted between them. Thus, only one thermometer and differential pressure gauge were needed.

The primary circuit (the district heating section) includes an electric heater rated 20 kW, used for heating the system water, a pneumatic control valve for adjusting the primary flow rate, a circulation pump, a flow meter, two Pt 100 temperature elements (one being placed upstream of the inlet and the other downstream of the outlet of the heat exchanger) a pressure vessel and an automatic vent valve.

The primary circuit was 10.9 m long, with a capacity of 50 litres. An array of ball valves allowed any one of the four heat exchangers and any one of the four flow meters to be inserted into the circuit. A differential pressure gauge was installed across the pump and the two headers in the primary circuit.

A fill vessel was connected to the primary circuit via ball valves. This was used for adding Habon-G and for pressurizing the primary circuit with nitrogen.

Water was fed to the secondary circuit (the domestic water supply section) from a closed booster system with a capacity of 50 m^3. The secondary system included a flow meter, two Pt-100 elements, a pneumatic control valve and a hand-operated vent valve.

The primary and secondary circuits, the heat exchangers and the heater were lagged to standards normally applied in the industry [5].

3.2.1 Heat exchangers

Four counter-current heat exchangers could be inserted into the primary circuit:

- Heat exchanger A was a compact, single-wall plate-type heat exchanger. The manufacturer's specifications indicated that the maximum hot-water capacity was 5 l/min. The header-to-header length was 1.15 m.
- Heat exchanger B was of a helix-shaped, multiple double-pipe design with a maximum hot-water capacity of 7 l/min (specified by manufacturer). The header-to-header length was 1.90 m.
- Heat exchanger C was of the spiral double-pipe design with a maximum hot-water capacity of 5 l/min. The header-to-header length was 1.40 m.
- Heat exchanger D was a coiled double-wall plate-type unit with a maximum hot-water capacity of 5 l/min. Its header-to-header length was 1.30 m.

3.2.2 Heat flow meters

The four heat flow meters were arranged in series just downstream of the heater outlet. Each measured the inlet and outlet temperatures with the aid of Pt-100 elements; these were all connected in the same way wherever possible. Each heat flow meter measured the heat content that passed through it. Three meters (A, C and D) gave readings in gigaJoules and one (B) in MWh. In addition, meters A and B showed the total volume passing through them in m^3.

The flow meter of heat flow meter C was of the magnetic-inductive type; those of the other heat flow meters were of the mechanical or mechanical-inductive type.

The percentage error of the heat flow meters depends on the accuracy with which the temperatures and flow rates are measured. In most flow meters the accuracy decreases with decreasing flow, so that the error of the heat flow meter, too, will decrease with decreasing flow.

In the present investigation, no attempt has been made to establish the relation between the flow and the errors, because the heat flow meters indicated the energy levels in too large quantities (MJ or kWh). This would make any such attempt extremely time-consuming.

3.2.3 Habon-G concentration

The Habon-G was supplied by the client as a concentrated liquid. It is viscous at room temperature with poor miscibility with water. As a result, as appeared in a number of preliminary experiments, it is difficult and takes long to prepare a liquid having the desired concentration. Also, Habon-G is known to readily oxidize. Therefore, a closed fill system with a nitrogen connection was added to the system.

3.3 Measuring programme

The measurement setting is dictated by three parameters: the primary inlet temperature, the primary flow rate and the secondary flow rate.

Measurements were conducted at primary inlet temperatures of 70 and 90 °C so as to simulate summer and winter conditions. The two flow rates were varied over as wide as practicable a range: from 4 to 12 l/min on the primary side and from 2 to 8 l/min on the secondary side, both increasing in increments of 2 l/min. These set points yield a measuring programme comprising 40 settings.

The number of attainable settings is limited, however, by the pump capacities on the primary and the secondary side and the power rating of the electric heater. The setting with a secondary flow rate of 8 l/min, for instance, was not always attainable because either the pump power or the heater power was inadequate to maintain the primary inlet temperature with water being withdrawn at that rate. In the end, because of these constraints, a suitable measuring programme was devised comprising 28 different settings.

3.4 Control

The system was to be in equilibrium if correct measuring results were to be obtained. A preliminary study [6] indicated that true equilibrium was made impossible by the noise, which interfered with the setting in various ways. External factors such as the environmental climate, other users of the water supply booster and the stability of the measuring instruments all affected the readings. In order to suppress these effects as much as possible it was decided to control, and take samples from, the system by means of a PLC. A PC operating in tandem with the PLC took care of the controller set points and data storage.

The system exhibited a non-linear behaviour because the heat transfer to the surrounding area and to the secondary system was not proportional to the primary temperature. On changing the set point, it took from 25 minutes to two hours until a fairly stable condition was attained. Control performance was improved by changing the control action (PI or PID) of the controller and entering different control parameters for each heat exchanger and each setting in the measuring programme.

It was decided to adjust the controller once and for all to values believed to be optimum for all four heat exchangers.

3.5 Accuracies

The accuracy of the measurements was limited by two factors:

- The finite accuracy of the measuring instruments and
- Systematic errors.

Given the importance of the measuring accuracy in the present investigation, a number of preliminary studies were carried out. These are discussed below.

3.5.1 Finite accuracy of measuring instruments

The accuracies as specified by the manufacturer are listed in Appendix C. As can be seen, the accuracy of each instrument is equal to or better than 1 % of full-scale deflection. Some experiments were conducted for a more accurate determination of these accuracies:

- **Temperature sensing elements**

  Since the temperature differences across the inlet and outlet of a circuit are much more important here than the temperatures *per se*, a preliminary study [6] was made to assess the relative accuracy of the temperature sensors. This was done by simultaneously submerging the sensors pair by pair in a water-ice bath. The results are given in Appendix C.

- **Flow meters**

  Earlier work [1] had shown that Habon-G has an adverse effect on the accuracy of certain types of flow meter. Flow meters of the magnetic-inductive type have appeared not to be affected by Habon-G so that this type was used in both the primary and the secondary circuit without any further investigation on our part.

3.5.2 Systematic errors

The systematic errors can be broken down as follows:

- **Stability of the setting**

  The controllers mentioned earlier ensure optimum stability of the system at a particular setting. However, the primary inlet temperature was found to slightly oscillate with an amplitude of about 0.15K and at a frequency of about 0.0006 Hz (T_{cycle} approx. 30 minutes). This proved to be independent of the set values and the control parameters. This condition arose only some time after the set points for the primary temperature and primary flow rate and the secondary flow rate were adjusted. This delay is due to the large (heat) buffer capacity of the system.

  Preliminary study [5] showed it is safe to assume that a stable condition is attained when the deviation of the primary inlet temperature is less than 0.1 K and the rate of change of the primary inlet and outlet temperatures is less than 0.05 K/min. The 10-minute measurement is started when these requirements are met.

- **Heat losses to the surrounding area**

  Because of the design of the headers to which the heat exchangers are connected, the temperature sensors may be placed rather far away from the heat exchangers. The amounts of heat delivered on the primary side and taken up on the secondary side that are calculated from this temperature measurement are different. A preliminary study [5] indicates that this difference is too large too ignore. Indeed, it constitutes a sizeable error because it is not exactly known where these "losses" occur. However, the measured values can well be corrected if the heat losses are assumed to be proportional to the pipe length and the temperature difference between the pipeline and the surrounding area. The correction used in this investigation is detailed in Appendix E.

- **Differences in secondary inlet temperature**

  These differences are not really an error but do distort the basis on which the measured values are compared. With the aid of the thermal efficiency, however, the values can be converted to a fixed inlet temperature. This conversion is given in Appendix G.

- **Pressure drop across heat exchangers**

  Because of the header design, the measured pressure drop equals the pressure drop across the heat exchanger plus the pressure drop across the connections to and from the headers. Some heat exchangers had more bends because of the various connection possibilities. This may cause the measurements to yield a distorted picture. However, since these additional bends result from the geometry and the construction of the heat exchanger, the connections have been regarded as forming an integral part of the heat exchanger.

- **Fouling in the test facility**

  As time went by, the heat transfer and the pressure drop across a heat exchanger may have been affected by fouling in the tubes. This effect is not likely to have been appreciable given the duration of the investigation and the use of Habon-G. All the same, this effect will be assessed by conducting a second reference measurement without Habon-G after all measurements have been taken.

- **Degradation of Habon-G**

  Habon-G readily oxidizes. Thus, any oxygen entering the test facility would affect the measurements. Therefore, it was decided to use demineralized water as the system water. It was circulated through the system for some days and at elevated temperature so as to rid the system of oxygen. The concentration of Habon-G was measured at regular intervals.

4. Results of measurements

Besides the parameters that dictate a setting (the primary inlet temperature and primary flow rate and the secondary flow rate), the following parameters were measured:

- the primary outlet temperature
- the secondary inlet and outlet temperatures
- the pressure drop across the heat exchanger and the pressure rise across the pump
- the reading of the heat flow meter.

The secondary inlet temperature is dependent here on a number of external factors such as other uses of the water supply booster. The other parameters are dependent on the setting. The settings and the measured values were stored in a computer because of the accuracy and further processing of the raw data.

Once stable conditions were established in the facility, the raw data were stored for ten minutes and processed to obtain a single mean value per measuring period. These values are given in Appendix H and are rearranged in this chapter as follows for ease of interpretation.

- Habon-G concentration
- heat exchangers
- heat flow meters
- pressure measurements
- reference measurements

The example given in Appendix I shows how the measured values have been further processed and corrected.

4.1 Habon-G concentration

Starting from three concentrations between 100 and 1000 wppm, attempts were made to take measurements at 100, 500 and 1000 wppm. In all instances, the calculated required amount of Habon-G was added from the fill system. Representative samples were taken only after extensive mixing and heating. The samples were then analysed by the method described in Appendix D. The average Habon-G concentration for at least five samples are as follows.

measurement	concentration of Habon-G [wppm]
concentration 1	119
concentration 2	520
concentration 3	1470

Tab. 4.1: Average Habon-G concentrations

In view of the deviation between the 'set' concentration and the measured concentration, a large number of samples taken for a particular concentration at different points in the measuring period were analysed so as to check the analysis.

4.2 Heat exchangers

As mentioned earlier, the measured values needed to be corrected because of the heat losses (Appendix E) and converted to a fixed secondary inlet temperature (Appendix G). This was necessary to bring the measured values to comparable values that are representative of the heat exchanger performance. The results for each heat exchanger are presented in two different ways:

- In order to be able to assess the effect of Habon-G on heat exchanger performance the power transferred in each heat exchanger has been plotted against the reference measurement and the highest habon-G concentration at the various secondary flow rates.
- Since the secondary outlet temperature is of prime concern to the consumer whilst the primary outlet temperature is of prime concern to the operator, these two temperatures have been plotted for a number of measuring points that are relevant to the domestic water supply. These points were chosen with the following considerations in mind:
- The design of domestic water supply systems assumes that the user will turn the hot-water tap wide open (about 5 l/min) and will then add cold water until the desired temperature is reached. That is why the secondary flow rates of 2 and 8 l/min were dropped as being representative of the requirements in a district heating system.
- Assuming tap water needs to be heated 45K during winter, the primary and the secondary flow rates need to be about equal. In summer, however, the primary flow rate will need to be about twice as large as the secondary flow rate.

In the light of these considerations, the measuring points Nos. 8, 15, 23 and 26 in the measuring programme are considered relevant. No. 14 has been included in the presentation inasmuch as, in practice, optimization will take place at this particular point.

4.2.1 Heat exchanger A

The primary and the secondary outlet temperature of heat exchanger A are plotted below against the five settings and against various measured Habon-G concentrations.

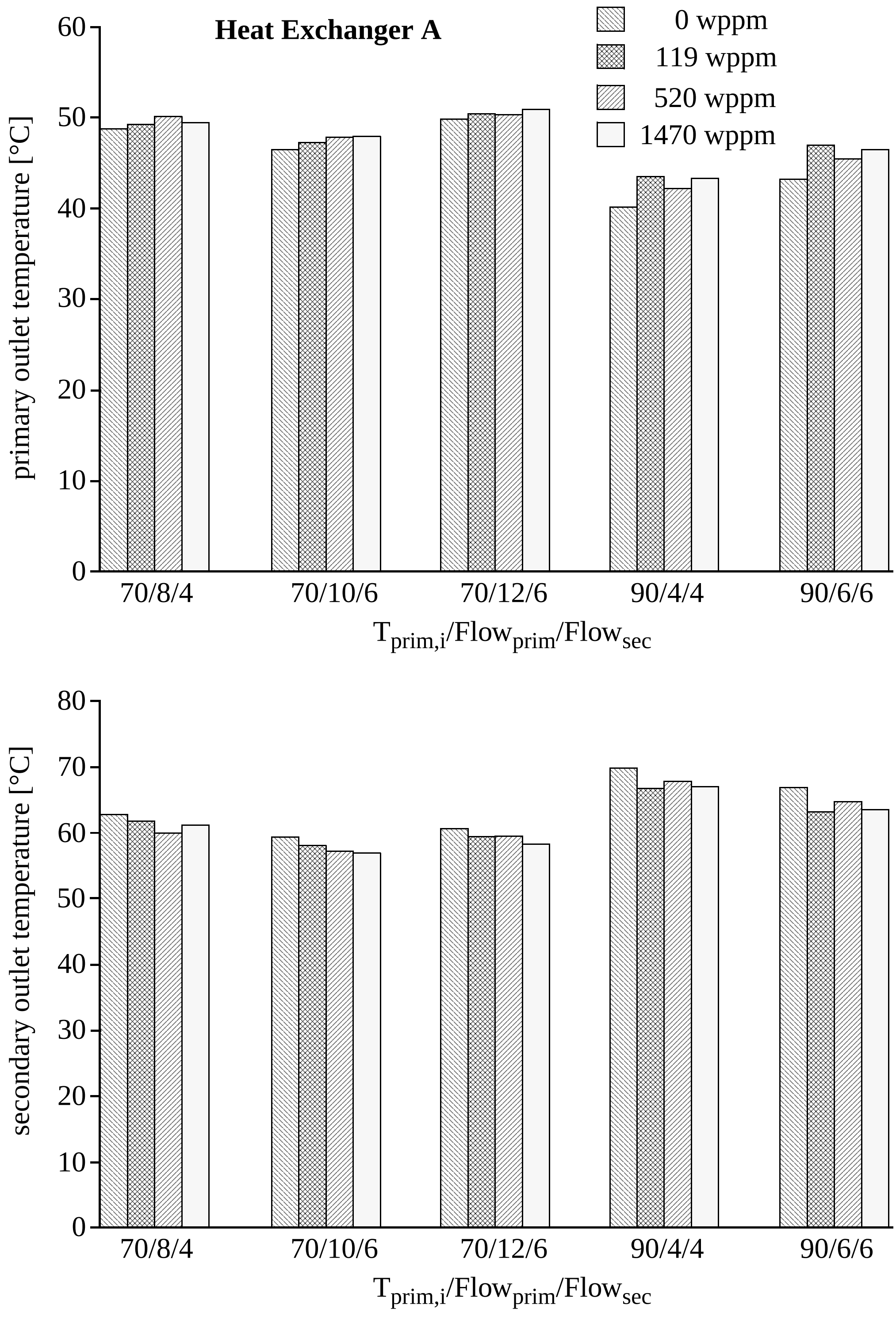


Fig. 4.1: Outlet temperatures of heat exchanger A

Plotted below are the power levels transferred at various secondary flow rates against the reference measurement and the highest Habon-G concentrations that were measured.

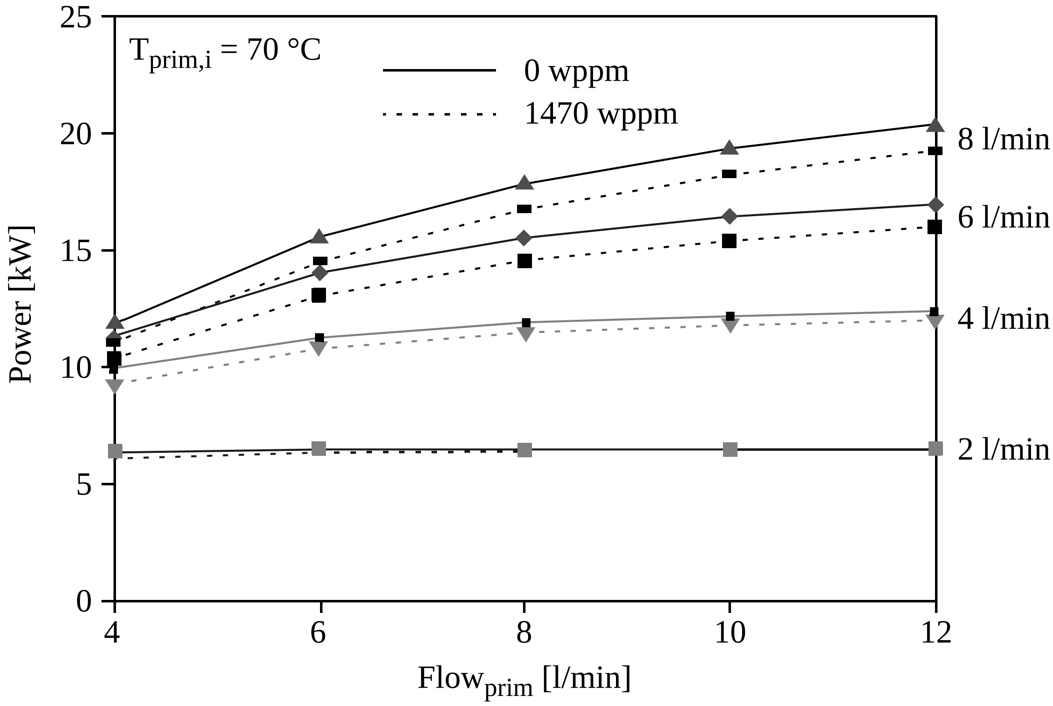


Fig. 4.2: Power levels transferred at various secondary flow rates

4.2.2 Heat exchanger B

The primary and the secondary outlet temperature of heat exchanger B are plotted below against the five settings and against various measured Habon-G concentrations.

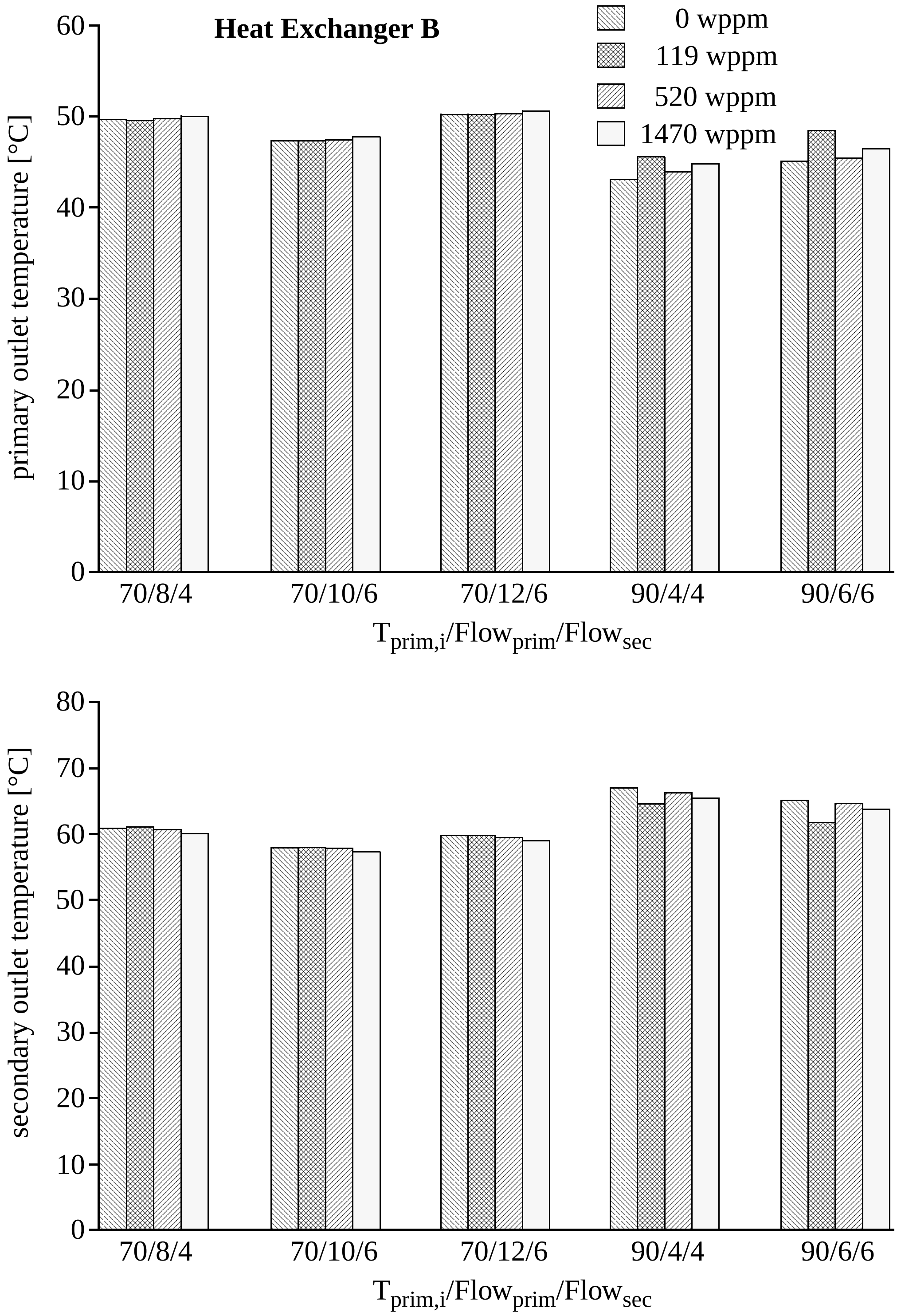


Fig. 4.3: Outlet temperatures of heat exchanger B

The power levels transferred in heat exchanger B are plotted below against for the reference measurement and the highest Habon-G concentration.

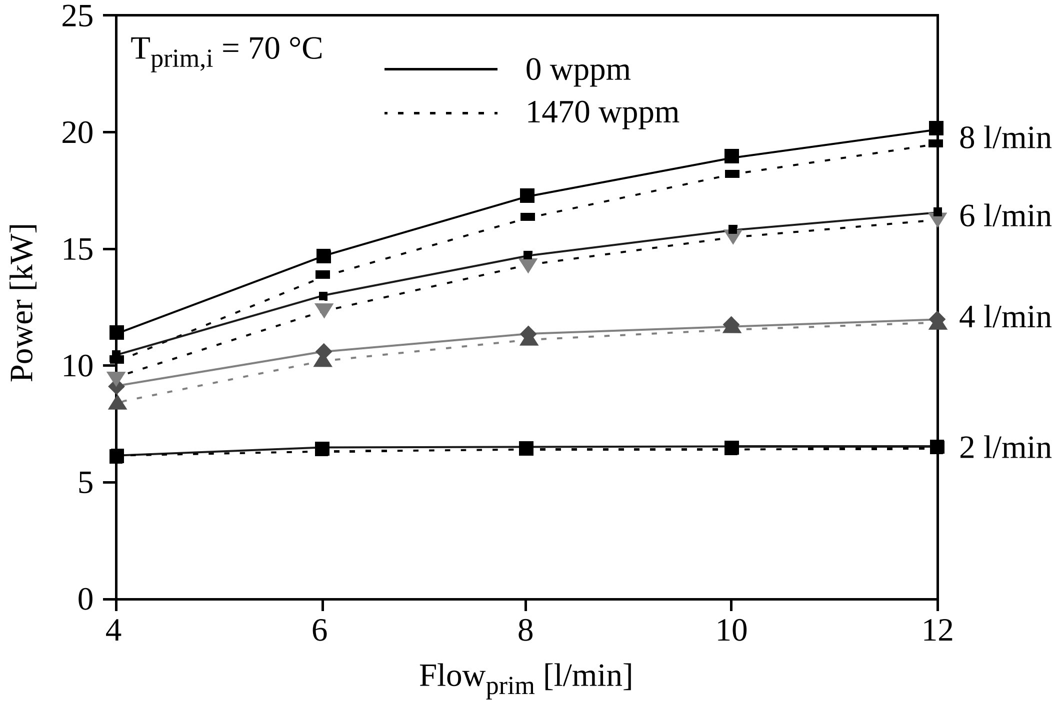


Fig. 4.4: Power levels transferred in heat exchanger B

4.2.3 Heat exchanger C

The primary and the secondary outlet temperature of heat exchanger C are plotted below against the five settings and against various measured Habon-G concentrations.

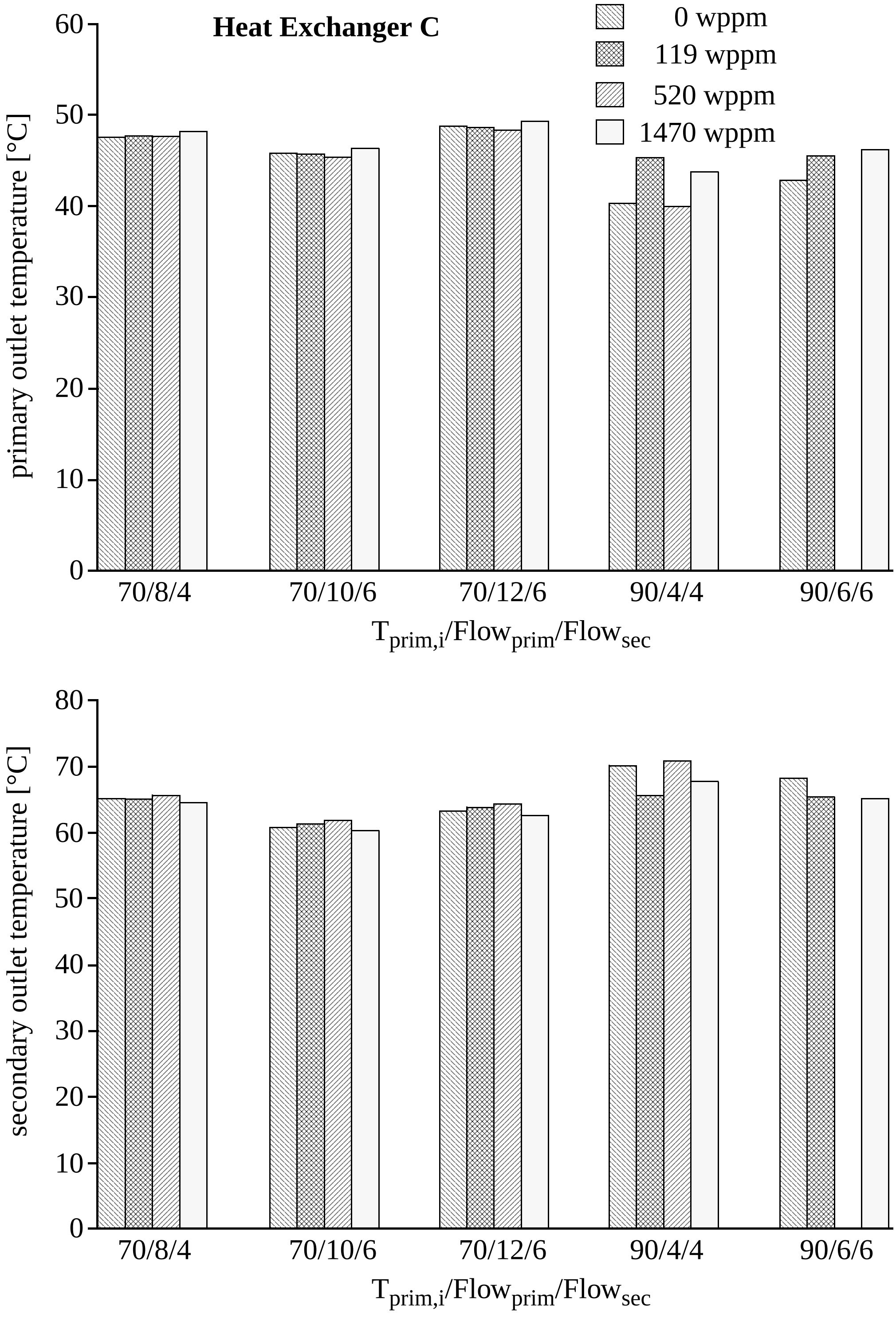


Fig. 4.5: Outlet temperatures of heat exchanger C

The power levels transferred in heat exchanger C are plotted below against for the reference measurement and the highest Habon-G concentrations.

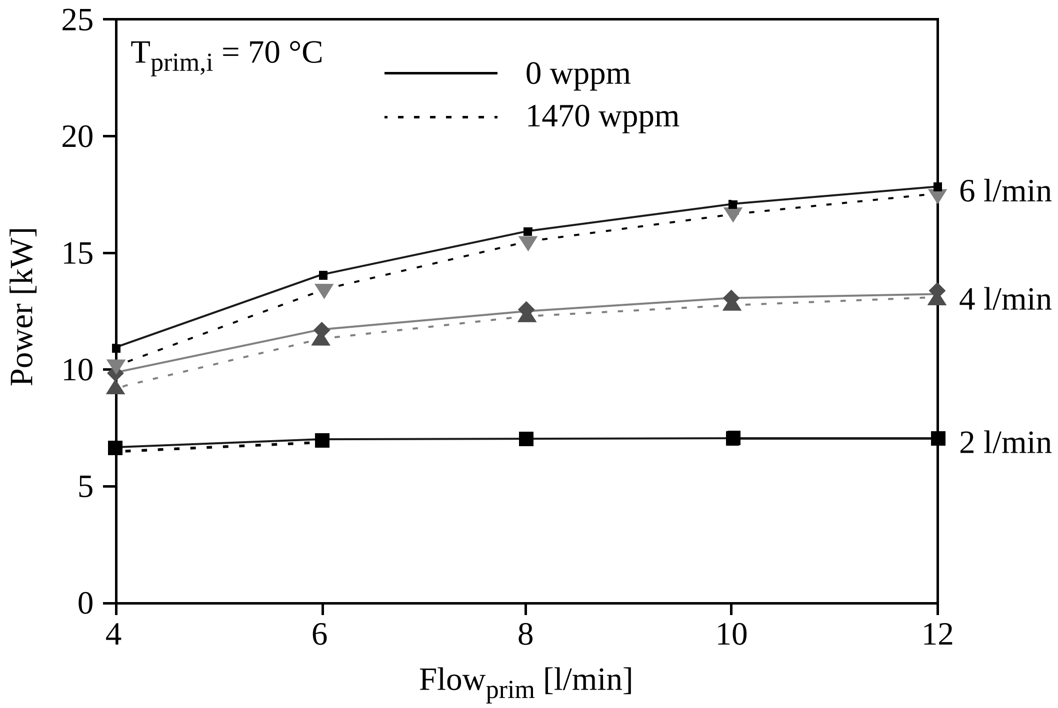


Fig. 4.6: Power levels transferred in heat exchanger C

4.2.4 Heat exchanger D

The primary and the secondary outlet temperature of heat exchanger D are plotted below against the five settings and against various measured Habon-G concentrations.

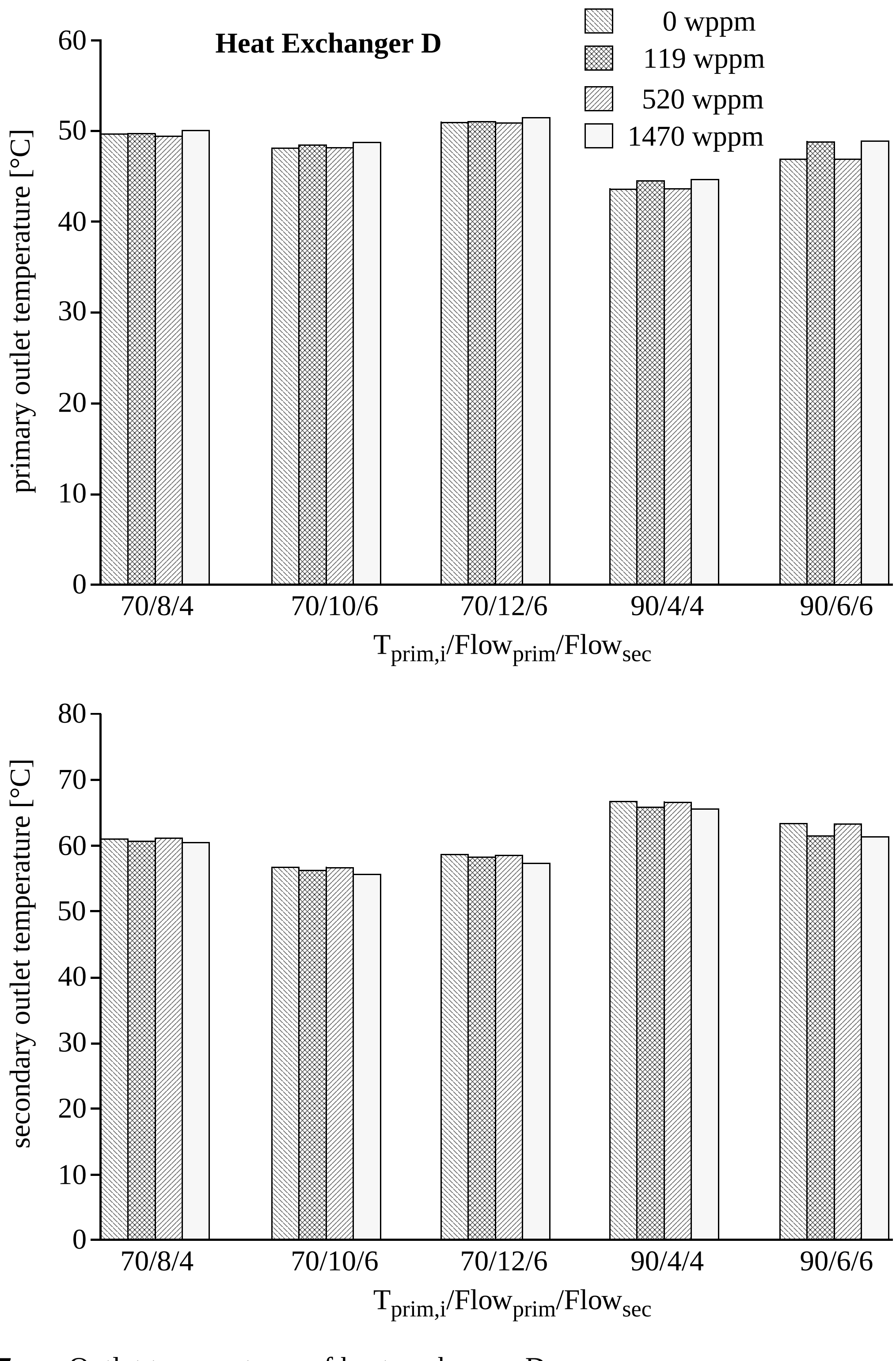


Fig. 4.7: Outlet temperatures of heat exchanger D

The power levels transferred in heat exchanger D are plotted below against for the reference measurements and the highest Habon-G concentration.

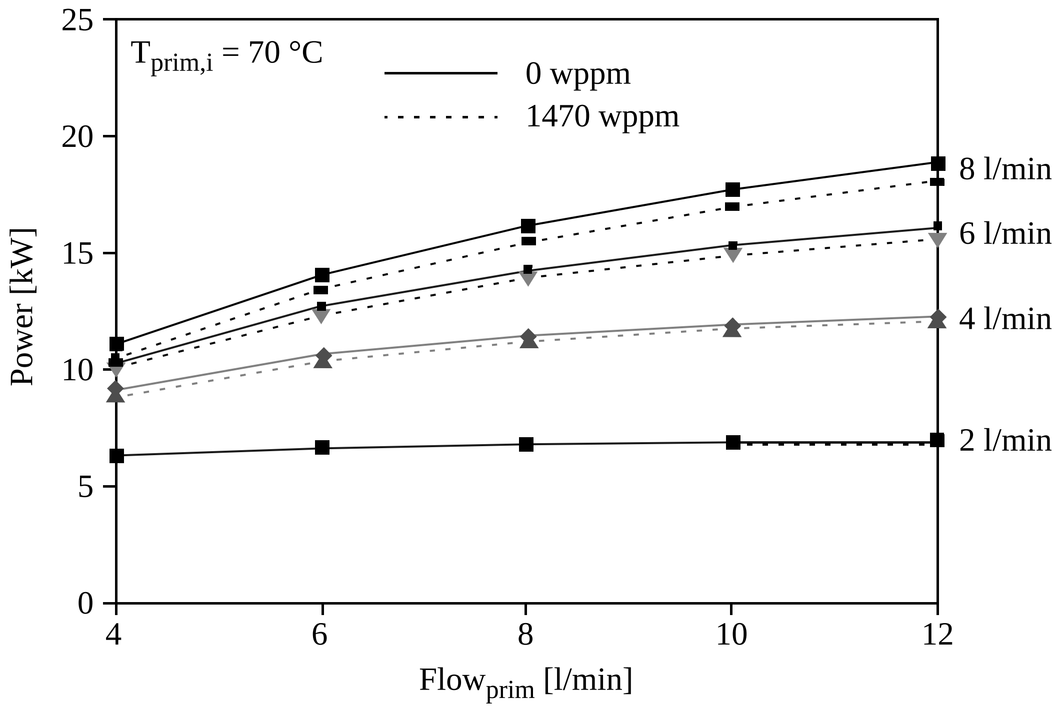
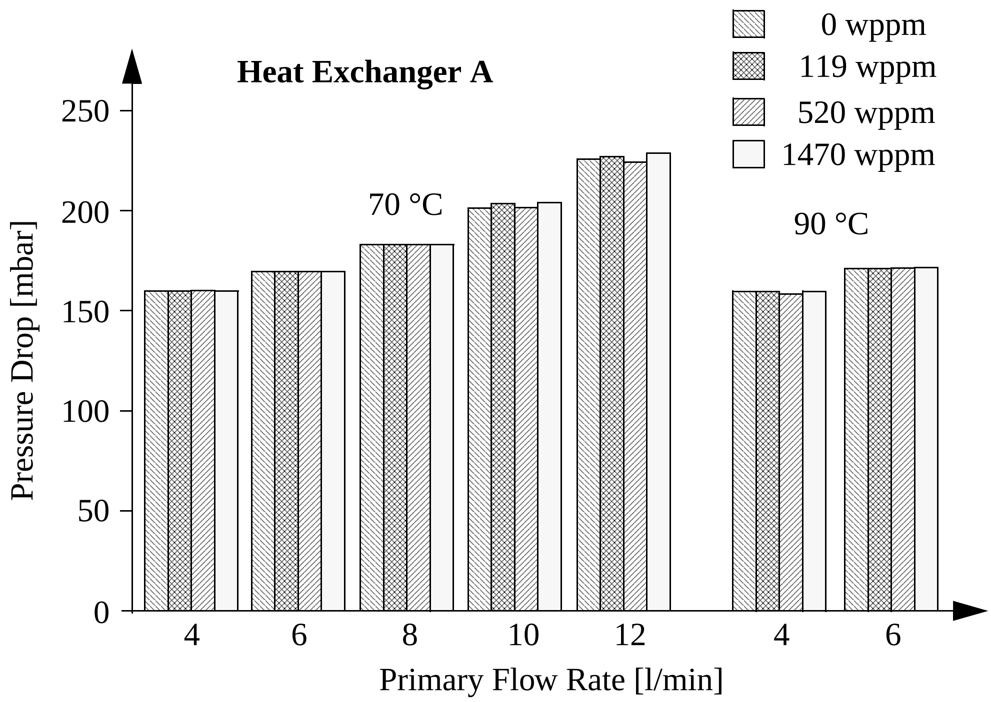


Fig. 4.8: power levels transferred in heat exchanger D

4.3 Pressure drop measurements

4.3.1 Heat exchangers

The figures below show the effect of Habon-G on the average decrease in pressure drop across each heat exchanger in relation to the reference measurement.



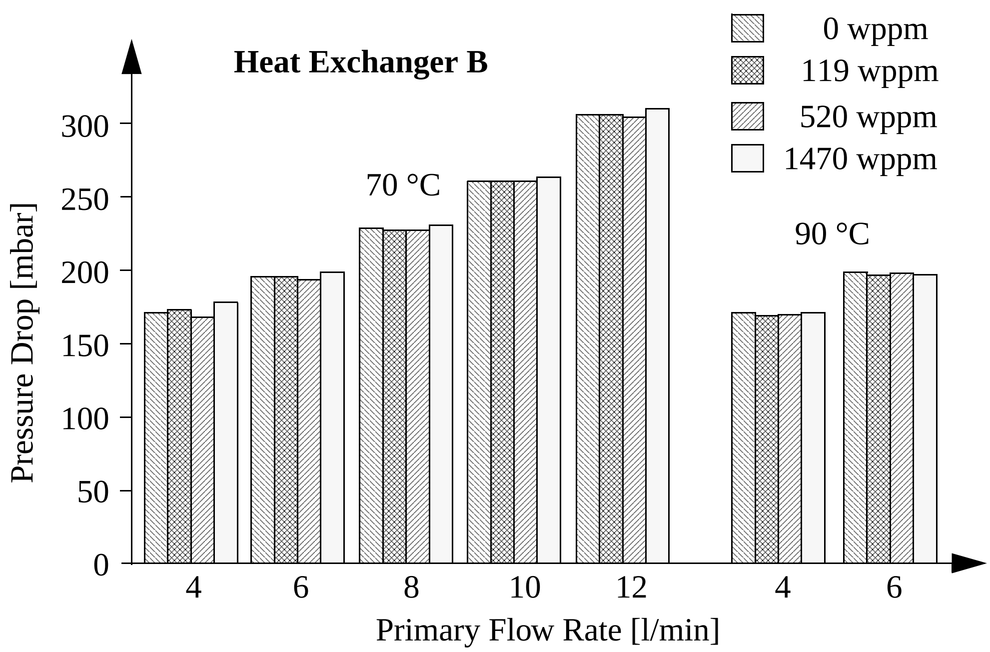
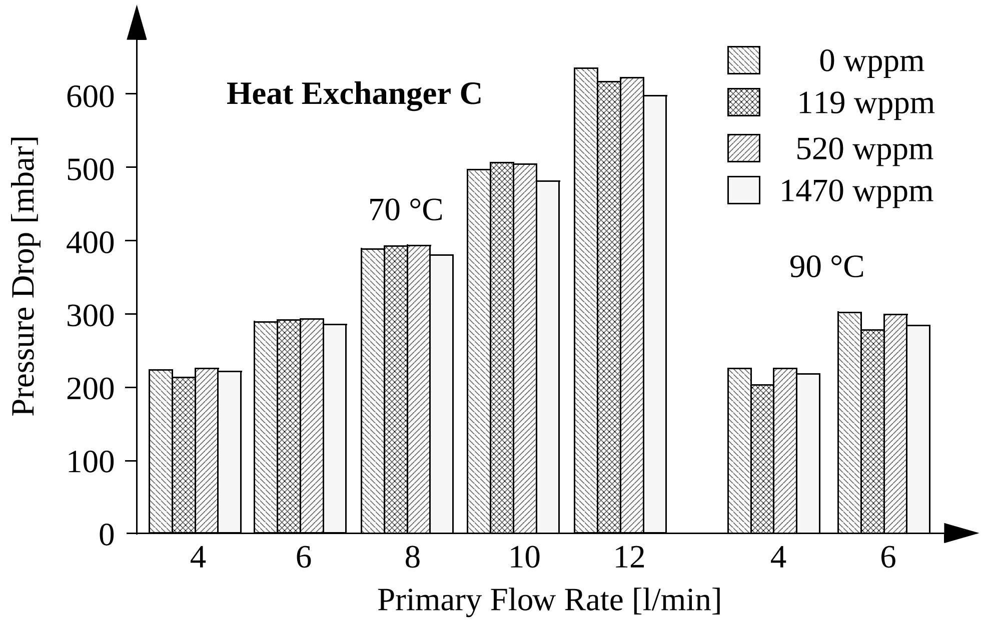


Fig. 4.9: Pressure drop over heat exchangers A & B



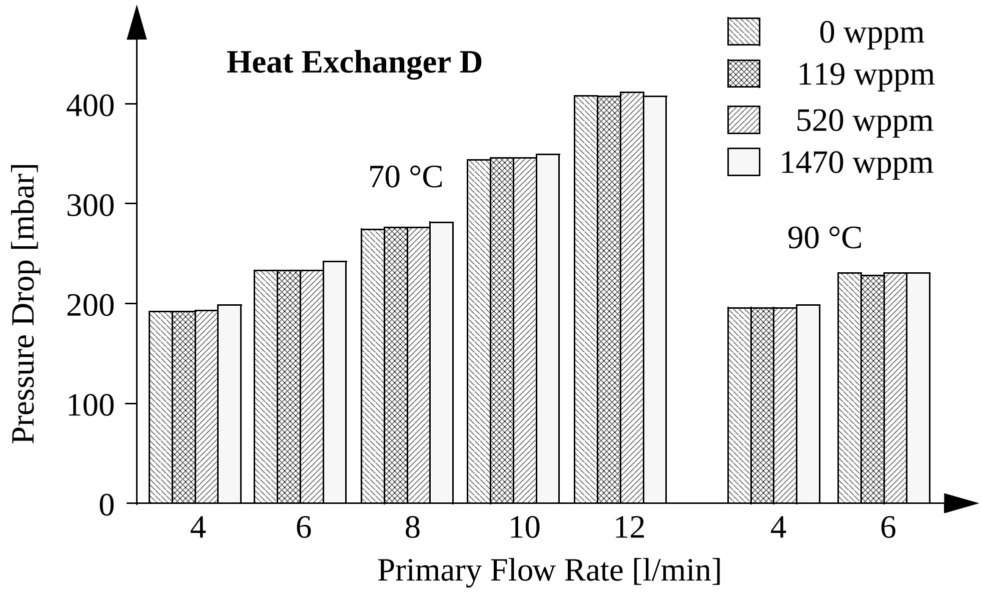


Fig. 4.10: Pressure drop over heat exchangers C & D

4.3.2 Pump delivery head

The pump delivery heads shown below have been derived from the measured values. The pressure is the average pressure measured throughout the programme across each of the heat exchangers at 70 and 90 °C.

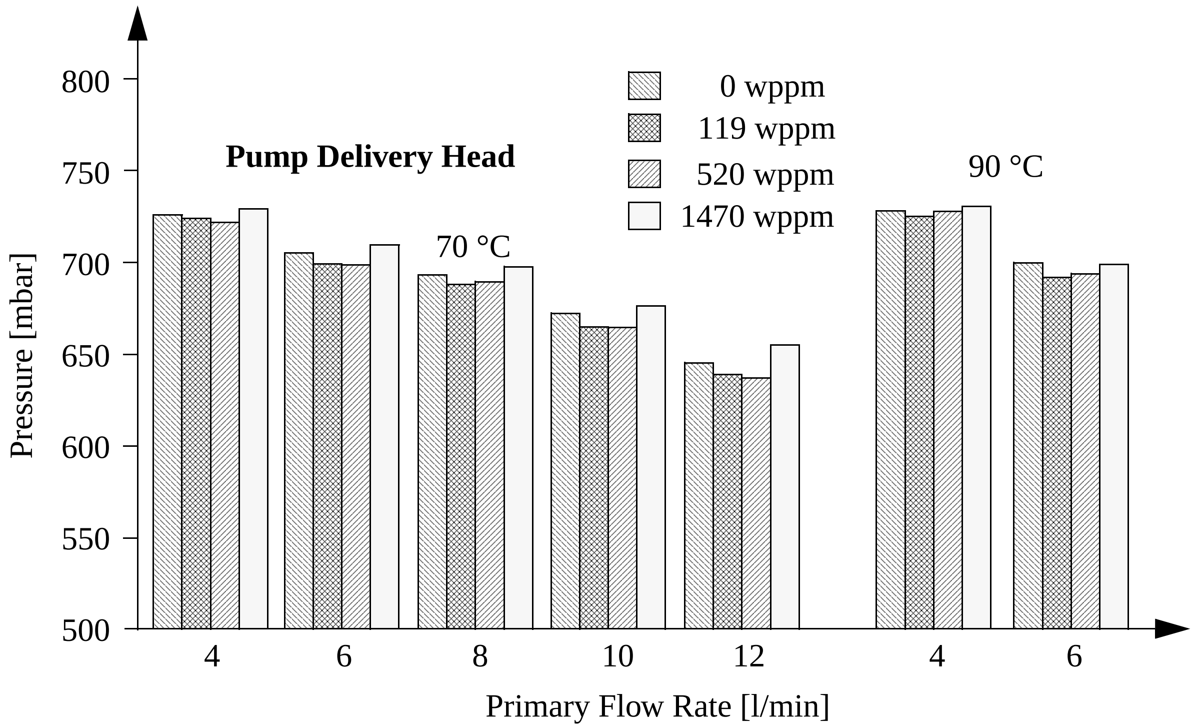


Fig. 4.11: Pump delivery head

Arranging the data according to temperature, it appears that at 70 °C pump performance diminishes by max. 1.3 % and improves at the highest concentration by max. 2.6 %. At 90 °C, pump performance diminishes at the first concentration by max. 1.6 % and rises to the original level at higher concentrations.

4.4 Heat flow meters

Measurements on the heat flow meters were conducted simultaneously with those on the heat exchangers. Thus, the results given in Appendix J are the averages of the values found in the measuring programme, during which the flow rate was varied between 4 and 12 l/min.

The values measured by the PLC/PC needed to be corrected since the temperature sensors of the PLC were located at some distance from the sensors of the heat flow meters. For that reason, the results of the energy measurements by the heat flow meter and the PLC were inherently different. The method of correction is based on the assumption that the heat loss is proportional to the pipe length and the difference between the metal temperature and ambient. The method of calculation is described in Appendix F; one of the measurements is worked out in Appendix I by way of example.

4.4.1 Flow meters

Flow meters A and B indicated not only the energy levels but also the volumes passing through them. The figure shown below gives the accuracy of the measurement of flow of these two heat flow meters at various Habon-G concentrations.

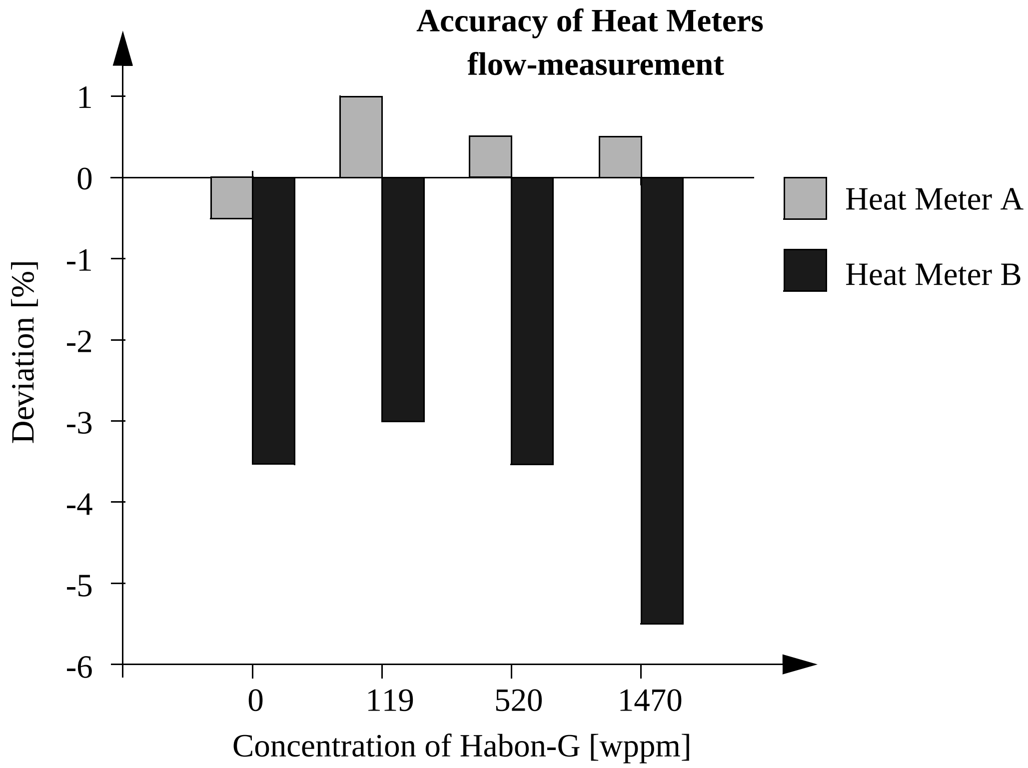


Fig. 4.12: Accuracy of heat meters (flow measurement)

4.4.2 Heat flow measurements

When using system water without additives, i.e. demineralised water, the percentage error of the heat flow meters ranges from less than 1 % to, occasionally, 7 %.

The results for various Habon-G concentrations are summarized below.

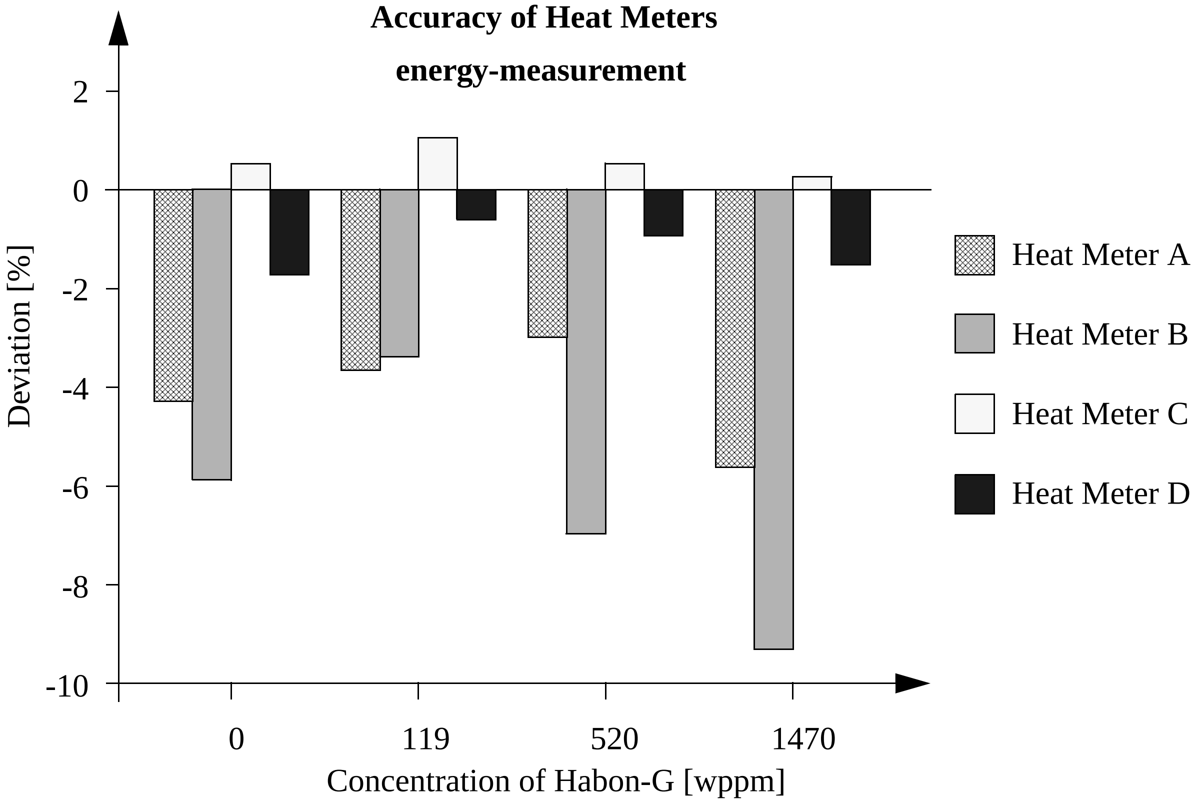


Fig. 4.13: Accuracy of heat meters (energy measurement)

4.5 Reference measurements

Initially, all measurements were taken with demineralized water being used as system water, without any addition of Habon-G. The results of these measurements serve as a reference for those taken with addition of Habon-G.

On completion of all Habon-G measurements the reference measurements were repeated for three heat exchangers. This was done on the one hand to determine the repeatability of the measurements and on the other to estimate the fouling from rust formation, if any.

The raw data from the second reference measurement is to be found in Appendix K. This data, too, has been adjusted to take account of heat losses (as described earlier) and converted to the same secondary inlet temperature. The adjusted primary and secondary outlet temperatures so obtained have been compared with the results of the first reference measurement. The discrepancies found are summarized as follows:

Secondary outlet temperature:	mean difference: + 0.3 % = 0.2 K, standard deviation: 0.8 % = 0.4 K and maximum values: - 1.5 to 1.9 %.
Primary outlet temperature:	mean difference: +0.5 % = 0.2 K, standard deviation: 1.0 = 0.5 K and maximum values: - 4.9 to 0.7 %.

5. Interpretation

5.1 Comparative evaluation of heat exchanger performance in the reference measurements

Important parameters of heat exchangers in district heating systems are the power transferred, the primary return temperature and the pressure drop. The figures below show the results of the reference measurements for these parameters.

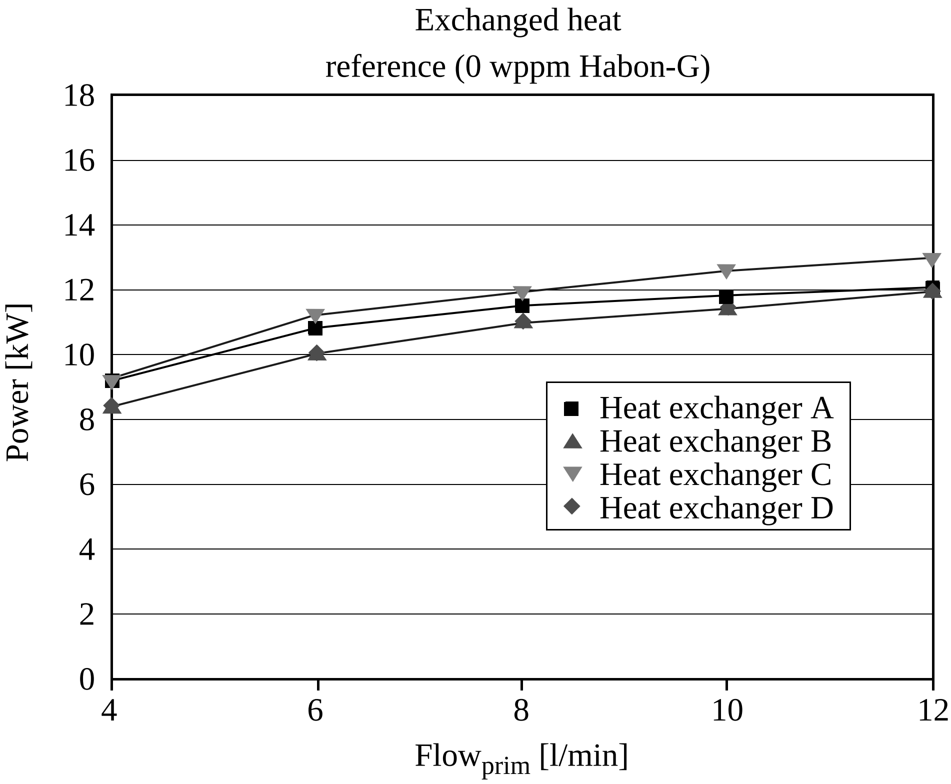


Fig. 5.1: Exchanged heat

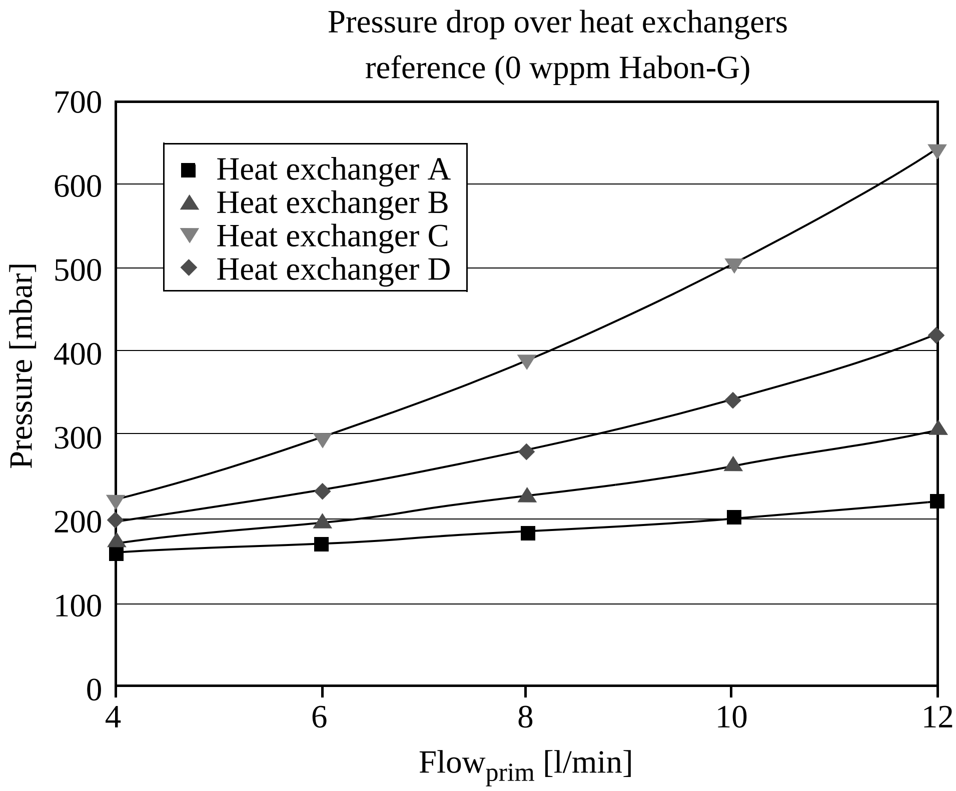


Fig. 5.2: Pressure drop over heat exchangers

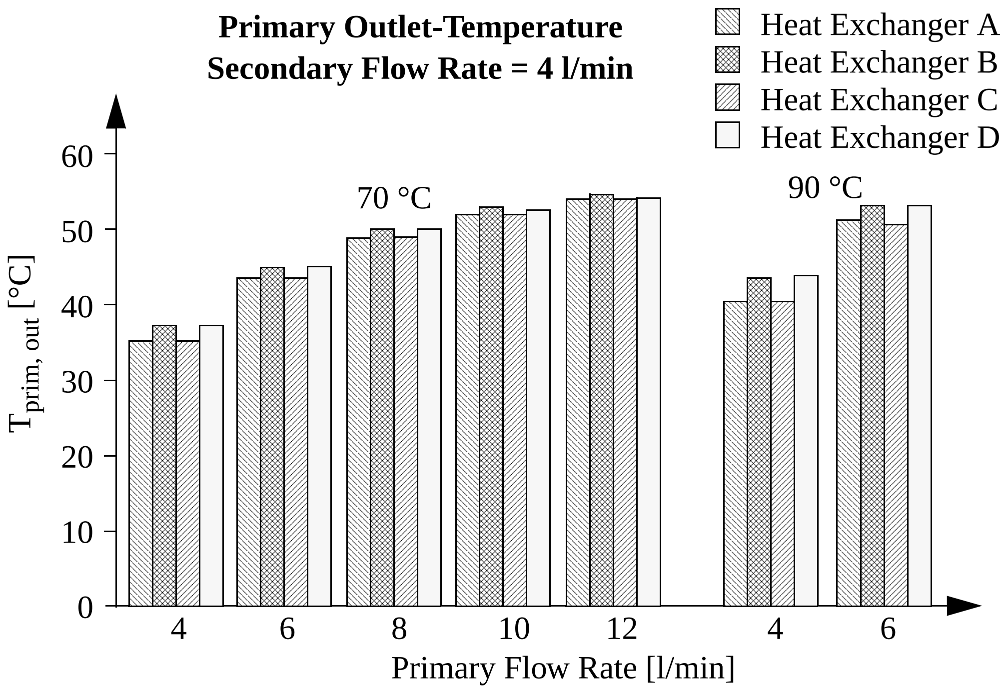


Fig. 5.3: Primary outlet-temperature (secondary flow = 4 l/min)

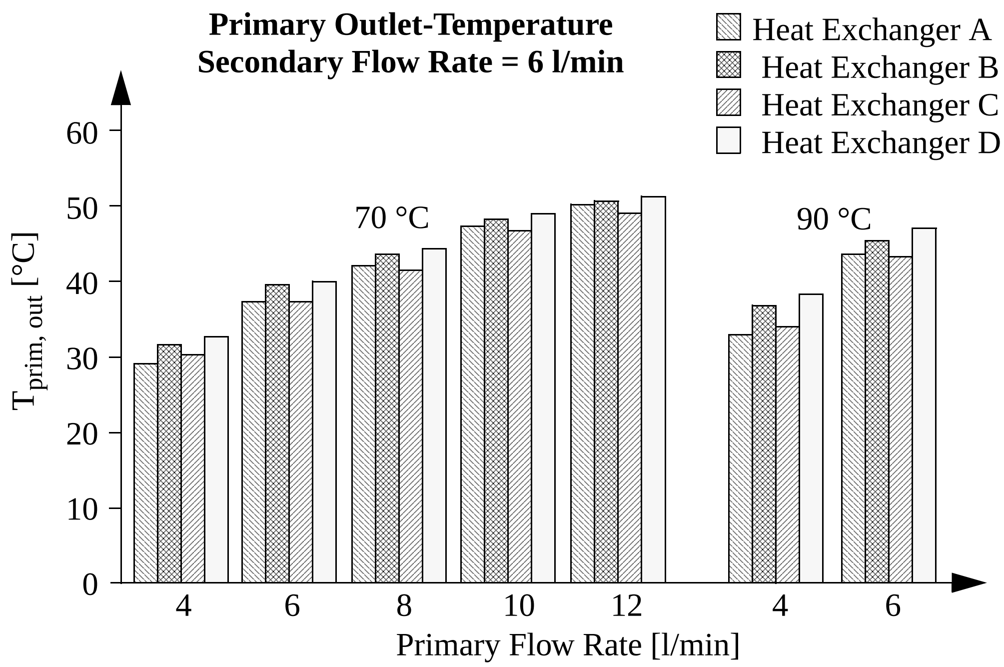


Fig. 5.4: Primary outlet-temperature (secondary flow = 6 l/min)

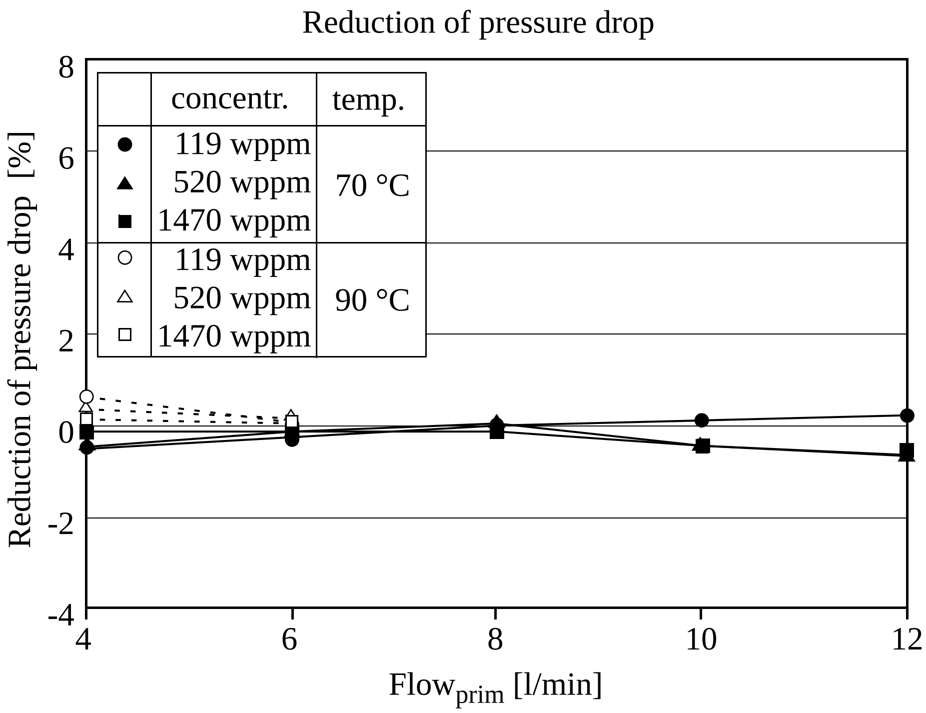
The return temperatures and heat transfer are practically the same for all heat exchangers, despite their different designs, geometries and prices. The differences in friction loss are substantial, mostly because of the different designs.

Heat exchanger C gives the best performance in terms of heat transfer (during the reference measurements), closely followed by unit A. Units D and B give about the same performance. All heat exchangers amply meet the requirement that the return temperature must be less than 50 °C on heating from 10 to 55 °C and at a secondary flow rate of 5 l/min.

5.2 Effect of Habon-G on flow regime and heat transfer

Considering the effects of Habon-G as observed in earlier work [2], i.e. laminarization of the flow at higher Reynolds numbers, one might expect the flow to pass a transition point at which, above a particular primary flow rate, the pressure drop and the transferred power strongly increase. These two effects are compared below. No transition region is observed.

Heat exchanger A



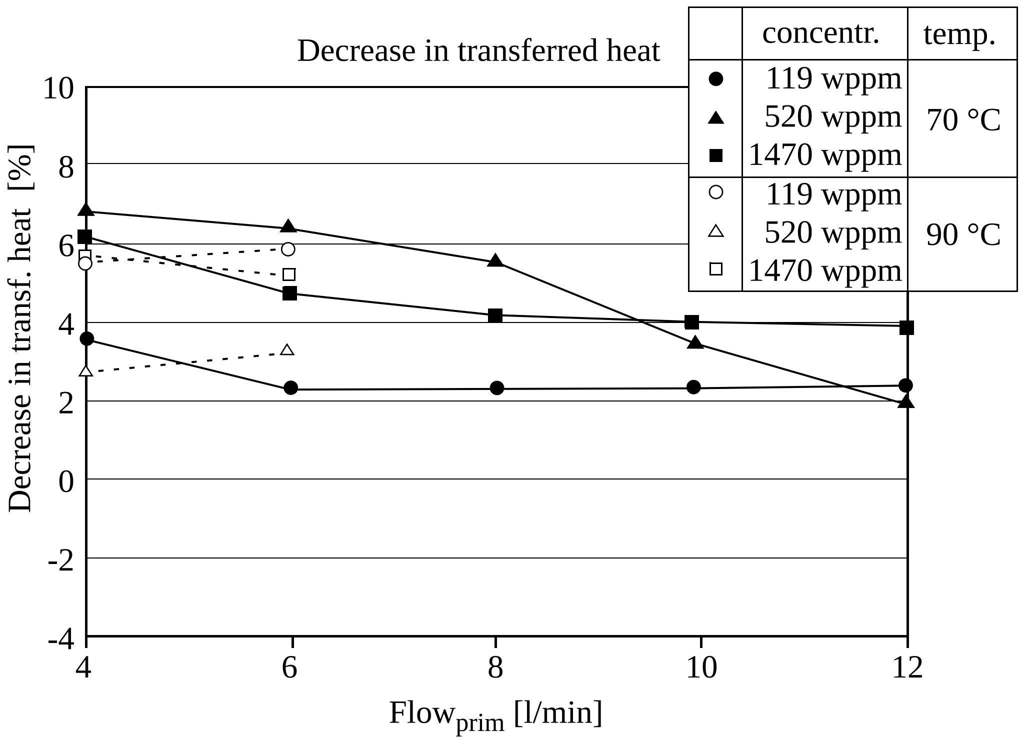
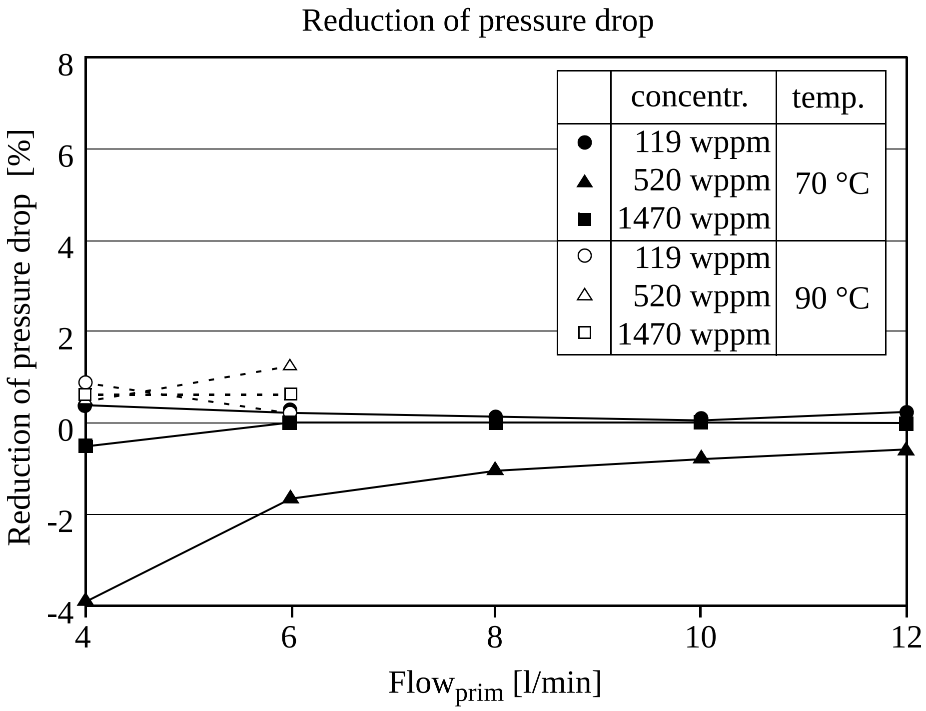


Fig. 5.5: Reduction of pressure drop & decrease in transferred heat (heat exchanger A)

Heat exchanger B



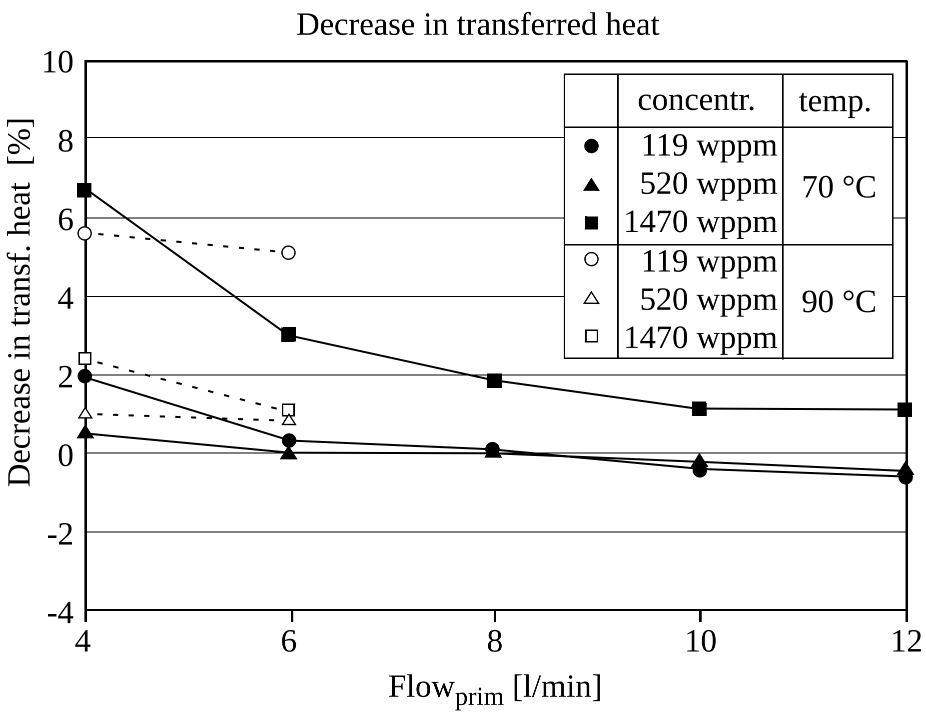


Fig. 5.6: Reduction of pressure drop & decrease in transferred heat (heat exchanger B)

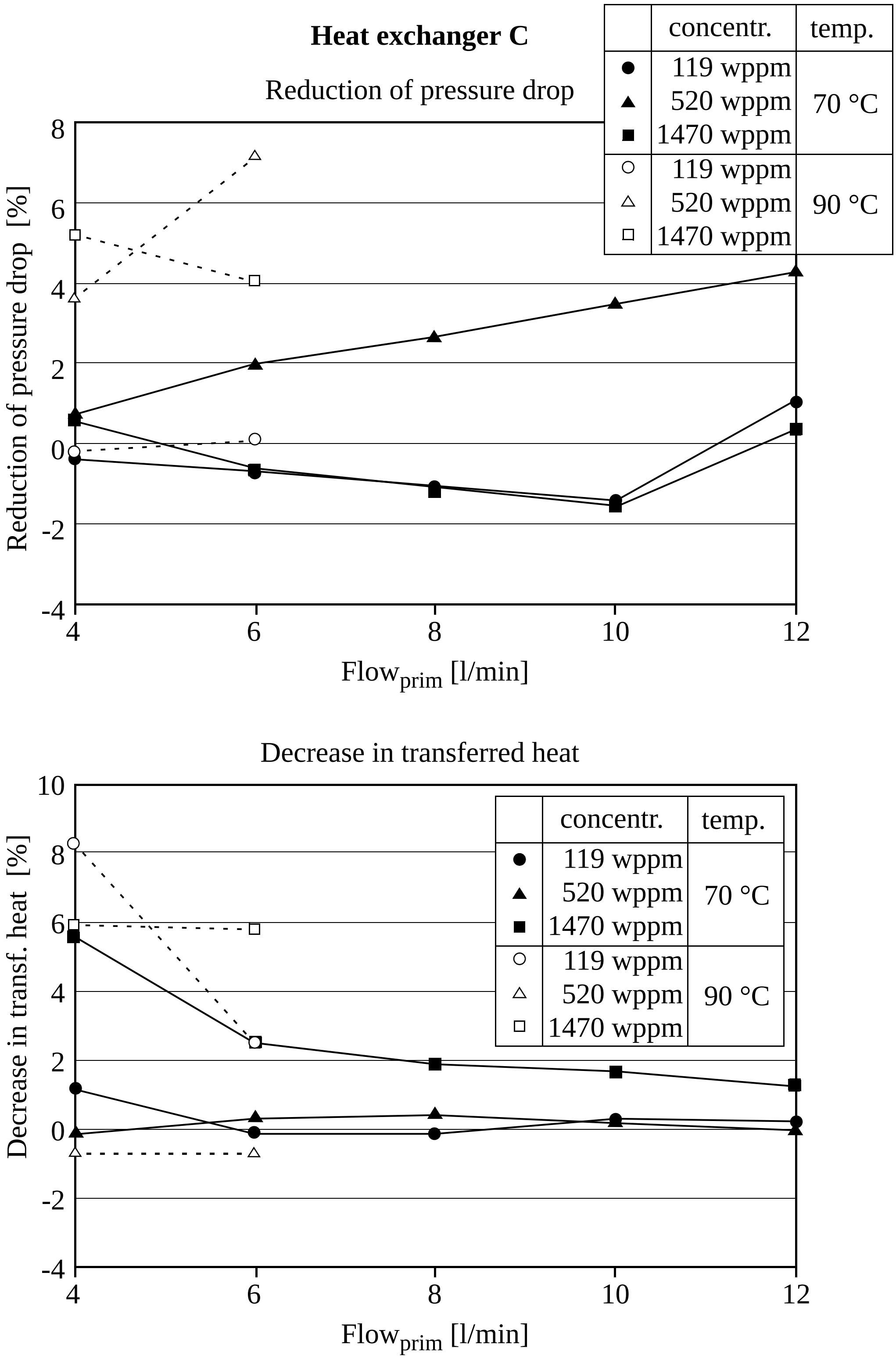


Fig. 5.7: Reduction of pressure drop & decrease in transferred heat (heat exchanger C)

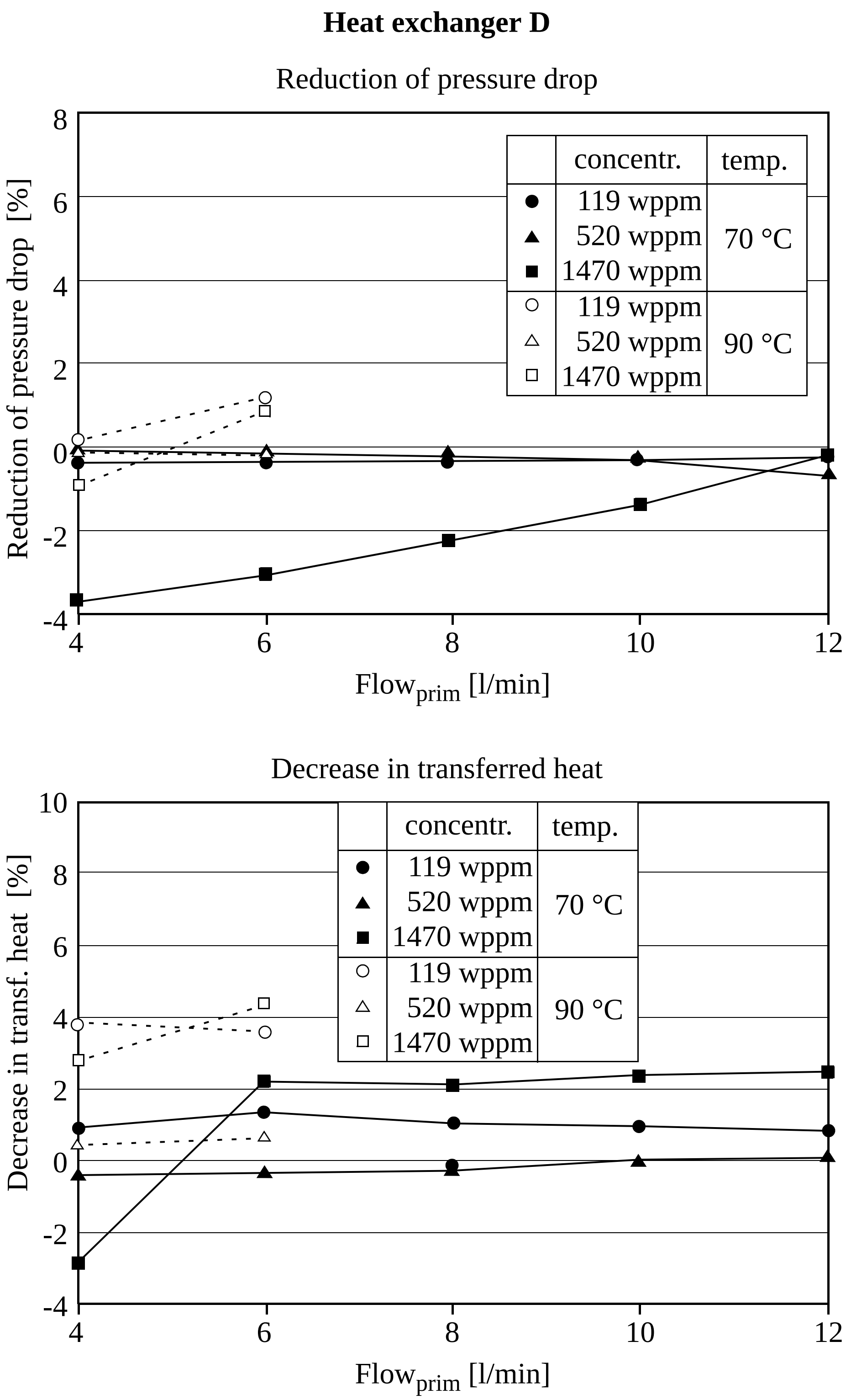


Fig. 5.8: Reduction of pressure drop & decrease in transferred heat (heat exchanger D)

At the highest concentration, the power transferred in three heat exchangers decreased by 7 % relative to the reference measurements. This was at 70 °C and a primary flow of 4 l/min. On increasing the flow to 6 l/min, this value dropped in two heat exchangers to approx. 3 % and did not drop any further at higher flows. This decrease might be indicative of a laminar/turbulent transition point. This change does not occur, however, at 90 °C. Apparently, this temperature lies outside the operating range of Habon-G at the concentrations used.

The pressure drop across the heat exchangers changes when the heat transfer changes. However, no clear relation could be established that might indicate the existence of a transition point.

The maximum decrease in heat transfer lies at the border of the practical area of application of heat exchangers in a district heating system. It does not constitute any impediment, since the primary flow rate can be increased without the primary return temperature exceeding 50 °C.

Calculations made on one of the heat exchangers indicate that, under the test conditions, the flow in it is turbulent (33,000 < Re < 80,000) but that it is within the region where it should have been influenced even by low Habon-G concentrations. Apparently, a laminar flow is prevented by the "hydraulic entry effect". The path length of the undisturbed flow is too short for laminar flow to develop, given the many bends and twists in heat exchangers. This is a deliberate choice made by the designer so as to produce a compact unit and to increase the degree of turbulence and so the heat transfer.

5.3 Effect of Habon-G on pump curve

The performance of, i.e. the pressure rise across, a pump depends on the viscosity of the fluid, which in turn depends on the fluid temperature. Thus, in determining the differences in pump performance, the fluid temperature had to be the same during all measurements.

In the test facility, the pump was placed next to the heat exchangers. Accordingly, the fluid temperature in the pump was the primary outlet temperature. This temperature is strongly dependent on the secondary flow rate. The plotted values are the averages for each heat exchanger of all secondary flow rate measurements at a particular primary flow rate. Thus, differences in the primary return temperatures have been averaged for these measurements. The viscosity was expected to be comparable therewith at the plotted values.

The pump curve appeared to be hardly affected by the presence of Habon-G. The figure given elsewhere shows that the pump performance decreases slightly at the first two concentrations but that it increases at the highest concentration. At no time were the differences in pump performance greater than 3 %; in actual fact, all percentage figures were below the threshold, or within the dead space, of the meters.

5.4 Effect of Habon-G on heat flow meters

The figures in section 3.4 indicate that the accuracy of the flow meter in heat flow meter A is good (better than 1 %). The accuracy of the flow meter in heat flow meter B is disappointing and is affected by Habon-G. As regards the measurement of the heat content, the following is noted:

- The results for heat flow meter A are remarkable in that the flow measurement is accurate but the overall percentage error is disappointing. Apparently, the temperature measurement is inaccurate.

- The accuracy of the flow measurement in heat flow meter B is about 3 %. The accuracy diminishes in the presence of Habon-G. The overall accuracy ranges from 3 to 9 %.
- In the case of heat flow meter C (which incorporates a magnetic-inductive flow meter), the errors that were measured are below the threshold. No change in percentage error was observed on adding Habon-G.
- Heat flow meter D is somewhat less accurate than C, but here again the error is below the threshold. Its accuracy is not affected by Habon-G in any material way.

5.5 Repeatability of measurements

Comparison of the first series of measurements (using demin. water without additives) and the last series of reference measurements indicates that, on average, the differences in outlet temperature are less than 0.5 % (= 0.4 K). Thus, the repeatability is satisfactory. Given that there has been a slight improvement rather than a deterioration, there has not been any serious fouling.

The repeatability of the concentration measurement has also been assessed (Appendix D).

The standard deviation after repeated titration is less than 2 wppm.

6. Diligence, conclusions and recommendations

The care exercised in the present investigation will be evident from a number of sections in this report and from the results presented. The repeatability figures should be proof of the reproducibility of the raw data whilst the correction and conversion methods given in the appendices render the results legitimate and suitable for meaningful comparison.

Extraneous influences have been accounted for suitably and reliably by the methods of measurement, correction and conversion.

The test facility used for the investigation was operated for 1200 hours. Over that period, a total of 12 MWh of electrical power was consumed; the volumes passed through the primary and secondary circuits totalled 450 and 200 m^3, respectively. The measurements described herein lasted 700 hours in all. The remaining time was taken up by testing of parts and components and the assembly, the preliminary experiments and setting of controllers.

The results of the reference measurements indicate that:

- The heat exchangers give practically the same performance as far as power transfer is concerned.
- The friction losses across the heat exchangers show major differences.
- Two of the heat flow meters are unreliable.

The measurements with Habon-G added indicate that:

- The concentration of Habon-G is difficult to adjust.
- The heat transfer in the heat exchangers slightly deteriorates (not more than 2 % on average), but without impairing proper performance.
- The addition of Habon-G has no appreciable effect on friction losses in the heat exchangers.
- Pump performance is not affect by adding Habon-G.
- Two of the four heat flow meters are sensitive to the use of Habon-G.

6.1 Recommendations for further investigation

Given the importance of the temperature measurements and of proper interpretation of their results, it would seem useful to measure the temperatures nearer to the heat exchangers. The temperature sensors could be placed at the inlet and outlet of each heat exchanger. In that case, the method of correction now used to compensate for the distance between the heat exchangers and temperature sensors could be omitted. Such a modification would be fairly drastic, would reduce the flexibility of the installation and would call for more sensors.

Prior thereto, the accuracy of the measuring results could be improved by basing the method of correction on a logarithmic co-current heat dissipation rather than the linear (average) heat dissipation now used and by applying an iterative method for correction of the outlet temperatures.

Changes are most distinct at the highest Habon-G concentrations. A higher concentration may be needed in this type of small-scale installations because the hydraulic entry effect is more pronounced. This makes it more difficult for laminar flow to be attained. The highest concentration that was tested might coincide with the lower limit of the range in which Habon-G is effective. This ought to be established in a follow-up investigation.

As to the percentage error of the heat flow meters it would be useful to initiate long-term tests one aim of which should be to determine the deviations now found in relation to the volume passing through.

7. Summary

This report discusses the results a NOVEM-supervised investigation aimed at assessing in how far the surfactant Habon-G can reduce friction losses in domestic water supply systems utilizing heat from district heating systems. Earlier work has shown that Habon-G, when added to heat transport systems, has a beneficial effect on the required pump capacity. Habon-G produces a laminar flow, and this reduces not only the friction losses in pipelines but also the heat transfer.

This report discusses the effect of Habon-G on both parameters as observed in four different heat exchangers and heat flow meters used for domestic water supply systems.

For the purposes of the present investigation a test facility was made in which the district heating circuit is simulated by a closed loop which included an adjustable electric heater. The domestic water circuit was connected to a high-capacity water supply booster. The heat exchangers and heat flow meters were integrated in the facility and could be inserted one at a time into either circuit by means of ball valves.

Measurements made on the heat exchangers indicate that all four heat exchangers meet the specified requirements, although there are some differences. The flow in them still seems to be turbulent, despite the laminising effect of Habon-G.

The heat flow meters do not all meet the requirements. Two were found to be at error and their inaccuracy increased with increasing Habon-G concentrations. The percentage errors of the other two meters were below the threshold and were not affected by the presence of Habon-G.

As observed earlier, adding Habon-G to the water in district heating systems has a beneficial effect on the flow resistance and reduces the heat losses in the feed lines. The present investigation shows that addition of Habon-G does not affect the heat transfer in the domestic water supply system in any material way. However, a critical assessment of the type of heat flow meter to be used is called for.

8. Symbols

Symbol	Quantity	Unit
A	area	[m^2]
c	concentration	[wppm]
c_p	heat capacity	[J/kgK]
D	diameter	[m]
L	length	[m]
m	mass flow	[kg/s]
p	pressure	[Pa]
P	power	[W]
Q	volume	[m^3]
r	radius	[m]
T	temperature	[K]
v	(flow) velocity	[m/s]
V	volume rate of flow	[l/min]
α	heat transfer coefficient	[W/m^2K]
λ	dynamic viscosity	[$Pa \cdot s$]
λ	coefficient of conductivity	[W/mK]
ν	kinematic viscosity	[m^2/s]
ξ	friction factor	[1]
ρ	specific mass	[kg/m^3]
τ	shear stress	[Pa]

9. Literature

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10. APPENDIX A
Calculation of Habon-G Concentration

The method cited in [1] is used to determine the concentration needed to influence the flow condition at various primary flow velocities.

The temperature is assumed to be constant as the flow passes through the heat exchanger. If the Habon-G concentration is high enough to influence the flow condition at that inlet temperature, it is also high enough to have an effect at lower temperatures elsewhere in the heat exchanger.

The figure on the next page showing the maximum shear stresses has been derived from experiments at constant temperature. It is not clear in how far this information is valid for non-isothermic flows.

Formulae used:

$$v = \frac{Q}{A} = \frac{\frac{Q}{60} \cdot \frac{1}{1000}}{\frac{1}{4} \cdot \pi \cdot D^2} \text{ [m/s]}, \qquad \text{Gl. (10.1)}$$

$$Re = \frac{v \cdot D \cdot \rho}{\eta}, \qquad \text{Gl. (10.2)}$$

$$\frac{1}{\sqrt{\xi}} = 2 \cdot \log(Re \cdot \sqrt{\xi}) - \dot{0}.8 \quad \text{and} \qquad \text{Gl. (10.3)}$$

$$\tau_W = \frac{\xi}{8} \cdot \rho \cdot v^2, \qquad \text{Gl. (10.4)}$$

Knowns: $D = 10.35$ [mm],

$\eta = 0.40 \cdot 10^{-3}$ [Pa·s] (70 °C) and

$\eta = 0.35 \cdot 10^{-3}$ [Pa·s] (90 °C)

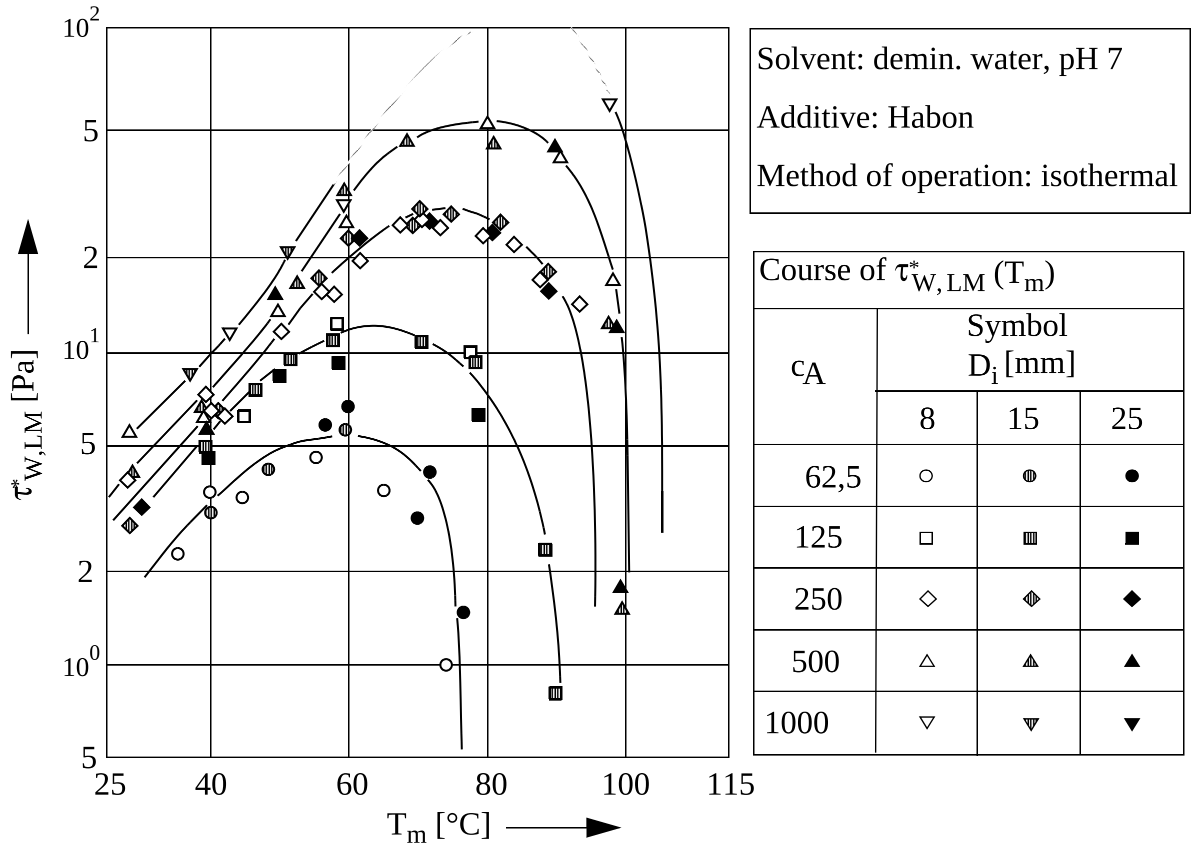

Fig. 10.1: Critical wall shear stress of a Habon/water mixture vs temperature and concentration [1]

$T_{prim,in}$ [°C]	Flow rate V [1/min]	Mean Velocity v [m/s]	Re [1]	ξ [1]	τ_{wall} [1]	laminair at $c_{Habon\text{-}G}$ of [wppm]
90	4	0.79	26,000	0.024	1.9	125
90	6	1.19	39,000	0.022	3.9	125
90	8	1.59	52,100	0.021	6.5	190
70	4	0.79	20,300	0.026	2.0	50
70	6	1.19	30,400	0.024	4.2	60
70	8	1.59	40,600	0.022	6.9	85
70	10	1.98	50,700	0.021	10.2	120
70	12	2.38	60,800	0.020	14.1	125

Tab. 10.1: Operating conditions

11. APPENDIX B
Measurement setup

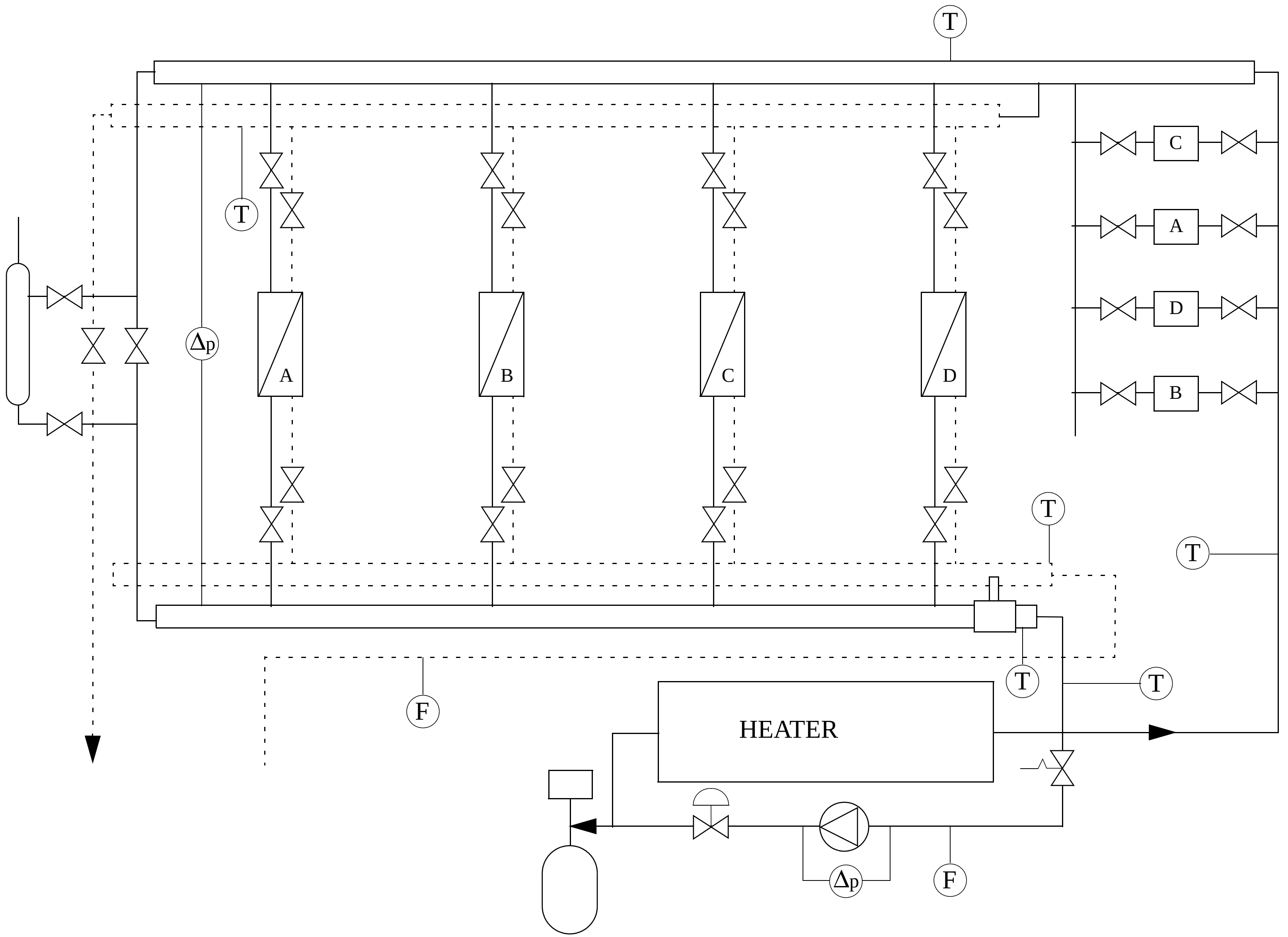

Fig. 11.1: The test rig

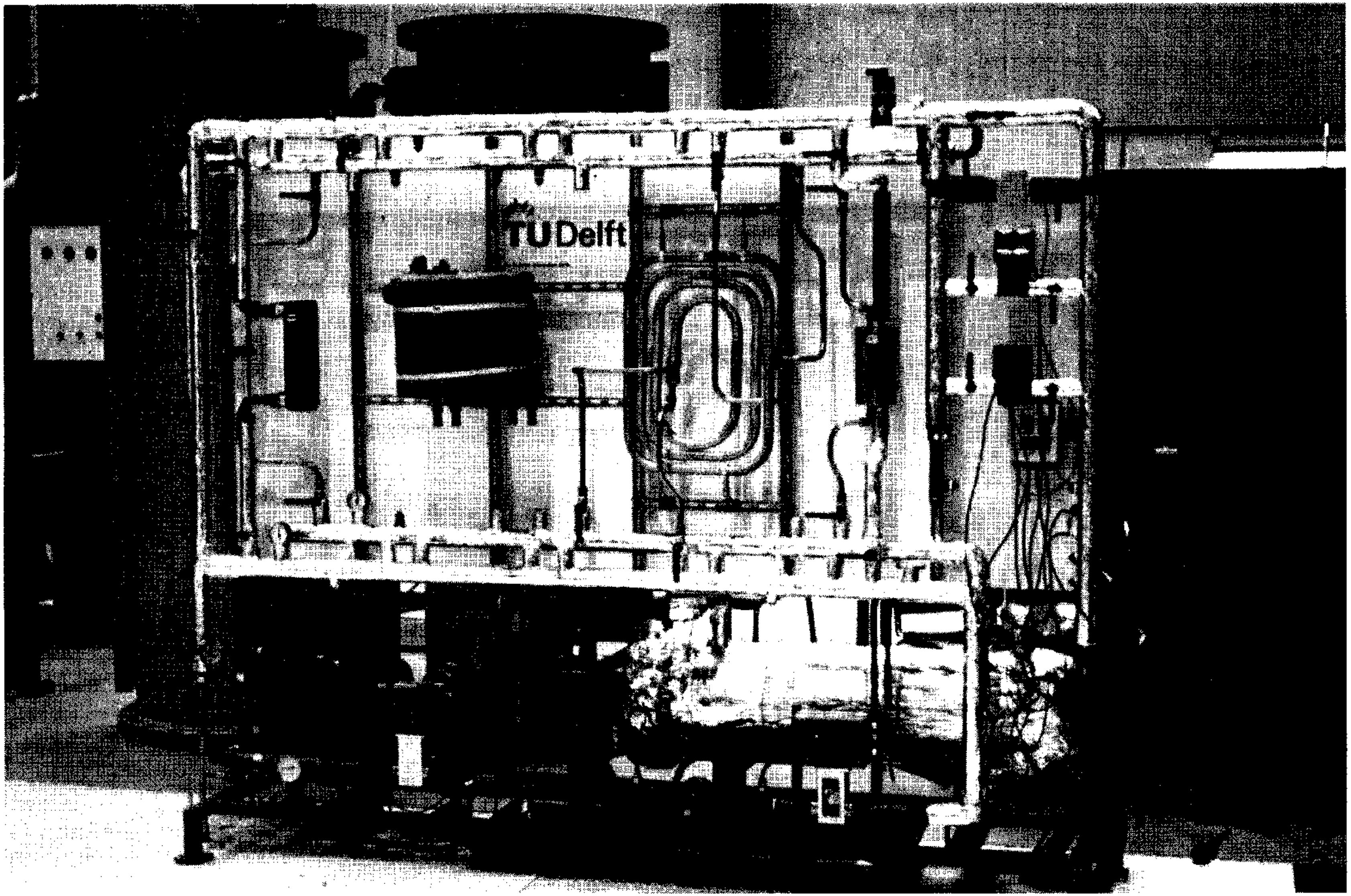

Fig. 11.2: Photo of the test rig

12. Appendix C
Measurement plan

Point	Primary flow [l/min]	Secondary flow [l/min]	Primary entrance-temperature [°C]
1	4	2	70
2	6	2	70
3	8	2	70
4	10	2	70
5	12	2	70
6	4	4	70
7	6	4	70
8	8	4	70
9	10	4	70
10	12	4	70
11	4	6	70
12	6	6	70
13	8	6	70
14	10	6	70
15	12	6	70
16	4	8	70
17	6	8	70
18	8	8	70
19	10	8	70
20	12	8	70
21	4	2	90
22	6	2	90
23	4	4	90
24	6	4	90
25	4	6	90
26	6	6	90
27	4	8	90
28	6	8	90

Tab. 12.1: Measurement plan

13. APPENDIX D
Accuracy of measuring instruments

- Flow meters

- Picomag II magnetic-inductive type, supplier: Endress & Hauser of Naarden
  - primary circuit: range 0-30 l/min, accuracy 1 %
  - secondaryu circuit: range 0-12 l/min, accuracy 1 %

Differential pressure gauge

- 843 dP cell, supplier: Foxboro Nederland of Soest
  - heat exchanger: range 0-750 mbar, accuracy 0.25 %
  - pump: range 0-750 mbar, accuracy 0.25 %

Temperature sensors

- Pt-100 elements, supplier: Thermo-Electric B.V. of Pijnacker
  - primary circuit: range 0-100 °C, accuracy 0.1 K
  - secondary circuit: range 0-100 °C, accuracy 0.1 K

Relative accuracy of Pt-100 (in comparison with one another) measured by submersion pairby pair in water/ice bath:

- Pt-100 elements in primary circuit: < 0.03 K
- Pt-100 elements in secondary circuit: < 0.04 K

These figures amply meet the requirements.

14. APPENDIX E
Measurement of Habon-G concentration by the titration method

According to information from the supplier of Habon-G, concentrations of Habon-G in water in the range we are dealing with here can be measured by two analytical methods. One is based on infrared technology using an IR-Photometer. A major drawback of this method is that it takes long to calibrate the equipment. Given the small number of samples to be analysed, we therefore preferred to use the other method, a two-phase titration technique. That method, too, requires a competent operator but is not difficult for any laboratory analyst.

The titration technique

The method involves two steps: a sample is divided into two phases, one above the other, with the aid of a number of liquids, one of which is an indicator solution.

In the second step, a titration solution is slowly added until the lower phase in the sample reaches a transition point. The amount of titration solution used is a measure of the concentration.

The indicator solution

This solution is prepared by dissolving in a 250-ml graduated flask 0.4 gramme of dimidiumbromide (3.8-diamino-5-methyl-6-phenylphenantridinium bromide) and 0.2 gramme of disulfin blue in 250 ml of 10-% ethanol/water (2.5 ml of ethanol in 247.5 ml of distilled water).

As the solution is light-sensitive, it should be stored in homogenised condition in a brown bottle.

The titration solution

The titration solution is prepared by dissolving 1.442 grammes of sodium laurylsulphate in some distilled water in a 1000-ml graduated flask. Foam develops during the dissolution process, which is eleminated by adding 60 ml of n-butanol and a few drops of concentrated sulphuric acid. The flask is topped up with distilled water to 1000 ml.

Procedure

The concentration of a surfactant in a solution is determined by transferring 20 ml of the solution into a sealable 250-ml graduated flask togther with 30 ml of chloroform and 10 ml of indicator solution. On brief shaking, this mixture divides into two phases: a non-polar upper phase and a polar lower phase. Next, sulphuric acid should be added with a pipette, while constantly slewing the flask, until the upper phase turns light brown and the lower phase a greenish blue.

The titration is carried out by adding a small, known amount of titration solution to the solution. This should be repeated, while constantly shaking, until the lower phase strongly discolours to light pink. The amount of titration solution added until that happens is a measure of the surfactant concentration in the sample. The concentration can finally be calculated using the following formula.

$$c_{Habon-G}[wppm] = A[ml] \cdot M_{Habon-G} \cdot 0.25 \quad , \qquad \text{Gl. (14.1)}$$

with $M_{habon-G}$ = 524 gram/mole.

The measurements

In order to have some certainty as to the reliability of the analytical method and its procedure,we took a large number of samples at the first concentration and at different points in time. The results of the titrations are tabulated below.

Titration No.	Concentration Habon-G [wppm]	Titration No.	Concentration Habon-G [wppm]
1	122	10	117
2	118	11	118
3	121	12	120
4	118	13	119
5	119	14	119
6	120	15	120
7	118	16	118
8	118	17	119
9	119	18	118

Tab. 14.1: Concentration measurements

Mean concentration =119 wppm (deviation σ=1.45 wppm)

15. APPENDIX F
Summary of heat losses

The overall heat loss to the surrounding area is defined as the difference between the primary power, that is, the power determined from the two Pt-100 elements and the flow meter in the primary circuit, and the secondary power (ditto in the secondary circuit).

A distribution key has been devised on the basis of the temperature difference with the surrounding area and the pipe length. The assumptions made are realistic inasmuch as the amount of heat transmitted through the pipe wall is largely determined, or limited, by the lagging (some centimetres, λ = 0.04 W/mK) and natural convection ($\alpha_{outside}$ = 25 W/m^{2}K) and to a much lesser degree by the steel pipe wall (some millimetres, λ = 50 W/mK) the flow velocity (α_{inside} = 15 kW/m^{2}K, possibly affected by the Habon-G concentration. Other compounding factors such as radiation and thermal leaks from one pipe to another have been ignored. In this way, the overall heat loss is distributed to correct the temperatures.

The overall heat loss is the sum total of the following losses:

- Loss 1 Primary, upstream of the heat exchanger inlet, between the Pt-100 element and the heat exchanger inlet (pipe length L1, temperature T1)
- Loss 2 Primary, downstream of heat exchanger outlet, between the heat exchanger and the Pt-100 element (line length L2, temperature T2).
- Loss 3 Secondary, downstream of the heat exchanger outlet, between the heat exchanger and the Pt-100 element (pipe length L3, temperature T3).

This data is tabulated below.

Heat Exchanger	L1 [m]	L2 [m]	L3 [m]
A	2.34	2.44	1.26
B	2.6	1.6	1.74
C	1.25	1.12	2.60
D	0.81	0.61	2.47

Tab. 15.1: Length of heat exchanger

Any heat loss in the secondary circuit ahead of the heat exchanger inlet is negligible since the temperature is virtually ambient.

If the overall heat loss HL is equated to the difference between the primary power dissipation and the secondary power consumption, the loss can be distributed among the various line stretches using the following formula:

$$\mathrm{Loss1} = \frac{L1 \cdot (T1 - T_{amb})}{(L1 \cdot (T1 - T_{amb})) + L3 \cdot (T3 - T_{amb})} \cdot HL \quad . \qquad \text{Gl. (15.1)}$$

Loss 2 and Loss 3 can be calculated analogously.

Now that the overall heat loss has been apportioned to the three stretches, we can calculate the temperature difference resulting from the heat loss as follows.

$$\Delta T = \frac{Loss_n}{m \cdot c_p} \qquad \text{Gl. (15.2)}$$

Depending on the direction of flow, this temperature difference should be added to or deducted from the primary and the secondary inlet and outlet temperatures.

16. APPENDIX G
Determination of energy flow at heat flow meters

As the temperature sensors of the heat flow meters and those of the PLC were rather far apart, the energy measurements are not as a matter of course in agreement because of the heat losses. Therefore, the energy flow measured by the PLC has been corrected for meaningful comparison.

Appendix F gives a break-down of the overall energy loss for the various lines. Since we now know the energy loss in the primary feed and return line, and the pipe length of these two lines, we can determine the **average energy loss per metre**.

The distance between the Pt-100 elements of the heat flow meter and those of the test facility is known. Multiplying the average energy loss per meter and the pipe length between the Pt-100 elements of the PLC and those of the heat flow meter yields the energy loss between the sensor of the PLC and the heat flow meter. This has been done for both the feed line and the return line.

In the case of the feed line to the heat exchanger, the temperature is measured first by the heat flow meter and next by the PLC. On the return line from the heat exchanger, the temperaure is measured first by the PLC and next by the heat flow meter. Consequently, the two calculated losses should be **added** to the energy flow recorded by the PLC.

17. APPENDIX H
Conversion of secondary inlet temperature

During the measurements the secondary inlet temperature slowly varied between 18.3 and 25.8 °C. For a meaningful comparison of the heat exchangers (performance-wise) and the measured values of each heat exchanger, the data needs to be converted to a fixed inlet temperature. We have opted to convert to an average value of 20°C.

The thermal efficiency [7] of the heat exchanger in this situation has been calculated using the temperatures corrected for the heat loss (Appendix F). The thermal efficiency is the ratio of the transferred power to the power transferred by an ideal heat exchanger. An ideal heat exchanger should here be understood to mean one of infinite length, so that the primary and secondary outlet temperatures are equal. The new outlet temperatures are calculated using the thermal efficiency and assuming a secondary inlet temperature of 20 °C. The following formulae have been used:

- Where the primary flow rate is greater than the secondary flow rate:

$$\eta = \frac{T_{sec,out} - T_{sec,in}}{T_{prim,in} - T_{sec,in}}, \qquad \text{Gl. (17.1)}$$

$$T_{sec,out,new} = T_{sec,in,new} + \eta \cdot (T_{prim,in} - T_{sec,in}) \text{ and} \qquad \text{Gl. (17.2)}$$

$$T_{prim,out} = T_{prim,in} - \frac{\Phi_{sec}}{\Phi_{prim}} \cdot (T_{sec,out} - T_{sec,in}) \ . \qquad \text{Gl. (17.3)}$$

- Where the secondary flow rate is greater than the primary flow rate:

$$\eta = \frac{T_{prim,in} - T_{prim,out}}{T_{prim,out} - T_{sec,in}}, \qquad \text{Gl. (17.4)}$$

$$T_{prim,out} = T_{prim,in} + \eta \cdot (T_{sec,in} - T_{prim,in}) \text{ and} \qquad \text{Gl. (17.5)}$$

$$T_{sec,out} = T_{sec,in} - \frac{\Phi_{prim}}{\Phi_{sec}} \cdot (T_{prim,in} - T_{prim,out}) \ . \qquad \text{Gl. (17.6)}$$

18. APPENDIX I
Results Heat Meters

reference

Type of heat meter	reading heat meter			according PLC/PC			PLCV/PC corrected	
	GJ	MWh	m^3	GJ	MWh	m^3	GJ	MWh
A	1.438		13.01	1.482		13.07	1.499	
B		0.545	17.77		0.571	18.41		0.577
C	1.554			1.529			1.547	
D	0.804			0.809			0.818	

Tab. 18.1: Reference

Habon-G concentration = 119 wppm

Type of heat meter	reading heat meter			according PLC/PC			PLCV/PC corrected	
	GJ	MWh	m^3	GJ	MWh	m^3	GJ	MWh
A	1.128		10.08	1.157		9.98	1.170	
B		0.409	12.3		0.419	12.65		0.424
C	2.292			2.250			2.271	
D	1.294			1.286			1.301	

Tab. 18.2: Habon-G concentration = 119 wppm

Habon-G concentration = 520 wppm

Type of heat meter	reading heat meter			according PLC/PC			PLCV/PC corrected	
	GJ	MWh	m^3	GJ	MWh	m^3	GJ	MWh
A	3.354		25.46	3.417		25.3	3.454	
B		0.436 0.143	14.55 4.44		0.462 0.15	15.14 4.57		0.467 0.15
C	0.424 3.1			0.412 3.07			0.421 3.099	
D	1.17			1.166			1.18	

Tab. 18.3: Habon-G concentration = 520 wppm

Habon-G concentration = 1470 wppm

Type of heat meter	reading heat meter			according PLC/PC			PLCV/PC corrected	
	GJ	MWh	m^3	GJ	MWh	m^3	GJ	MWh
A	1.027		9.99	1.071		9.926	1.084	
B		0.534	18.3		0.577	19.34		0.584
C	1.594			1.571			1.590	
D	1.324			1.331			1.347	

Tab. 18.4: Habon-G concentration = 1470 wppm

19. APPENDIX J
Example calculation using method of correction

This example shows how the measured values from a random point of measurement are corrected to allow meaningful comparison.

The correction consists of three parts:

- correction for heat loss
- conversion to new inlet temperatures
- conversion of the power measured at the heat flow meter

Data used:

Measured values: Heat exchanger B, reference measurement, point of measurement 15

$T_{prim,i}$ = 69.8 °C,

$T_{prim,out}$ = 49.2 °C,

Φ_{prim} = 6.0 l/min,

$T_{sec,i}$ = 21.6 °C,

$T_{sec,out}$ = 57.1 °C,

Φ_{sec} = 6.0 l/min,

Distance Sensor $T_{prim,i}$ and entrance heat exchanger = 2.60 m

Distance Sensor $T_{prim,out}$ and entrance heat exchanger = 1.60 m

Distance Sensor $T_{sec,out}$ and entrance heat exchanger = 1.74 m

Correction Heat Loss:

$$P_{prim} = \Phi_{prim} \cdot \rho \cdot c_p \cdot \Delta T = 17.9\text{ kW}, \quad \text{Gl. (19.1)}$$

$$P_{sec} = \Phi_{sec} \cdot \rho \cdot c_p \cdot \Delta T = 14.84\text{ kW}, \quad \text{Gl. (19.2)}$$

$$P_{loss} = 17.9\text{ kW} - 14.84\text{ kW} = 2.35\text{ kW}. \quad \text{Gl. (19.3)}$$

$$Loss_1 = \frac{L_1 \cdot (T_{prim,in} - T_{amb.})}{L_1 \cdot (T_{prim,in} - T_{amb.}) + L_2 \cdot (T_{prim,out} - T_{amb.}) + L_3 \cdot (T_{sec,out} - T_{amb.})} \quad \text{Gl. (19.4)}$$

$Loss_1$ = 1.26 W,
$Loss_2$ = 0.46 W,
$Loss_3$ = 0.63 W.

The corrections for the temperatures are:

$$\Delta T_1 = \frac{P}{\Phi_{prim} \cdot \rho \cdot c_p} = 1.5\ K, \qquad \text{Gl. (19.5)}$$

$$\Delta T_2 = \frac{P}{\Phi_{prim} \cdot \rho \cdot c_p} = 0.5\ K, \qquad \text{Gl. (19.6)}$$

$$\Delta T_3 = \frac{P}{\Phi_{prim} \cdot \rho \cdot c_p} = 1.5\ K. \qquad \text{Gl. (19.7)}$$

The corrected temperatures are:

$$T_{prim,in} = T_{prim,in} - \Delta T_1 = 68.3\ °C, \qquad \text{Gl. (19.8)}$$

$$T_{prim,out} = T_{prim,out} + \Delta T_2 = 49.8\ °C, \qquad \text{Gl. (19.9)}$$

$$T_{sec,out} = T_{sec,out} + \Delta T_3 = 58.6\ °C. \qquad \text{Gl. (19.10)}$$

Calculation to standard temperatures:

$T_{prim,i}$ = 70 °C/$T_{sec,i}$ = 20 °C,

The efficiency is:

$$\eta = \frac{T_{sec,out} - T_{sec,in}}{T_{prim,in} - T_{sec,in}} = 0.79 \qquad \text{Gl. (19.11)}$$

The corrected standard output temperatures at $T_{prim,i}$ = 70 °C and $T_{sec,i}$ = 20 °C become:

$$T_{sec,out} = T_{sec,in} + \eta \cdot (T_{prim,in} - T_{sec,in}) = 59.7\ °C \quad \text{and} \qquad \text{Gl. (19.12)}$$

$$T_{prim,out} = T_{prim,in} + \frac{\Phi_{sec}}{\Phi_{prim}} \cdot (T_{sec,out} - T_{sec,in}) = 50.2\ °C\ . \qquad \text{Gl. (19.13)}$$

Heat Flow at Heat Meter:

Average heat loss pro meter:

$$P_{av.\ loss,\ in} = \frac{1.26}{2.6} = 0.48 \frac{kW}{m}, \qquad \text{Gl. (19.14)}$$

$$P_{av.\ loss,\ out} = \frac{0.46}{1.6} = 0.29 \frac{kW}{m}. \qquad \text{Gl. (19.15)}$$

The heat flow through the heat meter is:

$$P_{heatmeter} = P_{prim} + P_{loss,in} + P_{loss,out} = 17.79\ kW. \qquad \text{Gl. (19.16)}$$

Table with the measured and calculated temperatures:

Temperatures	$T_{measured}$ [°C]	$T_{corrected}$ [°C]	$T_{calculated}$ [°C]
$T_{prim,i}$	69.8	68.3	70
$T_{prim,out}$	49.2	49.8	50.2
$T_{sec,i}$	21.6	21.6	20
$T_{sec,out}$	57.1	58.6	59.7

Tab. 19.1: Table with the measured and calculated temperatures

20. APPENDIX K
Heat meters:

A: ICM RV 81.A

Temperature:

ΔT:	1 °C .. 100 °C
Temp. range:	20 °C .. 150 °C
Temp. sensor:	PT 100, DIN 43760

Flow:

Type	430
Q_n	0.6 m^3/h
DN	15
PN	16
meter class	C
Impuls	1/l

B: Thermiflo

Temperature:

ΔT:	3 °C .. 70 °C
Temp. range:	20 °C .. 90 °C
Temp. sensor:	PT 100, IEC 751

Flow:

Type	430
Q_n	1 m^3/h
DN	15
PN	16
meter class	C/H-B/V
Impuls	1/l

C: Clorius combimeter E 25

Temperature:

ΔT:	5 °C .. 80 °C
Temp. range:	20 °C .. 120 °C
Temp. sensor:	PT 100, ITL 21

Flow:

Type	6300015
Q_n	0.03 .. 1.5 m^3/h
DN	3/4"
PN	16
meter class	C QIML Class 4
Impuls	1/l

D: Pollux polluSonic-K

Temperature:

ΔT:	3 °C .. 100 °C
Temp. range:	0 °C .. 150 °C
Temp. sensor:	PT 100, ITL 21

Flow:

Type	DWU 90
Q_n	0.6 m^3/h
DN	15
PN	16
meter class	C/B
Impuls	1/l

21. APPENDIX L
Raw heat exchanger data

HEAT EXCHANGER A Reference with 0 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.0	46.7	2.0	23.2	62.3	723	160
2	6.0	70.0	53.9	2.0	23.3	63.8	703	170
3	8.0	70.0	57.7	2.0	23.4	64.1	688	184
4	10.0	70.1	60.2	2.0	23.5	64.3	675	201
5	12.0	70.0	61.8	2.0	23.6	64.4	642	222
6	4.0	70.2	34.7	4.0	22.6	53.1	734	159
7	6.0	70.0	42.4	4.0	22.7	58.0	718	169
8	8.0	69.9	47.9	4.0	22.7	60.3	696	184
9	10.0	70.0	51.7	4.0	22.7	61.5	677	201
10	12.0	70.1	54.6	4.0	22.7	62.3	645	222
11	4.0	70.0	30.0	6.0	22.2	45.7	736	159
12	6.0	69.8	36.1	6.0	22.1	51.6	716	170
13	8.0	70.1	41.4	6.0	21.9	55.1	699	184
14	10.0	70.0	45.5	6.0	21.9	57.2	680	201
15	12.0	70.0	48.7	6.0	21.9	58.5	647	222
16	4.0	69.8	27.3	8.0	21.5	40.0	731	159
17	6.0	70.1	32.4	8.0	21.4	46.2	705	170
18	8.0	70.0	37.1	8.0	21.3	50.1	690	184
19	10.0	70.0	41.0	8.0	21.3	52.6	675	201
20	12.0	69.9	44.3	8.0	21.2	54.5	646	223
21	4.0	90.0	56.5	2.0	23.0	79.2	712	162
22	6.0	89.9	66.7	2.0	23.0	81.0	682	171
23	4.0	90.1	39.1	4.0	21.8	65.5	730	161
24	6.0	90.1	50.2	4.0	21.7	72.9	706	171
25	4.0	90.0	32.8	6.0	21.8	55.3	734	161
26	6.0	90.1	41.9	6.0	21.8	63.7	716	170
27	4.0	89.9	29.6	8.0	21.5	47.8	734	160
28	6.0	90.0	36.9	8.0	21.4	56.0	718	171

Tab. 21.1: Heat exchanger A - reference with 0 wppm

HEAT EXCHANGER A - Habon-G concentration = 119 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.0	46.9	2.0	22.5	61.3	727	160
2	6.0	70.0	53.8	2.0	22.4	63.1	708	170
3	8.0	69.8	57.5	2.0	22.3	63.3	687	184
4	10.0	70.1	60.0	2.0	22.3	63.6	673	202
5	12.0	69.9	61.5	2.0	22.3	63.7	637	223
6	4.0	70.1	35.2	4.0	21.0	51.1	738	159
7	6.0	70.0	42.1	4.0	20.7	56.7	725	170
8	8.0	70.0	47.5	4.0	20.6	59.1	702	184
9	10.0	70.0	51.4	4.0	20.5	60.3	683	202
10	12.0	70.1	54.2	4.0	20.5	61.1	648	223
11	4.0	70.0	29.8	6.0	19.8	43.4	743	159
12	6.0	70.0	35.5	6.0	19.7	49.7	719	170
13	8.0	69.9	41.0	6.0	19.7	53.3	696	184
14	10.0	70.0	45.2	6.0	19.7	55.5	681	202
15	12.0	69.9	48.4	6.0	19.8	56.9	645	224
16	4.0	69.9	26.7	8.0	19.4	38.7	732	159
17	6.0	70.1	32.1	8.0	20.0	44.9	711	170
18	8.0	70.0	36.8	8.0	19.9	49.0	691	184
19	10.0	69.9	40.9	8.0	19.8	51.7	668	202
20	12.0	70.0	44.3	8.0	19.6	53.6	644	224
21	4.0	90.0	56.2	2.0	21.7	78.3	721	160
22	6.0	90.0	66.5	2.0	21.7	80.2	686	171
23	4.0	89.9	41.1	4.0	20.5	62.7	731	161
24	6.0	90.0	51.8	4.0	21.1	70.0	700	170
25	4.0	90.0	35.1	6.0	20.0	51.7	729	161
26	6.0	89.9	43.9	6.0	19.8	59.4	706	170
27	4.0	89.9	31.8	8.0	19.4	45.1	728	161
28	6.0	90.0	39.5	8.0	19.4	52.6	711	171

Tab. 21.2: Heat exchanger A - Habon-G concentration = 119 wppm

HEAT EXCHANGER A - Habon-G concentration = 520 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.0	48.2	2.0	24.3	60.3	715	161
2	6.0	70.0	54.6	2.0	24.5	62.3	689	171
3	8.0	70.0	58.1	2.0	24.6	63.0	656	185
4	10.0	70.1	60.0	2.0	24.6	63.6	640	201
5	12.0	70.1	61.6	2.0	24.7	64.3	602	221
6	4.0	70.0	38.0	4.0	23.5	50.9	718	160
7	6.0	70.0	44.9	4.0	23.6	55.4	698	171
8	8.0	70.0	49.5	4.0	23.6	58.0	679	185
9	10.0	70.0	52.4	4.0	23.7	59.6	662	201
10	12.0	70.1	55.1	4.0	23.7	60.9	634	221
11	4.0	70.1	33.3	6.0	23.1	44.8	723	160
12	6.0	70.0	39.2	6.0	22.9	49.9	701	170
13	8.0	69.9	43.7	6.0	22.8	53.2	684	183
14	10.0	70.2	47.2	6.0	22.8	55.7	665	200
15	12.0	70.1	49.6	6.0	22.7	57.7	636	222
16	4.0	69.9	29.5	8.0	21.9	39.3	723	159
17	6.0	69.9	34.7	8.0	21.8	44.8	702	169
18	8.0	70.0	39.1	8.0	21.9	49.2	685	183
19	10.0	69.9	42.1	8.0	21.9	52.5	664	201
20	12.0	70.0	45.3	8.0	22.0	54.2	639	223
21	4.0	90.0	57.2	2.0	24.1	78.3	709	160
22	6.0	90.0	67.0	2.0	24.2	80.2	681	172
23	4.0	90.0	41.8	4.0	23.1	64.4	726	160
24	6.0	90.1	52.2	4.0	23.0	71.2	692	171
25	4.0	90.0	35.6	6.0	22.9	54.6	727	160
26	6.0	89.9	44.6	6.0	22.9	62.3	700	170
27	4.0	89.9	32.1	8.0	22.5	47.9	728	160
28	6.0	89.6	39.4	8.0	22.4	55.4	705	170

Tab. 21.3: Heat exchanger A - Habon-G concentration = 520 wppm

HEAT EXCHANGER A - Habon-G concentration = 1470 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.2	47.8	2.0	24.7	61.4	727	160
2	6.0	70.0	54.4	2.0	24.9	63.3	708	170
3	8.0	70.0	58.0	2.0	25.1	63.8	687	184
4	10.0	70.0	60.3	2.0	25.2	64.2	673	202
5	12.0	70.1	61.8	2.0	25.2	64.3	648	224
6	4.0	70.0	37.6	4.0	23.9	51.7	735	160
7	6.0	70.0	44.0	4.0	23.8	56.6	712	170
8	8.0	70.1	49.0	4.0	23.9	59.0	698	184
9	10.0	70.1	52.6	4.0	23.8	60.4	681	202
10	12.0	70.1	55.2	4.0	23.8	61.2	664	224
11	4.0	70.0	33.5	6.0	23.3	44.6	738	160
12	6.0	70.1	38.9	6.0	23.2	50.1	719	170
13	8.0	70.0	43.5	6.0	23.1	53.3	704	184
14	10.0	70.0	47.3	6.0	23.0	55.3	682	202
15	12.0	70.0	50.3	6.0	23.0	56.8	662	224
16	4.0	70.0	31.1	8.0	22.6	39.8	737	160
17	6.0	70.1	35.5	8.0	22.6	45.3	717	170
18	8.0	70.1	39.7	8.0	22.5	49.1	694	184
19	10.0	70.2	43.4	8.0	22.5	51.8	682	202
20	12.0	69.9	46.4	8.0	22.5	53.4	661	224
21	4.0	89.9	57.7	2.0	24.6	78.5	706	161
22	6.0	90.0	67.5	2.0	24.8	80.7	678	171
23	4.0	90.1	43.0	4.0	23.6	64.1	724	160
24	6.0	89.9	53.0	4.0	23.7	70.9	701	170
25	4.0	90.2	37.8	6.0	23.4	53.9	733	160
26	6.0	90.0	46.0	6.0	23.6	61.5	711	170
27	4.0	90.0	35.0	8.0	23.1	47.6	736	160
28	6.0	90.0	41.4	8.0	22.9	54.8	710	170

Tab. 21.4: Heat exchanger A - Habon-G concentration = 1470 wppm

HEAT EXCHANGER B - Reference with 0 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.2	47.8	2.0	23.3	60.8	733	173
2	6.0	70.0	54.4	2.0	23.3	62.6	708	195
3	8.0	70.0	58.0	2.0	23.4	63.3	691	225
4	10.0	70.0	60.3	2.0	23.5	63.7	679	261
5	12.0	70.1	61.8	2.0	23.5	63.7	642	306
6	4.0	70.0	37.6	4.0	22.4	50.6	738	173
7	6.0	70.0	44.0	4.0	22.3	55.1	715	195
8	8.0	70.1	49.0	4.0	22.2	57.9	693	225
9	10.0	70.1	52.6	4.0	22.2	59.3	677	262
10	12.0	70.1	55.2	4.0	22.2	60.4	647	307
11	4.0	70.0	33.5	6.0	21.9	43.8	733	173
12	6.0	70.1	38.9	6.0	21.8	49.1	710	196
13	8.0	70.0	43.5	6.0	21.7	52.7	697	226
14	10.0	70.0	47.3	6.0	21.6	55.3	676	263
15	12.0	70.0	50.3	6.0	21.6	57.1	647	308
16	4.0	70.0	31.1	8.0	21.4	38.8	731	173
17	6.0	70.1	35.5	8.0	21.4	44.3	715	196
18	8.0	70.1	39.7	8.0	21.4	49.8	698	226
19	10.0	70.2	43.4	8.0	21.3	51.6	680	264
20	12.0	69.9	46.4	8.0	21.4	53.7	653	308
21	4.0	89.9	57.7	2.0	23.2	77.3	715	174
22	6.0	90.0	67.5	2.0	23.4	79.9	694	195
23	4.0	90.1	43.0	4.0	22.4	62.9	731	174
24	6.0	89.9	53.0	4.0	22.5	70.2	709	195
25	4.0	90.2	37.8	6.0	22.2	53.3	737	174
26	6.0	90.0	46.0	6.0	22.0	61.6	717	195
27	4.0	90.0	35.0	8.0	21.7	46.7	737	174
28	6.0	90.0	41.4	8.0	21.7	55.2	720	196

Tab. 21.5: Heat exchanger B - reference with 0 wppm

HEAT EXCHANGER B - Habon-G concentration = 119 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.1	45.9	2.0	21.1	61.4	720	220
2	6.0	70.0	53.0	2.0	20.7	63.1	700	293
3	8.0	70.0	57.0	2.0	20.8	63.6	679	368
4	10.0	70.2	59.6	2.0	20.9	63.7	647	503
5	11.8	70.0	60.9	2.0	20.9	63.8	619	627
6	4.0	70.1	34.1	4.0	19.8	50.7	726	223
7	6.0	69.9	41.2	4.0	19.8	56.8	703	298
8	8.0	70.0	46.5	4.0	19.7	59.6	684	392
9	10.0	70.0	50.4	4.0	19.6	61.0	664	509
10	11.9	70.1	53.1	4.0	19.5	61.9	633	639
11	4.0	70.1	29.4	6.0	18.8	42.4	723	224
12	6.0	70.1	34.9	6.0	18.6	49.2	702	300
13	8.0	70.0	39.8	6.0	18.6	53.5	682	397
14	10.0	70.1	43.9	6.0	18.6	56.1	658	514
15	11.8	70.1	46.9	6.0	18.6	57.8	634	642
16	4.0	70.0	27.5	7.5	18.3	38.2	722	225
17	6.0	70.0	32.1	7.6	18.5	44.8	699	302
18	8.0	70.1	36.6	7.6	18.5	49.2	683	400
19	10.0	70.1	40.5	7.6	18.7	52.5	665	518
20	11.8	70.1	43.7	7.7	19.3	54.6	638	645
21	4.0	90.1	56.0	2.0	21.8	78.6	712	218
22	6.0	89.7	66.0	2.0	22.0	80.3	680	287
23	4.0	90.0	43.0	4.0	20.0	60.4	731	210
24	6.0	90.0	49.5	4.0	19.7	71.6	708	283
25	4.0	89.9	39.7	6.0	19.0	48.4	728	208
26	6.0	90.1	42.7	6.0	18.8	60.0	714	279
27	4.0	90.1	38.8	7.6	18.6	42.3	734	207
28	6.0	90.1	40.3	7.6	18.5	52.9	717	276

Tab. 21.6: Heat exchanger B - Habon-G concentration = 119 wppm

HEAT EXCHANGER B - Habon-G concentration = 520 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.0	47.7	2.0	24.2	60.4	717	171
2	6.0	70.0	53.8	2.0	24.2	62.6	695	193
3	8.0	70.0	57.6	2.0	24.3	63.5	680	223
4	10.0	70.2	60.0	2.0	24.2	63.8	658	259
5	12.0	70.1	61.6	2.0	24.2	64.2	629	304
6	4.0	69.9	38.3	4.0	23.3	50.8	730	172
7	6.0	70.1	45.3	4.0	23.6	55.6	709	195
8	8.0	70.3	50.0	4.0	24.0	58.5	691	226
9	10.0	69.8	53.0	4.0	24.0	59.7	674	263
10	12.0	69.9	55.5	4.0	24.0	60.7	642	308
11	4.0	70.1	33.9	6.0	23.2	44.6	728	173
12	6.0	70.0	39.6	6.0	23.3	49.9	713	196
13	8.0	70.1	44.1	6.0	23.2	53.3	696	226
14	10.0	70.0	47.3	6.0	23.1	55.9	671	264
15	12.0	69.9	50.1	6.0	23.1	57.5	637	309
16	4.0	70.2	30.1	8.0	22.4	40.0	728	173
17	6.0	70.2	35.1	8.0	22.2	45.3	709	196
18	8.0	69.9	39.3	8.0	22.2	49.4	690	227
19	10.0	69.8	42.9	8.0	22.5	52.2	668	264
20								
21	4.0	89.9	58.5	2.0	24.9	77.1	718	172
22	6.0	89.9	67.7	2.0	25.0	79.5	689	195
23	4.0	90.0	44.2	4.0	23.7	63.1	726	172
24	6.0	90.3	54.0	4.0	24.4	70.7	711	195
25	4.0	90.0	37.5	6.0	23.1	53.7	732	173
26	6.0	90.2	45.6	6.0	23.3	62.2	709	195
27	4.0	89.9	33.5	8.0	22.8	47.6	732	173
28								

Tab. 21.7: Heat exchanger B - Habon-G concentration = 520 wppm

HEAT EXCHANGER B - HABON-G CONCENTRATION = 1470 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.0	48.2	2.0	25.4	60.6	724	179
2	6.0	70.0	54.3	2.0	25.5	62.8	703	197
3	8.0	70.0	57.9	2.0	25.6	63.5	687	228
4	10.0	70.0	60.3	2.0	25.7	63.9	670	265
5	12.0	70.1	62.0	2.0	25.8	64.1	648	309
6	4.0	70.0	40.7	4.0	24.6	49.6	730	179
7	6.0	70.0	46.0	4.0	24.6	55.1	715	198
8	8.0	69.9	50.1	4.0	24.6	57.7	699	228
9	10.0	69.9	53.2	4.0	24.7	59.4	685	264
10	12.0	70.0	55.8	4.0	24.7	60.5	661	309
11	4.0	69.9	37.3	6.0	24.1	43.3	735	180
12	6.0	70.0	41.1	6.0	24.0	49.0	717	199
13	8.0	70.1	44.7	6.0	24.0	52.8	701	228
14	10.0	70.0	47.9	6.0	23.9	55.3	685	264
15	12.0	70.1	50.6	6.0	23.8	57.1	667	309
16	4.0	69.7	34.5	8.0	23.4	38.8	737	181
17	6.0	70.2	37.6	8.0	23.3	44.6	720	200
18	8.0	70.2	40.8	8.0	23.2	48.3	708	228
19	10.0	69.9	43.9	8.0	23.2	51.4	682	265
20	12.0	70.0	46.6	8.0	23.1	53.5	658	309
21	4.0	90.0	57.7	2.0	25.1	77.0	702	173
22	6.0	89.9	66.7	2.0	24.9	79.9	672	193
23	4.0	90.0	44.2	4.0	23.2	61.6	730	173
24	6.0	89.8	53.0	4.0	23.0	69.1	705	193
25	4.0	90.1	38.8	6.0	22.3	52.1	735	174
26	6.0	89.8	45.5	6.0	22.4	60.3	715	193
27								
28								

Tab. 21.8: Heat exchanger B - Habon-G concentration = 1470 wppm

HEAT EXCHANGER C - Reference with = 0 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.1	46.3	2.0	23.2	62.4	727	220
2	6.0	70.0	53.2	2.0	23.2	63.9	709	292
3	8.0	70.0	57.0	2.0	23.0	64.1	684	384
4	10.0	70.0	59.4	2.0	22.7	64.5	671	497
5	12.0	70.0	61.2	2.0	22.8	64.5	645	635
6	4.0	69.9	34.8	4.0	21.7	51.8	733	222
7	6.0	69.8	42.0	4.0	22.0	57.7	712	297
8	8.0	70.0	47.2	4.0	22.0	60.5	703	390
9	10.0	70.0	51.0	4.0	22.0	61.9	676	504
10	12.0	70.1	53.7	4.0	21.9	62.7	649	639
11	4.0	70.1	31.0	6.0	21.4	44.3	730	224
12	6.0	70.0	36.4	6.0	21.3	50.8	709	300
13	8.0	70.0	41.2	6.0	21.2	54.7	688	396
14	10.0	70.4	45.3	6.0	21.1	57.4	674	511
15	12.0	70.1	48.2	6.0	21.1	59.0	653	645
16	4.0	70.0	28.5	7.6	19.8	38.8	725	225
17	6.0	69.9	32.8	7.6	19.7	45.4	707	303
18	8.0	70.1	37.2	7.6	19.7	50.0	690	403
19	10.0	70.1	41.0	7.6	19.7	53.1	673	523
20	12.0	70.0	43.9	7.6	19.7	55.2	650	665
21	4.0	90.0	56.4	2.0	22.8	79.5	718	219
22	6.0	90.0	66.6	2.0	23.0	81.2	693	287
23	4.0	90.0	40.5	4.0	22.2	64.7	733	222
24	6.0	90.0	50.5	4.0	22.1	72.8	714	292
25	4.0	90.0	34.9	6.0	22.8	54.1	730	224
26	6.0	90.0	42.6	6.0	21.9	63.1	713	297
27	4.0	90.1	31.7	7.6	20.1	47.4	725	224
28	6.0	90.0	37.6	7.7	19.9	56.6	698	301

Tab. 21.9: Heat exchanger C - reference with = 0 wppm

HEAT EXCHANGER C - Habon-G concentration = 119 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.0	45.5	2.0	21.2	60.3	725	212
2	6.0	69.9	52.3	2.0	21.4	63.1	690	293
3	8.0	70.2	56.6	2.0	21.4	63.8	665	387
4	10.0	70.0	59.1	2.0	21.5	63.7	639	504
5	11.7	70.1	60.7	2.0	21.5	63.8	607	617
6	4.0	70.1	34.3	4.0	20.6	51.1	719	222
7	6.0	70.0	41.4	4.0	21.0	57.4	701	298
8	8.0	70.0	46.8	4.0	21.1	60.0	683	392
9	10.0	70.0	50.7	4.0	21.1	61.5	663	510
10	11.9	70.1	53.4	4.0	21.1	62.2	635	641
11	4.0	70.0	30.5	6.0	20.6	43.4	730	224
12	6.0	69.8	35.8	6.0	20.6	49.9	703	300
13	8.0	70.0	40.7	6.0	20.6	54.2	685	398
14	10.0	70.0	44.5	6.0	20.6	56.7	668	514
15	11.9	70.0	47.5	6.0	20.6	58.3	639	646
16	4.0	70.1	28.6	7.7	20.1	38.8	724	224
17	6.0	70.0	32.9	7.8	20.0	45.2	702	302
18	8.0	70.1	37.2	7.8	20.0	49.7	682	401
19	10.0	70.0	40.5	7.8	19.4	52.5	666	519
20	11.8	69.9	43.1	7.7	18.8	54.4	638	646
21	4.0	90.0	55.4	2.0	21.1	78.3	715	218
22	6.0	90.0	65.7	2.0	21.2	80.2	675	288
23	4.0	90.0	43.4	4.0	20.0	59.9	728	210
24	6.0	89.9	50.0	4.0	20.0	70.8	707	280
25	4.0	90.1	40.6	6.0	19.4	48.1	734	207
26	6.0	90.0	43.2	6.0	19.3	59.9	714	277
27	4.0	90.0	40.2	7.6	20.3	42.8	734	207
28	6.0	90.0	41.4	7.7	20.4	53.5	709	276

Tab. 21.10: Heat exchanger C - Habon-G concentration = 119 wppm

HEAT EXCHANGER C - Habon-G concentration = 520 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.2	47.5	2.0	25.1	62.6	732	221
2	6.0	70.1	54.5	2.0	25.1	64.3	713	294
3	8.0	70.0	58.1	2.0	25.1	64.4	689	388
4	10.0	70.1	60.2	2.0	25.3	64.6	662	503
5	11.7	70.0	61.6	2.0	25.3	64.6	625	621
6	4.0	70.3	36.8	4.0	24.4	53.3	736	223
7	6.0	70.2	43.5	4.0	24.5	58.8	715	297
8	8.0	69.8	48.3	4.0	24.4	61.2	696	393
9	10.0	69.9	52.0	4.0	24.2	62.3	670	509
10	11.8	70.1	54.4	4.0	24.1	62.9	643	633
11	4.0	69.9	32.1	6.0	23.1	45.0	728	224
12	6.0	69.8	37.0	6.0	22.7	51.4	708	300
13	8.0	69.9	42.1	6.0	23.5	55.7	699	397
14	10.0	70.0	45.9	6.0	23.5	58.3	680	514
15	11.9	69.9	48.7	6.0	23.5	59.6	652	644
16	4.0	70.0	29.7	7.8	22.1	39.9	729	224
17	6.0	70.0	34.6	7.9	23.1	47.2	720	302
18	8.0	70.0	38.5	7.9	23.1	51.5	701	400
19	10.0	69.9	42.0	7.9	23.1	54.4	683	518
20								
21	4.0	90.4	57.3	2.0	24.9	79.7	718	219
22	6.0	90.0	67.2	2.0	24.9	81.3	695	289
23	4.0	90.2	41.2	4.0	23.8	66.2	734	222
24	6.0	90.1	51.3	4.0	24.1	74.2	710	294
25	4.0	89.7	35.6	6.0	23.7	55.4	731	223
26								
27	4.0	89.9	33.1	7.8	23.3	49.1	734	224
28								

Tab. 21.11:Heat exchanger C - Habon-G concentration = 520 wppm

HEAT EXCHANGER C - Habon-G concentration = 1470 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	69.9	47.4	2.0	24.3	61.0	742	218
2	6.0	70.0	53.6	2.0	24.5	63.5	717	286
3	8.0	70.0	57.6	2.0	24.7	64.0	689	374
4	10.0	70.1	60.0	2.0	24.8	64.3	669	477
5	12.0	70.0	61.6	2.0	24.9	64.4	659	598
6	4.0	70.0	38.4	4.0	23.8	50.8	740	220
7	6.0	69.9	43.7	4.0	23.7	56.8	719	289
8	8.0	70.2	48.6	4.0	23.8	60.1	701	380
9	10.0	70.0	52.0	4.0	23.7	61.6	683	485
10	12.0	70.1	54.7	4.0	23.7	62.5	664	611
11	4.0	70.0	34.7	6.0	23.0	43.5	740	221
12	6.0	70.0	38.7	6.0	23.0	50.1	717	293
13	8.0	70.0	42.8	6.0	23.0	54.0	703	382
14	10.0	70.0	46.4	6.0	22.9	56.6	679	491
15	12.0	69.9	49.2	6.0	22.9	58.4	656	617
16	4.0	69.9	32.8	7.7	22.5	38.7	739	222
17	6.0	70.0	36.1	7.8	22.4	45.0	720	295
18	8.0	70.0	39.5	7.8	22.3	49.5	697	384
19	10.0	70.0	42.7	7.8	22.2	52.6	683	494
20	12.0	70.0	45.7	7.8	22.2	54.9	666	624
21	4.0	90.0	58.3	2.0	24.2	77.0	715	209
22	6.0	89.9	67.6	2.0	24.3	79.3	684	258
23	4.0	90.0	43.9	4.0	23.1	62.3	737	214
24	6.0	89.7	53.6	4.0	23.1	69.5	711	269
25	4.0	90.1	38.9	6.0	22.8	52.4	744	215
26	6.0	89.9	46.2	6.0	23.0	60.7	723	276
27	4.0	89.7	36.5	7.8	22.9	46.7	744	217
28	6.0	89.9	42.2	7.8	22.9	55.0	723	280

Tab. 21.12: Heat exchanger C - Habon-G concentration = 1470 wppm

HEAT EXCHANGER D - Reference with 0 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.0	47.9	2.0	22.8	59.4	719	192
2	6.0	70.0	54.2	2.0	22.8	63.0	699	229
3	8.0	70.0	57.9	2.0	22.8	63.0	677	277
4	10.0	70.0	60.1	2.0	22.9	63.5	658	339
5	12.0	70.0	61.6	2.0	22.9	63.7	624	415
6	4.0	70.0	37.6	4.0	21.8	49.8	716	194
7	6.0	70.0	44.7	4.0	21.8	54.4	702	231
8	8.0	70.0	49.4	4.0	21.8	56.9	672	280
9	10.0	70.0	52.8	4.0	21.9	58.6	654	342
10	12.0	70.0	55.2	4.0	21.8	59.6	625	417
11	4.0	69.9	33.1	6.0	21.3	42.1	717	196
12	6.0	70.1	39.4	6.0	21.1	47.8	704	234
13	8.0	70.0	44.2	6.0	21.1	51.1	683	283
14	10.0	70.1	47.8	6.0	21.2	53.5	661	345
15	12.0	70.0	50.5	6.0	21.2	55.2	625	421
16	4.0	70.0	30.8	7.9	21.0	38.4	727	196
17	6.0	70.0	36.3	7.9	20.7	43.0	714	235
18	8.0	69.9	40.7	7.9	20.7	46.5	698	285
19	10.0	70.0	44.7	8.0	21.9	49.3	671	346
20	12.0	69.9	47.3	8.0	21.7	51.1	641	420
21	4.0	89.9	57.6	2.0	22.7	76.0	708	190
22	6.0	90.0	66.9	2.0	22.8	79.0	685	226
23	4.0	89.9	43.5	4.0	21.9	62.0	720	193
24	6.0	90.0	53.4	4.0	21.8	68.7	703	228
25	4.0	90.1	37.6	6.0	21.6	51.8	726	194
26	6.0	90.0	46.5	6.0	21.5	59.5	702	231
27	4.0	90.0	34.4	8.0	21.5	46.0	724	195
28	6.0	90.0	42.2	8.0	21.4	53.0	705	232

Tab. 21.13: Heat exchanger D - reference with 0 wppm

HEAT EXCHANGER D - Habon-G concentration = 119 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	69.9	47.7	2.0	21.8	59.2	710	192
2	6.0	70.0	54.1	2.0	21.7	61.4	697	229
3	8.0	70.0	57.6	2.0	21.7	62.2	670	278
4	10.0	70.1	59.9	2.0	21.8	62.8	653	340
5	12.0	70.0	61.5	2.0	21.8	63.1	622	414
6	4.0	70.0	36.8	4.0	20.3	48.8	724	194
7	6.0	69.9	43.9	4.0	20.0	53.5	702	232
8	8.0	70.0	48.8	4.0	19.9	56.3	683	281
9	10.0	70.0	52.2	4.0	20.1	57.9	663	343
10	12.0	70.0	54.8	4.0	20.4	58.9	632	418
11	4.0	70.0	32.9	6.0	20.7	42.2	723	196
12	6.0	70.0	39.4	6.0	20.6	47.3	704	234
13	8.0	70.1	44.0	6.0	20.4	50.4	690	284
14	10.0	70.0	47.4	6.0	20.1	52.5	666	346
15	12.0	70.1	50.2	6.0	20.1	54.1	635	421
16	4.0	69.8	30.1	8.0	19.9	37.3	725	197
17	6.0	69.9	36.0	8.0	19.9	41.9	701	236
18	8.0	70.0	40.5	8.0	19.8	45.7	686	286
19	10.0	70.0	44.0	8.0	19.7	48.1	667	348
20	12.0	69.9	46.8	8.0	19.7	50.0	639	424
21	4.0	89.9	57.7	2.0	21.7	75.2	702	190
22	6.0	89.9	66.7	2.0	21.8	78.0	663	226
23	4.0	89.9	43.3	4.0	20.6	60.2	711	192
24	6.0	89.9	53.3	4.0	20.6	67.0	689	227
25	4.0	90.0	38.2	6.0	19.1	49.0	715	193
26	6.0	90.1	46.7	6.0	19.1	56.4	687	227
27	4.0	89.9	35.4	8.0	18.4	42.4	709	195
28	6.0	90.0	43.5	8.0	19.0	49.7	685	229

Tab. 21.14: Heat exchanger D - Habon-G concentration = 119 wppm

HEAT EXCHANGER D - Habon-G concentration = 520 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.0	48.2	2.0	24.1	59.8	722	193
2	6.0	70.0	54.4	2.0	24.2	62.4	708	229
3	8.0	70.0	58.0	2.0	24.3	63.2	689	278
4	10.0	70.1	60.4	2.0	24.5	63.7	655	340
5	12.0	70.1	62.1	2.0	24.6	63.7	628	418
6	4.0	70.0	38.4	4.0	23.2	50.6	723	194
7	6.0	70.1	45.4	4.0	23.2	55.4	700	232
8	8.0	69.8	49.9	4.0	23.2	57.7	679	281
9	10.0	70.0	53.2	4.0	23.4	59.2	657	343
10	12.0	70.1	55.7	4.0	23.6	60.2	621	418
11	4.0	70.0	34.6	6.0	23.3	44.1	717	195
12	6.0	70.2	40.8	6.0	23.3	49.0	698	234
13	8.0	70.1	45.3	6.0	23.3	52.0	683	283
14	10.0	70.0	48.6	6.0	23.2	54.0	668	346
15	12.0	70.1	51.3	6.0	23.2	55.6	638	422
16	4.0	69.9	32.0	8.0	22.7	39.2	729	196
17	6.0	70.0	37.5	8.0	22.7	43.9	704	235
18	8.0	70.0	41.8	8.0	22.5	47.2	686	286
19	10.0	70.0	45.2	8.0	22.5	49.6	668	348
20	12.0	69.9	47.9	8.0	22.5	51.6	641	425
21	4.0	89.9	58.9	2.0	24.5	76.7	712	190
22	6.0	90.2	68.1	2.0	24.5	79.5	681	226
23	4.0	89.7	44.5	4.0	23.3	62.6	715	192
24	6.0	90.0	54.2	4.0	23.2	69.3	689	229
25	4.0	90.0	38.3	6.0	22.6	52.6	721	194
26	6.0	90.0	47.1	6.0	22.6	59.9	695	231
27	4.0	90.0	35.1	8.0	22.2	46.0	722	195
28	6.0	90.0	42.8	8.0	22.1	53.0	699	232

Tab. 21.15: Heat exchanger D - Habon-G concentration = 520 wppm

HEAT EXCHANGER D - Habon-G concentration = 1470 wppm

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.1	48.4	2.0	24.6	59.3	724	198
2	6.0	70.0	54.6	2.0	24.6	61.8	700	236
3	8.0	70.1	58.2	2.0	24.4	62.6	677	284
4	10.0	70.0	60.5	2.0	24.3	63.0	662	344
5	12.0	70.0	62.0	2.0	24.2	63.4	638	414
6	4.0	70.0	39.0	4.0	23.0	49.5	729	201
7	6.0	70.0	45.7	4.0	23.0	53.9	715	238
8	8.0	69.9	50.3	4.0	23.1	56.7	699	287
9	10.0	69.9	53.5	4.0	23.1	58.4	681	346
10	12.0	69.9	55.7	4.0	22.9	59.4	658	417
11	4.0	69.9	34.9	6.0	22.5	42.9	741	203
12	6.0	69.9	41.1	6.0	22.6	47.8	721	241
13	8.0	70.0	45.6	6.0	22.7	50.9	696	289
14	10.0	70.2	49.1	6.0	22.8	53.1	678	349
15	12.0	70.0	51.6	6.0	22.8	54.6	667	420
16	4.0	69.8	32.8	8.0	22.5	38.2	742	204
17	6.0	69.9	38.3	8.0	22.4	42.6	719	243
18	8.0	69.9	42.5	8.0	22.4	45.9	705	291
19	10.0	69.9	45.8	8.0	22.3	48.6	685	352
20	12.0	70.0	48.6	8.0	22.3	50.4	669	424
21	4.0	90.0	59.1	2.0	24.2	75.6	718	191
22	6.0	89.9	68.1	2.0	24.3	78.2	687	223
23	4.0	90.0	45.2	4.0	23.1	61.1	729	194
24	6.0	90.1	55.5	4.0	23.1	67.2	700	227
25	4.0	90.1	39.8	6.0	22.7	51.5	730	195
26	6.0	90.0	48.9	6.0	22.7	57.9	702	230
27	4.0	90.2	39.3	8.0	21.7	45.1	734	197
28	6.0	89.9	44.4	8.0	21.9	51.6	707	232

Tab. 21.16: Heat exchanger D - Habon-G concentration = 1470 wppm

22. APPENDIX M
Result second reference measurement

HEAT EXCHANGER B - Reference 2

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.1	46.8	2.0	21.5	60.1	729	174
2	6.0	70.0	52.9	2.0	21.5	61.7	693	196
3	8.0	70.0	57.0	2.0	21.5	62.5	689	225
4	10.0	69.9	59.2	2.0	21.5	62.9	666	262
5	12.0	70.1	61.0	2.0	21.4	63.1	641	308
6	4.0	69.8	35.9	4.0	20.5	49.3	725	173
7	6.0	70.0	42.9	4.0	20.6	54.5	714	196
8	8.0	70.0	47.8	4.0	20.5	57.2	693	226
9	10.0	70.1	51.3	4.0	20.4	58.8	678	264
10	12.0	70.2	53.9	4.0	20.4	59.9	655	309
11	4.0	70.1	31.4	6.0	20.0	41.9	736	173
12	6.0	69.9	37.3	6.0	19.9	47.8	717	196
13	8.0	69.9	41.9	6.0	19.6	51.3	704	227
14	10.0	70.2	45.6	6.0	19.6	53.9	686	265
15	12.0	70.1	48.5	6.0	19.5	55.6	663	310
16								
17								
18								
19								
20								
21	4.0	90.1	56.4	2.0	20.7	75.6	724	173
22	6.0	90.0	65.8	2.0	20.7	78.2	698	195
23	4.0	90.0	41.7	4.0	19.8	60.3	728	173
24	6.0	89.9	51.3	4.0	19.8	68.2	703	196
25	4.0	90.0	35.6	6.0	19.3	50.5	729	174
26	6.0	90.0	43.3	6.0	19.2	59.0	711	196
27								
28								

Tab. 22.17: Heat exchanger B - reference 2

HEAT EXCHANGER C - Reference 2

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.1	46.0	2.0	22.3	61.4	711	222
2								
3	8.0	70.2	56.7	2.0	22.4	63.5	662	391
4	10.0	70.1	59.3	2.0	22.4	63.7	640	508
5								
6	4.0	70.2	34.7	4.0	21.2	51.1	711	222
7	6.0	70.0	41.6	4.0	21.3	56.9	689	299
8	8.0	70.0	46.8	4.0	21.3	59.8	671	395
9	10.0	70.1	50.7	4.0	21.3	61.1	652	514
10	12.0	70.0	53.5	4.0	21.2	61.9	624	654
11	4.0	70.1	30.8	6.0	20.7	43.4	717	224
12	6.0	69.9	35.9	6.0	20.6	50.2	699	302
13	8.0	69.9	40.6	6.0	20.5	54.2	686	400
14	10.0	70.1	44.5	6.0	20.4	56.7	669	519
15	12.0	70.0	47.5	6.0	20.4	58.4	644	659
16	4.0	70.0	28.5	7.6	19.8	38.8	725	225
17	6.0	69.9	32.8	7.6	19.7	45.4	707	303
18	8.0	70.1	37.2	7.6	19.7	50.0	690	403
19	10.0	70.1	40.9	7.6	19.7	53.1	673	523
20	12.0	70.0	43.9	7.6	19.7	55.2	650	665
21	4.0	90.0	55.6	2.0	21.6	78.2	712	220
22	6.0	90.1	65.9	2.0	21.7	80.1	681	291
23	4.0	90.0	39.2	4.0	20.6	63.7	716	222
24	6.0	90.0	49.5	4.0	20.7	72.1	692	296
25	4.0	90.0	33.9	6.0	20.4	52.8	720	223
26	6.0	90.2	41.2	6.0	20.4	62.5	698	300
27	4.0	90.1	31.7	7.5	20.1	47.4	725	224
28	6.0	89.9	37.6	7.5	19.9	56.6	698	301

Tab. 22.18: Heat exchanger C - reference 2

HEAT EXCHANGER D - Reference 2

point	primary system			secondary system			pressure drop	
	flow [l/min]	T_{in} [°C]	T_{out} [°C]	flow [l/min]	T_{in} [°C]	T_{out} [°C]	pump [mbar]	exch. [mbar]
1	4.0	70.0	47.2	2.0	22.1	59.5	724	194
2	6.0	70.0	53.6	2.0	22.1	61.5	705	231
3	8.0	70.0	57.4	2.0	22.2	62.2	691	281
4	10.0	70.0	59.9	2.0	22.2	62.7	665	343
5	12.0	70.0	61.4	2.0	22.3	62.9	645	418
6	4.0	70.0	37.0	4.0	21.1	49.3	726	195
7	6.0	70.0	44.2	4.0	21.1	54.0	710	233
8	8.0	70.1	48.8	4.0	21.1	56.7	685	283
9	10.0	70.1	52.2	4.0	21.1	58.3	665	345
10	12.0	70.0	54.7	4.0	21.0	59.3	641	421
11	4.0	70.1	32.4	6.0	20.5	42.2	720	196
12	6.0	70.0	38.8	6.0	20.3	47.1	701	235
13	8.0	70.1	43.5	6.0	20.2	50.4	681	286
14	10.0	70.1	47.1	6.0	20.0	52.6	666	349
15	12.0	69.9	49.8	6.0	20.0	54.2	642	424
16	4.0	70.0	29.6	8.0	19.6	37.1	723	198
17	6.0	70.0	35.5	8.0	19.5	41.9	704	237
18	8.0	70.1	40.0	8.0	19.4	45.4	685	288
19	10.0	69.9	43.5	8.0	19.4	48.0	666	350
20	12.0	70.0	46.4	8.0	19.4	50.0	637	426
21	4.0	89.9	57.8	2.0	21.5	75.0	697	191
22	6.0	89.9	66.9	2.0	21.6	77.6	670	228
23	4.0	90.0	43.1	4.0	20.6	60.5	709	193
24	6.0	90.0	53.3	4.0	20.7	67.4	680	230
25	4.0	90.0	37.6	6.0	21.0	51.1	714	195
26	6.0	90.0	46.7	6.0	21.1	58.4	695	233
27	4.0	89.9	34.7	8.0	21.0	44.8	720	196
28	6.0	90.0	42.7	8.0	21.0	51.8	697	234

Tab. 22.19: Heat exchanger D - reference 2