Measuring Selected Parameters of Polypropylene Fibre Heat Exchangers

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Heat exchangers whose heat exchange surfaces are made of the miniature polypropylene fibres are still under development. In the first phase of researching such exchangers, the possibility of attaching fibres into bundles was tested. The number of threads in one bundle ranges from several hundred to thousands of pieces. The sensitive element in the application of the fibres in a heat exchanger is the place where all the fibres are bundled together, into so-called potting, which must be perfectly tight. Pressure loss was measured in such bundles, depending on the water flow and the temperature at the entry and exit of the exchanger. The results allowed the definition of the overall heat transfer coefficient from one medium through the fibre wall to the other media and to determine the thermal performance of the exchanger. Experimental data shows that water-to-water heat exchanger reached the overall heat transfer coefficient value of to 800 W·m^{-2}·K^{-1}, depending on the release rate of the bundle. Subsequently, for the given conditions, the heat transfer rate depends only on the size of the heat transfer surface area, thus the number of fibres in the bundle.
Keywords: polypropylene fibre, heat exchanger, measurement

Highlights
- *A new type of heat exchanger whose heat exchange surface consists of polypropylene fibres has been designed and tested.*
- *A testing seal potting apparatus has been developed.*
- *Media temperature, flow rate and pressure drop in selected bundles of fibres with transparent and porous fibre were measured.*
- *The impact of fibre length on the value of the overall heat transfer coefficient for this new type of heat exchanger was examined.*

0 INTRODUCTION

Currently, the proposed design of heat exchangers and other equipment must satisfy complex requirements in terms of production technology [1] and [2], trouble-free operation [3] and economic feasibility [4] and [5]. The main requirements for heat exchangers include a large overall heat transfer coefficient, low flow resistance, a simple process of cleaning the heat transfer surface area, corrosion resistance in various transported media, adaptation of the shape of the heat exchanger to the specified manufacturing needs, as well as price [6] and [7].

The critical operating parameters being monitored in heat exchangers include [8] and [9]:
- Operating pressure: that can range from a deep vacuum in fractions of Pa to pressures reaching tens of MPa.
- Operating temperature: from values close to absolute zero up to 1000 °C and higher.
- Mass flow rate: from a few grams to hundreds of kilograms of media per second.
- Good accessibility to a heat exchange area (necessary condition for cleaning and checking the status of working surfaces, especially

when working with corrosive chemicals or a heterogeneous suspension with a tendency to form deposits, encrustations and corrosion).

Decontamination and hygiene of a heat exchange surface is a specific condition for heat exchangers in the area of food and medical technologies. In addition to physical and chemical cleanliness, decontamination requirements also include bacterial cleanliness and harmlessness of heat exchange surfaces.

In industrial practice, the most often used heat exchangers are constructed of steel or other metals; plastic is used less commonly as a construction material.

As for plastic heat exchangers, the advantage is the durability of the material (up to 50 years), resistance to corrosion, chemicals and bacteria, high sanitary standards and low volume weight.

One of the disadvantages of plastic heat exchangers is their lower material strength in comparison to metal exchangers, low resistance to higher temperatures (max. 150 °C), lower resistance to mechanical damage, risk of penetration of the diffused oxygen into the cooling medium, as well as a lower connection quality [10] and [11].

Individual parts of a heat exchanger are connected by glue or are welded. Welded constructions of heat exchangers are of a better quality and also find application in highly aggressive environments.

A particular feature of plastic heat exchangers is that they are not produced in a gilled configuration because of the low thermal conductivity of the plastic.

A separate group of plastic heat exchangers are heat exchangers in which the heat exchange surface is made of polypropylene fibres (capillaries) [12] and [13].

Other cited works state the results of experiments by individual authors related to, for example, the possibility of using heat exchangers with polypropylene fibres to obtain waste heat from domestic and industrial water was assessed [14] and [15], the studies of the affinity of polypropylene fibres for biological pollution in comparison with stainless steel (Escherichia coli bacteria) [16], the use of exchangers with polypropylene fibres (as a source of heat) for thermal pumps was investigated [17], the interaction between the movement of fibres and heat transfer was monitored, the impact of the shape and size of the heat exchanging area upon the output of the exchanger was assessed the use of exchangers with polypropylene fibres (as a source of heat) for thermal pumps was investigated [18] and [19], etc.

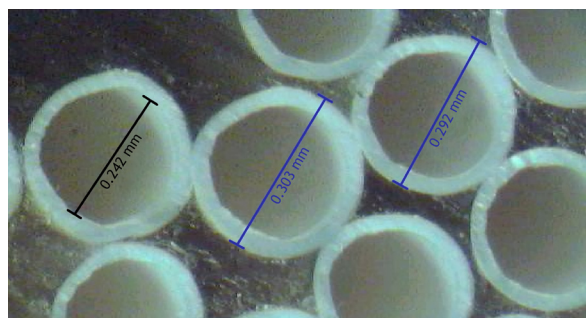The geometry of polypropylene fibres is shown in Fig. 1.

Fig. 1. *The polypropylene fibres - 200× magnifications*

Table 1. *Basic physical characteristics of propylene* [21]

Measured parameter	Value
Density [g·cm⁻³]	0.95 (crystal)
	0.895 (amorphous)
Melting point [°C]	173
Decomposition point [°C]	286
Thermal expansion [K⁻¹]	(100 to 180)·10⁻⁶
Specific thermal capacity [kJ·kg⁻¹·K⁻¹]	1.70 to 1.90
Water absorption [%]	0.03
Hardness [Rockwell]	R80 to R100
Thermal conductivity [W·m⁻¹·K⁻¹]	0.16 to 0.25

Polypropylene is a thermoplastic polymer selected from the group of polyolefins; it is colourless and odourless [20] and [21]. It has good stability, hardness and strength, but low impact strength. It is not susceptible to internal stress and can be appropriately welded. It has excellent electrical and chemical resistance. It becomes fragile at temperatures below zero. The basic physical properties of polypropylene are shown in Table 1.

1 STUDY AREA

In the first phase of designing a heat exchanger surface made of polypropylene fibres, research was carried out to see if there was the possibility of joining polypropylene fibres into bundles. A created bundle (Fig. 2) consists of 1400 pieces of fibre. Those fibres are inserted into a 20 mm diameter and 40 mm long PVC tube. The part of the fibres that is glued into a single unit, and forms a compact unit in a PVC tube, is the so-called potting. Fig. 3 shows a sectional view of an array of 18 pottings in a single shell of a heat exchanger. The manner in which the bundles are placed, and especially by their number, makes it possible to influence the thermal performance of the heat exchanger.
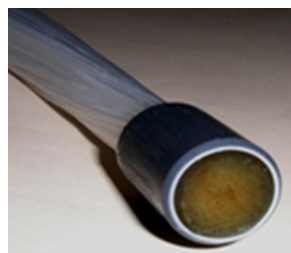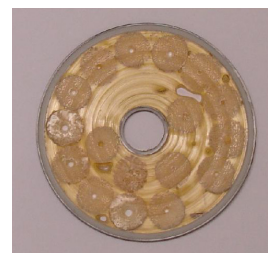

Fig. 2. *Fibre bundle in a potting*

Fig. 3. *System of pottings – side cut*

The fibres are produced by continuous casting of liquid polypropylene from an extruder. Subsequently, the fibre is cooled in an air stream, thereby shrinking into the given dimension. Fibres suitable for the use in a heat exchanger should have intact and smooth walls, i.e. so-called transparent fibres. In contrast, research is underway to examine the possibility of using a porous fibre mainly for medical purposes. The wall of such fibres consists of 30 % to 50 % air.

The second phase of the design tested the potting leaks. Table 2 contains the selected technical parameters of a bundle of polypropylene fibres.

The bundle is tested for the so-called *collapse pressure* and *burst pressure*. *Collapse pressure* is an overpressure from the outside of the fibre wall

towards the inside wall, following which the fibre wall collapses. *Burst pressure* indicates the overpressure inside of the capillary against the external pressure, following which there is a rupture of the capillary wall.

Table 2. *Technical parameters of a polypropylene fibre bundle*

Parameter	Value
Capillary material	Polypropylene
Potting material	Polyurethane
Number of capillarie	1400
Total length	750 mm
Capillaries inner diameter	0.225 mm
Outer diameter of capillaries	0.275 mm
Collapse pressure	0.2 MPa
Burst pressure	0.4 MPa
Maximal operating temperature	70 °C
Approx. heat transfer area	1 m²

2 CHARACTERISTICS OF POLYPROPYLENE FIBRES

Polypropylene fibres can deform or even break when cut, or after being glued in the potting. A rupture occurs when the adhesive does not completely fill the empty space between the fibres. A rupture is a permanent deformation of the fibre cross-section, i.e. reduced cross-section (Fig. 4).
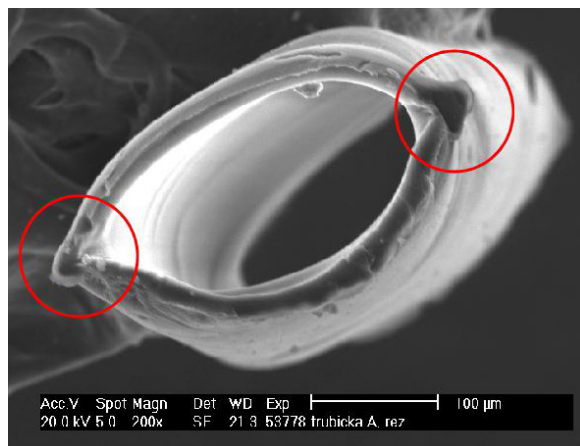

Fig. 4. *Polypropylene fibre cut- 200× magnification*

Wall thickness changes along the length of an intact fibre. Fig. 5 shows a microsection of the wall at 1500× magnification. The changing of the wall thickness is chaotic; it is not subject to any dependency, not only along the cross-section but also along the length of the capillary. The wall thickness of the presented capillary ranges from 30 μm to 33 μm.
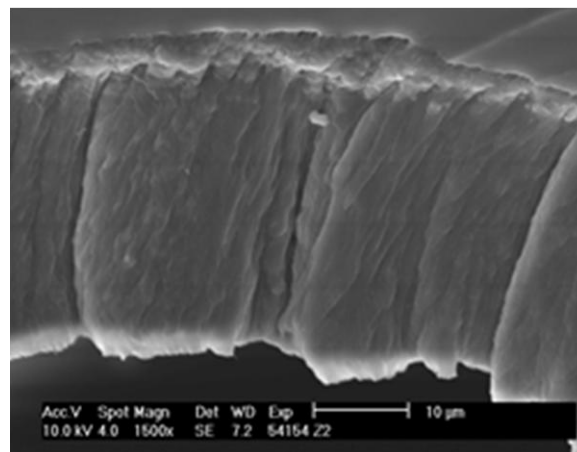

Fig. 5. *Microsection of the wall along the length of the fibre – 1500× magnification*

3 TESTING POTTING INTEGRITY

As a potting is made of three different materials with differing properties, it was necessary to conduct an integrity test. The test device is shown in Fig. 6.

Water coming from a pressurized water source passes through a water filter (1), continues through a closing valve (2) and after the control pressure gauge (3) it enters the first potting. The water flows through the fibre bundle and enters the second potting (5). Subsequently, the water flows through the control pressure gauge (6) and the closing valve (7), which flows into a collecting tank. The water pressure at the inlet of the water filter was set to 0.3 MPa. Water flowing under this pressure for 30 s expelled the air contained in the fibres of the bundle. Subsequently, the valves were closed before and after the bundle; the pressure drop in the fibre bundle was observed for 5 min.
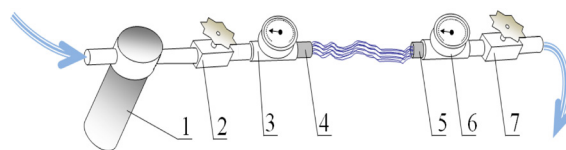

Fig. 6. *Scheme of a potting's' integrity measurement*

This particular experiment was conducted in order to identify a possible problem with the tightness of the bundle. A fibre bundle with detected leakage was immersed into a water tank at 50 °C to 70 °C together with a protective package perforated with about 30 holes, 3 mm in diameter. The packaging was tasked to protect fibres from mechanical damage during the repeat experiment. After cooling the fibre to the level of the inlet temperature, the fibre bundle

was again exposed to a water pressure of 0.3 MPa. The potting was tested in this manner over several cycles. The number of cycles at the time of individual testing increased with the increasing success of previous pressure tests. Table 3 shows the results of the tested fibre bundle.

The same procedure was used for testing the tightness of the pottings at a high water temperature in a water bath into which the bundle was immersed after the test. The results showed that the potting's exhibited leakage at a temperature above 52 °C.

4 MEASUREMENT OF PRESSURE LOSS FIBRE BUNDLES

The pressure drop was measured on six selected fibre bundles. Three fibre bundles consisted of transparent fibres and the other three with porous ones. Potting tightness before the measurement was 100 %. All parameters of the tested bundles (outer diameter, number of fibres in a bundle, and their length) were identical. A source of the pressurized water was represented by a pressurized water supply network with a pressure of 0.45 MPa and a temperature of 18 °C. The fibre bundle was connected to the rubber hoses via an inlet (4) and an output potting (5) (Fig. 7).
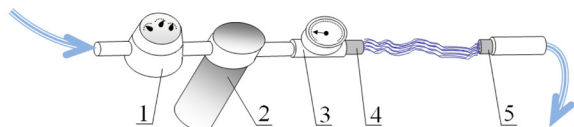

Fig. 7. *Schematic diagram of a fibre bundle during the measurement of a pressure loss*

The water flowed into the bundle through a flow metre (1) and a water filter (2). Water pressure was measured with a type PM 03.05 pressure gauge (3), with an amplitude between 0 MPa and 0.6 MPa and with an accuracy of ± 0.3 %. Fig. 8 shows the dependency of the pressure loss and water flow

through the fibre bundle. The bundles of transparent fibres (t1 to t3) and bundles of porous fibres (p1 to p3) show an almost linear progression of the change in a pressure drop in the flow rate.
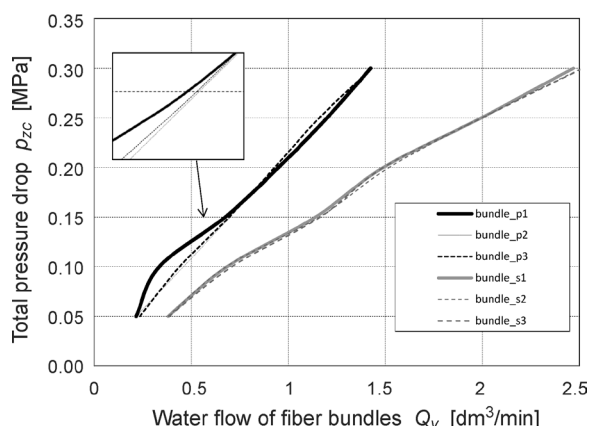

Fig. 8. *Pressure drop fibre*

5 MEASUREMENT OF TEMPERATURE AND FLOW

An experiment with an integrated bundle of transparent polypropylene capillaries was conducted on a heat exchanger that was constructed in a counter-current wiring with a tangential inlet of the secondary medium (Fig. 9).
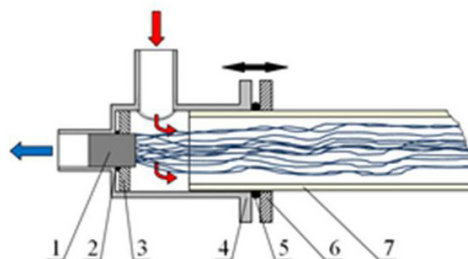

Fig. 9. *Heat exchanger with a tangential inlet and sliding head*

Table 3. *Integrity test – measurements results*

test number	Interval between individual tests [h]	Q_V [dm³·min⁻¹]	p [MPa]	t_i [°C]	l [m]	n_c [l]	t_w [°C]
basic test	–	1.61	0.3	19.2	0.726	–	–
2	18	1.61	0.3	19.1	0.724	3	52
3	15	1.58	0.3	18.8	0.722	13	52
4	151	1.63	0.3	18.3	0.720	13	52
5	151	1.66	0.3	18.1	0.716	18	52

Note: n_c the number of reheating cycles of the bundle and its subsequent re-cooling down, l bundle length, p pressure of water in the fibres during the test, t_i temperature of the test water in the capillaries before the test, t_w the temperature of the water in which the bundle was submerged.

The construction of the shell of heat exchanger allowed the release of fibres in a range from 0 % to 10 %. The exchanger has been studied for the impact of the fibres' tension on the intensity of the heat transport. A sliding head (4) placed on the shell of the heat exchanger (7) together with a rubber seal (5) and a thrustwasher (6) were used for this purpose. The potting of the investigated bundle itself (1) was sealed using a so-called O-ring (2) and pressed with a washer (3).

The experiment used three different versions of a fibre bundle. Each version had a different number of fibres, different outer fibre diameter and a variety of tensions. The parameters of the heat exchangers are shown in Table 4.

At zero tension, the fibre is at 100 % of its length, and the fibre axis is a straight line. When released, the bundle changes the distance between the clamping of the pottings; the fibre length remains constant. The bundle release Δl_u [%], expressed as a percentage of the total length of the fibres, is described by Eq. (1):

$$\Delta l_u = 100 - \frac{(l_z - \Delta_l) \cdot 100}{l_z}. \tag{1}$$

Given the diameter and the size of fibres, the release of individual bundles was chosen as per Table 5.

View of the experimental stand is shown in Fig. 10.

Table 4. *Parameters of used bundles*

Type of a bundle	Number of fibres [pc]	Outer diameter [mm]	Fibre length [m]	Heat transfer area [m²]
A	400	0.65	0.71	0.580
B	900	0.35	0.70	0.682
C	1385	0.275	0.70	0.834

Table 5. *Release values for different types of bundles*

Type of a bundle	Δl_u [%]		
A	0	0.7	1.4
B	0	1.5	3
C	0	1.4	3.7

During the experiment, the temperatures were measured at the inlet and outlet of the primary and secondary circuits of the heat exchanger as well as the water flow through the fibres. The measured data was to define the overall heat transfer coefficient k (W·m⁻²·K⁻¹) in accordance with Eq. (2):

$$k = \frac{P}{S \cdot \Delta T_{\ln}}, \tag{2}$$

where S is the total heat exchanger area of the bundle of fibres [m²], P is the heat transfer rate of the exchanger [W] and $\Delta T_{\ln}$ is the logarithmic mean temperature difference (LMTD) [K].

Fig. 10. *Heat exchanger with tangential inlet and sliding head*

The heat exchanger's performance is determined from the heated water in the secondary branch, i.e. in fibres. This medium herein is indicated with an index 2. Eq. (3) is valid:

$$P = Q_{m2} \cdot c_p \cdot (T_2'' - T_2'). \tag{3}$$

The mean temperature logarithmic gradient is calculated from the Eq. (4):

$$\Delta T_{\ln} = \frac{\Delta T_0 - \Delta T_S}{\ln \dfrac{\Delta T_0}{\Delta T_S}}. \tag{4}$$

At the counterflow heat exchanger, the individual differences of temperatures are determined from the Eqs. (5) and (6):

$$\Delta T_0 = T_1' - T_2'', \tag{5}$$

$$\Delta T_S = T_1'' - T_2', \tag{6}$$

where index 1 is the primary medium; one bar represents the incoming temperature and two bars the outgoing temperature of the medium [K].

6 DISCUSSION

Bundle type A was characterized by a large outer diameter of fibres (0.65 mm) and the fibres were relatively solid. When released by 0.7 %, the fibres were evenly deployed over the cross section and they were washed thoroughly. When released by 1.4 %, the fibres already touched the wall of the heat exchanger, which resulted in a decrease in the overall heat transfer coefficient. The course of the factor k according to the flow rate of the fibre bundle (bundle A) is shown in Fig. 11.

The course of the heat transfer coefficient for bundle B is shown in Fig. 12 and for bundle C in Fig. 13.

In all three bundle types, the smallest overall heat transfer coefficient values were obtained at 0 % release.

In a larger flow cross-section of fibres, higher overall heat transfer coefficients are reached when releasing a bundle up to circa 1 %. In smaller flow cross-sections of fibres, a greater release is more suitable (over 3 %). For example, with a flow of 100 dm³·h⁻¹ and approximately the same bundle release (1.4 % to 1.5 %), a greater overall heat transfer coefficient value is shown by a B-type bundle (circa 590 W·m⁻²·K⁻¹). With the same flow, bundles A and C reach value k of circa 420 W·m⁻²·K⁻¹.

In terms of evaluating the influence of measurement inaccuracies upon the results obtained, the following can be stated. The measured values included temperature, flow and pressure. The instruments that were used for measuring the stated values caused a so-called primary inaccuracy. A secondary inaccuracy resulted from the measurement of individual values of the given parameters due to the instruments used. A so-called tertiary inaccuracy should show what influence a particular parameter has upon the calculated value, i.e. upon overall heat transfer coefficient k.

If, in Eq. (2), we take into account the Eqs. (3) and (4), for overall heat transfer coefficient k we obtain an equation in the shape:

$$k = \frac{Q_{m2} \cdot c_p \cdot \left(T_2'' - T_2'\right)}{S \cdot \left[\left(T_1' - T_2''\right) - \left(T_1'' - T_2'\right)\right]} \cdot \ln \frac{\left(T_1' - T_2''\right)}{\left(T_1'' - T_2'\right)}. \quad (7)$$

The equation shows that the k value is influenced by an inaccuracy in measuring temperature and flow.

The development of a percentage deviation (error) in the final value of overall heat transfer coefficient k depend on the measurement error of the given parameters (each individually) is shown in
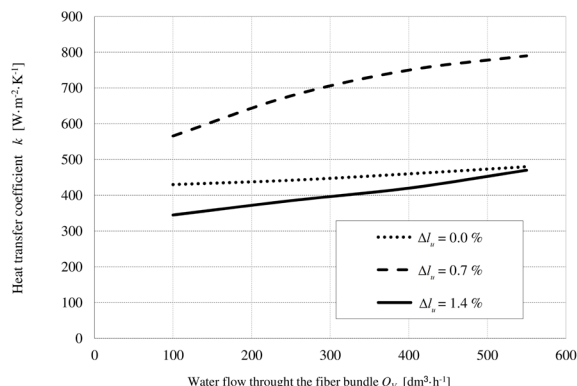

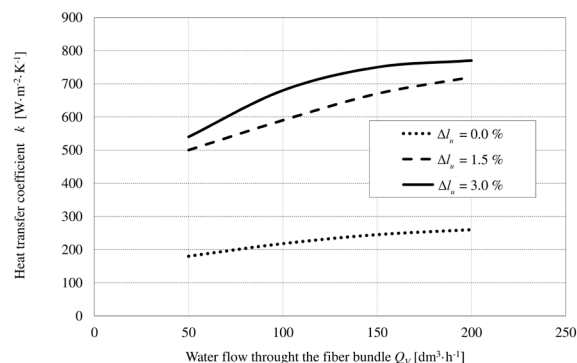**Fig. 11.** Overall heat transfer coefficient for bundle type A

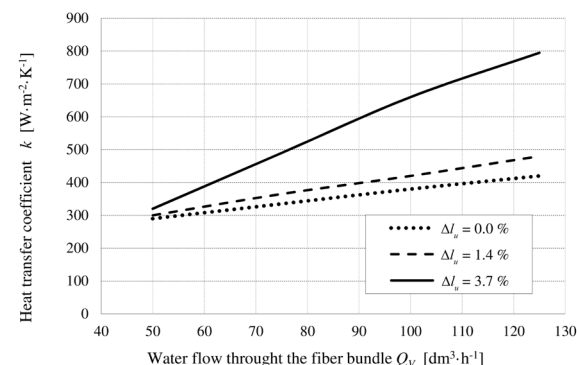**Fig. 12.** *Overall heat transfer coefficient for bundle type B*

Fig. 13. *Overall heat transfer coefficient for the bundle type C*

Fig. 14 on the vertical axis. The horizontal axis shows the measurement error for the appropriate temperature and flow. The diagram shows a strong dependence of the overall heat transfer coefficient k upon the temperature of outlet water from the exchanger T_2'' and flow Q_{m2} and relatively weaker dependence upon temperatures T_1', T_1'' and T_2'.

In order to achieve the required accuracy when determining the overall heat transfer coefficient at a level of 3 %, thermal sensors with an accuracy of
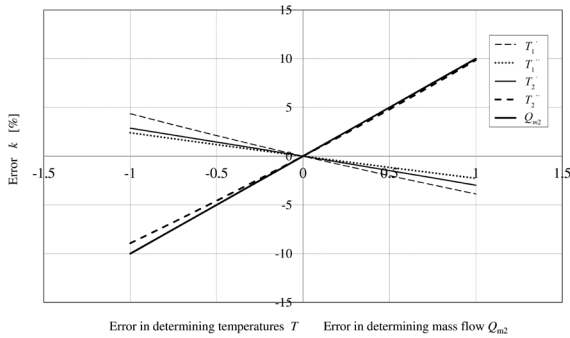
Fig. 14. *The influence of inaccuracies in measured values upon the heat transfer coefficient*
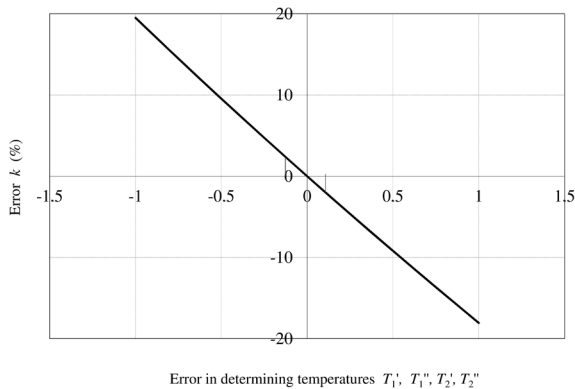

Fig. 15. *Overall heat transfer coefficient error depending upon the measured temperature*

±0.1 °C must be used. This can be seen in Fig. 15 where there is a visible influence of deviations of the red values of all temperatures upon the k value. For example, if temperature T_2'' were read with an inaccuracy of +0.5 °C and other temperatures with an inaccuracy of –0.5 °C, the resulting deviation in the overall heat transfer coefficient k would be as much as ±10 %.

7 CONCLUSIONS

Examination of the heat exchangers made of polypropylene fibres showed that one of the fundamental problems in their application is the tightness of fibres in the potting. It has been established that at a water temperature above 52 °C, it is very difficult to ensure a leak-proof performance of the exchanger.

It is clear from the above that heat exchangers made of polypropylene fibres may only achieve faultless operation up to 50 ºC. Above this temperature, a breakdown in potting occurs, since it

consists of three varying materials (metal, adhesive, polypropylene) whose change in shape depending upon temperature is expressed in different ways (each material has different thermal conductivity).

At the same time, measurements confirmed that a heat exchanger using fibres of a certain degree of release have a better performance in comparison to a design where fibres are under tension. To a certain degree, this result is related to the slight movement of the fibres along the cross-section which, at a certain release of fibre tension, causes a more intensive exchange of heat between the primary and secondary medium.

Testing the tightness of pottings took place at a pressure of 0.3 MPa. This pressure represents a sufficient reserve during application of the given exchangers in real operation when using low potential heat from waste water.

Finally, it is important to emphasize that the use of the heat exchangers of the polypropylene fibres is limited by the thermal, pressure, or strength resistance, respectively.

8 ACKNOWLEDGEMENTS

9 NOMENCLATURES

l_z is the length of the bundle without tension, [m]

Δl_z the size of release, [m]

S the total heat exchange area of given fibre bundle, [m²]

P heat transfer rate, [W]

ΔT_{ln} logarithmic mean temperature difference, [K]

Q_{m2} mass flow, [kg·s⁻¹]

c_p mean specific heat capacity, [J·kg⁻¹·K⁻¹]

T_2' incoming water temperature, [K]

T_2'' temperature of the exiting water, [K]

ΔT_0 temperature difference between the primary and the secondary medium at the beginning of the exchanger, [K]

ΔT_S similar difference but at the end of the exchanger, [K]

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