CONDENSATION IN TUBE HEAT EXCHANGER

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Contents

f	Liquid (Chapter 5, 6, 7, 9, 10).
film	Liquid film between bubble and wall (Chapter 10).
G	Gas (Chapter 2, 3); vapour (Chapter 4, 5) ; Gas phase (Chapter 4).
g	Gas (Chapters 2, 3); vapour (Chapter 4, 5, 6, 7, 9, 10).
go	Gas only, all flow taken as vapour (Chapter 10).
h	Heat (Chapter 1); hot (Chapter 10).
chan	Channel (Chapter 1).
IA	Intermittent to annular flow transition (Chapter 10).
i	Internal (Chapter 5, 7, 9, 10).
in, i	Inlet (Chapter 1, 2, 3, 4, 5, 6, 8, 9, 10).
L	Liquid (Chapter 2, 3, 5); liquid phase (Chapter 4).
l	Liquid (Chapter 2, 3, 4, 5, 7, 9, 10).
LM	Logarithmic mean (Chapter 1).
lam	Laminar flow (Chapter 10).
lo	Liquid only, all flow taken as liquid (Chapter 10).
M	Mixture (Chapter 4).
m	Determining (Chapter 4).
min	Minimum value (Chapter 5, 7, 9, 10).
MT	Mean temperature (Chapter 1).
nb	Nucleate boiling (Chapter 10).
o, out	Outlet (Chapters 1, 2, 3, 4, 5, 6, 8, 9, 10).
Ph	Phase (Chapter 4)
pre	Predicted (Chapter 5, 6, 10).
r	Reduced (Chapter 5).
S	Superficial (Chapter 4).
s	Vapour (Chapter 9).
s	Straight channel/vertical (Chapter 8, 10).
sat	Saturation (Chapter 5, 10).
sp	Single-phase (Chapter 10).
tp	Two-phase (Chapter 10).
tt	Turbulent liquid/turbulent gas (Chapter 10).
trans	Laminar-turbulent transition (Chapter 10).
v	Vapour phase (Chapter 2, 3); vapour (Chapter 4, 5, 7, 9, 10); viscous (Chapter 10).
W, w	Water, wall, heated surface, properties evaluated at wall conditions, (Chapter 1, 2, 3, 5, 6, 10).
w	Wavy channel/inclined, wall (Chapter 8, 10).

Experimental Setup

For investigating parameters affecting the effects of heat transfer and fluid flow, an experimental measuring line was set up to model the operating conditions during the condensation of water vapour in the tube bundle of a heat exchanger with wavy micro-channels. For the experimental investigation of the effects required parameters, the ideological design of the measuring line was initially performed, the main evaluated element, of which, was the tube heat exchanger with wavy micro-channels. The actual measuring line was set up on the basis of agreed design and technical documentation in the operating premises of the steam source and cooling water suppliers. The experimental setup for the description is divided into a water vapour circuit and cooling water circuit, see Figure 1. The water vapour circuit consists of a tank/source (A) where vapour is produced with a known temperature $t_{v,in}$ (°C) and pressure $p_{v,in}$ (Pa). The water vapour enters to the measured bundle of 55 copper thin-walled tubes (B), where it becomes to the condensation process. The condensate volume flow V_c (m^3/s) and of condensate temperature $t_{c,out}$ (°C) is measured on the outlet of the tube bundle wavy micro-channels before flowing into the tank (C). The internal distance between tubes in the bundle is cooled by a circuit from a source of cold water (D). Volume changes of the cooling water are compensated by the expansion tank (E). On the vapour condensate at level H(m) of standard a bundle of wavy micro-channels is shown the outer gauge on level (G). The tube casing of the exchanger is insulated by thermal insulation with a thickness of 10 cm, so the heat transfer is not affected and it doesn't lead to heat loss. The inner surface of the measuring wavy micro-channels is cleaned with a high percentage of alcohol cleaner and the purity of the water vapour from the steam generator is over 99.9 %. The object of experimental monitoring of the tube vapour/water heat exchanger was measured in a vertical position in combination with counterflow and parallel flow connection of cooling water. Besides that, changing the method of connection of the exchanger as counterflow/parallel flow parametric changes of input liquid were exercised, i. e. on the side of input vapour and on the side of input cooling water.

The side of vapour: One variable parameter on the water vapour side was in the form of a change of the pressure of the saturated water vapour at the inlet of the exchanger and there is a synergistically associated change in the mass flow of water vapour in the exchanger. The range of pressure change was from 0.10 barg (heat water approx. 100 °C) to 3.20 barg (saturated vapour approx. 138 °C). The pressure of inlet saturated vapour was measured by temperature, independently on two places with the sensitivity of the thermocouple ± 0.10 K.

The side of water: The two variable parameters on the water side were temperature and water flow. The volume flow of water was measured independently of a water meter and a flow meter placed one behind the other. The devices work cumulatively, so the status and time were recorded in the form of a digital photograph containing the time (transfer to seconds) and status (transfer to liters). The temperature of inlet water was measured independently on two places with the sensitivity of the thermocouple ± 0.10 K, see Table 1.1 – 10.1, see Appendix. The measurement took place in a stationary form with a fixed geometry of the exchanger (position and connection) in combination with a fixed setting of input parameters (vapour pressure, temperature and water flow) and during the measurement was not actively interfered to the above setting. The thermal response of the heat exchanger vapour/water was recorded with pre-positioned thermocouples with sensitivity 0.10 K in a time step of 5 seconds, see Figure 3, 4. The hydraulic response of the heat exchanger was monitored independently by a water meter and a flow meter on the water side in the form of a digital photograph (status and time), as the record of the mass flow of water vapour condensate which was performed by photographing a digital scale (status and time), with sensitivity 0.10 g and a range from 0 to 30 kg. The evaluated element of the assembled measuring line is the experimental inclined tube heat exchanger with wavy micro-channels, a total of 55 pieces of copper thin-walled wavy micro-channels of the length 1300, 3.0 inner diameter and 0.5 mm wall thickness see Figure 2, Table 2. The adaptation of wavy walls have been applied commercially since the 1980s on vehicles and transpiration re-entry cooling of rocket boosters, ablative surfaces cross-hatching and combustion chambers for film vaporization. A wavy design can induce Dean's vortices and an alternating secondary branch which helps in fluid mixing inside the channel where Dean's vortices occurs when the flow in the wavy channel is very high and the flow is unstable and secondary flows are developed which introduce pairs of streamwise-oriented vortices. Phase changes in wavy micro-channels currently are part of a little-explored field of thermodynamics. Channels are intentionally cast in a bundle of 55 pieces and thus, some small geometric imperfections of each channel are eliminated. The currently measured values in data files correspond more to the statistical average and the edge effect is also eliminated. The bundle is surrounded by an outer copper tube with a diameter of 64 mm. The number of measured data points in a time step of 5 seconds, for a vertical position of the heat exchanger is, in total 29 264 i.e. 40.65 hours (counterflow connection 12 491 points, i.e. 17.35 hours, parallel flow connection 16 773 points i.e. 23.30 hours). For the inclined position of the exchanger 45 % the total number of data points is 35 124 i.e. 48.78 hours (counterflow connection 16 857 points, i.e. 23.41 hours, parallel flow connection 18 267 points, i.e. 25.37 hours). For the purpose of evaluating the recorded data for displaying the time course of the temperature of the liquids in the heat exchanger as the basic characteristics for determining heat transfer and other parameters an interactive electronic 3D graphic tool INSION – UTZB was created for recorded values on the primer and the secondary of the heat exchanger, both for parallel flow and counterflow. This interactive electronic 3D graphical tool is the subject of patent protection of the authors of this article. The time course of temperatures of condensing water in wavy micro-channels is the essential starting point for the calculation of basic parameters according to suitable correlations and selected empirical relations of water for variants counterflow and parallel flow of the vertical heat exchanger and their evaluation.

A circuit wavy micro-channel is defined by its wavelength (λ), amplitude (A), hydraulic diameter (D_h), wall thickness (t), wavy ratio $Y = \lambda / D_h$, function $y_1(x) = A \cos(2\pi\ x/\lambda)$, $y_2(x) = A \sin(2\pi\ x/\lambda)$ for $x = <0, t>$

A parameter, α, whose absolute value is equal to the ratio of the upper wall wave amplitude to the lower wall amplitude, is used to describe the configuration of the channels. We indicate both plus and minus values for α in order to distinguish the difference between the channels that have a same wave amplitude at the upper walls. When $\alpha < 0$, the troughs of the lower wall and the crests of the upper wall face each other without phase difference. Whereas, for $\alpha < 0$, the flow enters at $x = x_0$ into an expanded part of the wavy channel and if $\alpha > 0$ at the entrance of the wavy channel it involves into a contracted region in the vicinity of the upper wall. Besides that, for $\alpha = 0$ the upper wall is straight and for $\alpha = 1$ the channel is so called serpentine and for $\alpha = -1$ it is a raccoon channel.

Another characteristic of the wavy channels is the critical Reynolds number to transition from laminar flow to turbulence. In the wavy-walled channel, the critical Reynolds number depends on 2a/λ and is less than the critical Reynolds number ($Re_c = 2\,300$) for straight channels (W. M. Keys *et al.* 1980). Tolentino *et al.* (2008) have shown that the critical Reynolds number is even less than 250 for 2a/ λ = 0.18.

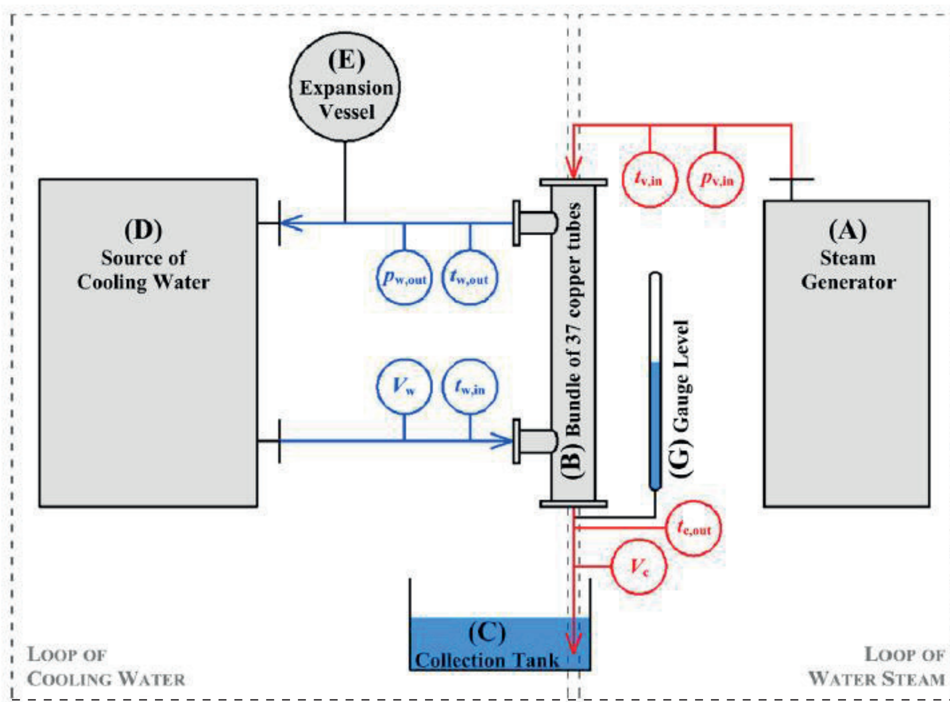
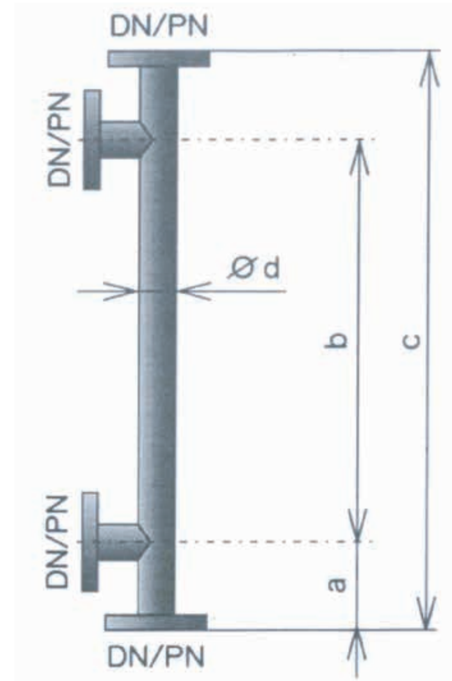
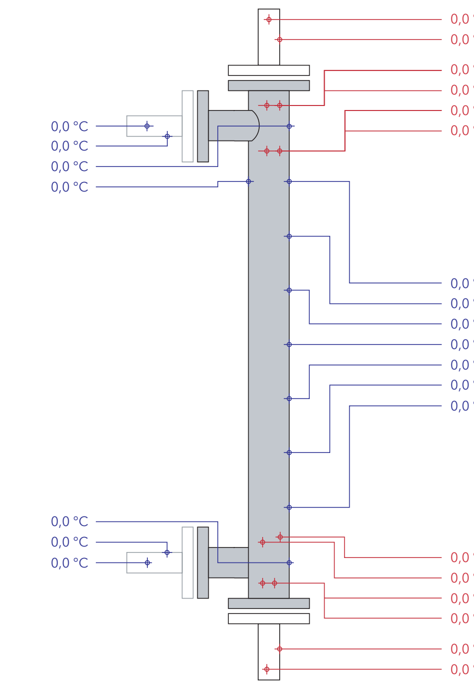
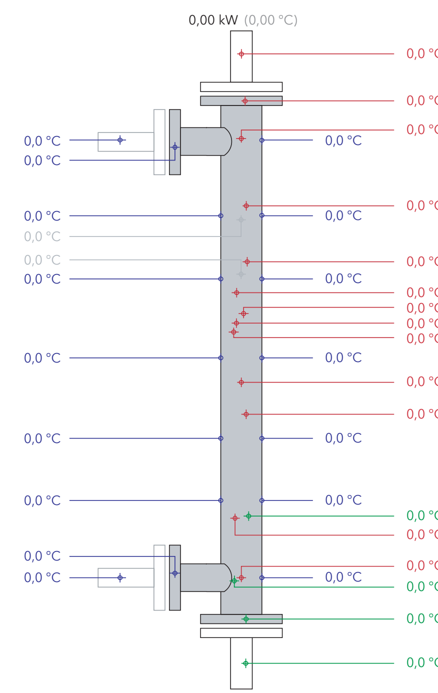


Figure 1 *Schematic of the experimental set up*





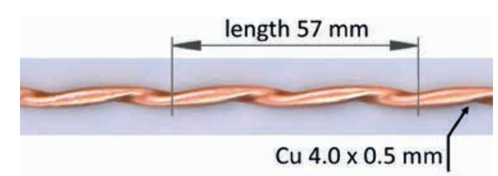


◤ Figure 2 *The experimental channel heat exchanger with wavy micro-channels*

▲ Figure 3 *Schematic of the location of the sensors on the heat exchanger for reading the measured data, vertical position*

◀ Figure 4 *Schematic of the location of the sensors on the heat exchanger for reading the measured data, inclined position*

▼ Figure 5 *Wavy micro-channels heat exchanger*



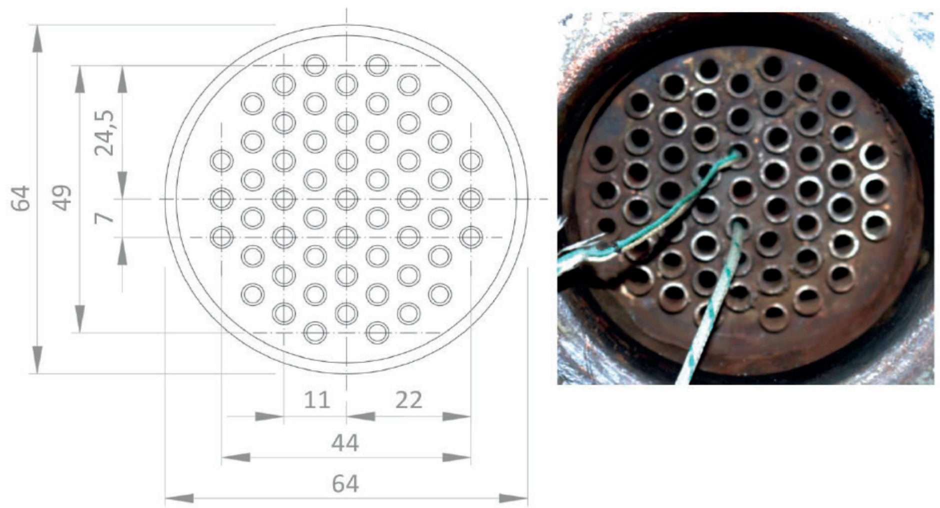


Figure 5 *Cross section of heat exchanger with wavy micro-channels (dimension mm)*

The total length channel		1 300 mm
The medium length of the channel in contact with water		1 142 mm
The corrugated length of the channel		800 mm
The uncorrugated length of the channel		171+171 mm
The number of waves on one channel		28
	External	**Internal**
The wave area of one channel	414,5	310,9 mm^2
The area of the corrugated part of the channel	11 606	8 705 mm^2
The area of the uncorrugated part of the channel	4 298	3 223 mm^2
The total area of the channel	15 904	11 928 mm^2
The area of 55 pcs channels	874 703	656 028 mm^2

Table 2 *The basic technical data wavy micro-channels of the heat exchanger*

Chapter I.
Time course of fluid temperatures in wavy micro-channels

1. Introduction

The time courses of fluid temperatures in energy equipment (of which heat exchangers of all qualifications are the necessary part) have been and are the subject of heat transfer work by many authors, for example [1], [2], [3], [4], [5], [6] [7]. The investigation of the course of temperatures of various fluids with a suitable flow arrangement of fluid in energy equipments and determining their optimal efficiency of transmission and operation characteristics can be found, for example [8], [9], [10], [11], [12], [13], [14], [15]. The special emphasis is placed on the fluid used and its physical and chemical properties. Not all of the fluids used in technical practice are suitable for their use in energy equipment and heat exchangers. Heat exchangers play a vital role in aerospace, automotive, medical, cryogenic, etc. engineering applications and processes such as refrigeration, chemical and oil refining, electric power generation and food processing, etc. In this article we will deal in more detail with the evaluation of the time course of fluid temperatures and selected temperature influences the parameters in wavy micro-channels of the heat exchanger in the vertical position and in the inclined position 45° in the view of the horizontal plane during the water condensation on the basis on the experimental investigation. As the base fluid for the examination water was chosen [16], [17] because of its being a quality, safe and non-flammable liquid with very good thermal properties. In addition water still finds its application not only as a refrigerant or temperature medium in technological processes and heating systems, cooling or air conditioning systems, but also in electrical engineering, the car industry, the pharmaceutical industry, etc. The contribution does not deal with the evaluation of the time course of temperatures of other types of waters (heavy water D_2O etc.) or water with different impurities in the heat exchanger.

For the purpose of evaluating the recorded data set for displaying of the time course of temperature of the fluids in the wavy micro-channels of the exchanger, the interactive electronic 3D graphic tool INSION – UTZB was created for recorded values on the primer and the secondary for vertical and inclined heat exchanger position (parallel flow, counterflow). The technology uses MySQL database, application logic on PHP7 and rendering to HTML5 with CSS3 and JS. An intuitive value selector is available that allows definitions of the required data from the database of approximately 1.600.000 records. In the interactive tool one can directly choose the required type of recorded values, time frame, range of sensors by defining intervals or specifically individually, rate of ignoring deviations and the way of presented display on 3D chart (for days, sensors, daily averages,

averages per sensors, details). The rendered 3D chart is fully interactive, it is possible to rotate, zoom in, omit graphic lines and take pictures into PNG or curve SVG format. Portability is also considered, so any given view, angle rendering, etc. is possible to be shared easily – by sending a link. The measuring line was based on the agreed technical documentation in the operating premises of the vapour and the cooling water supplier.

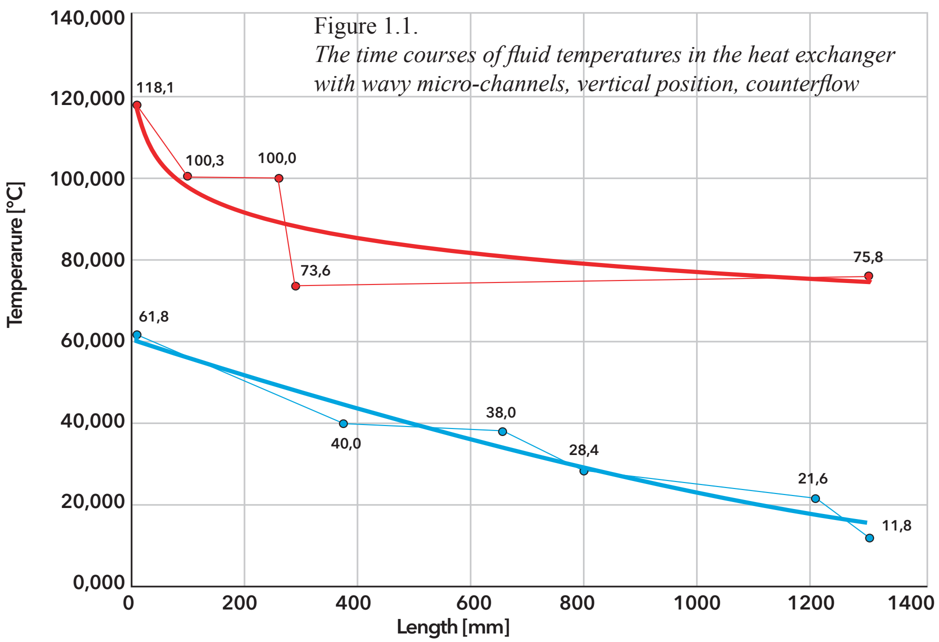


Figure 1.1.
The time courses of fluid temperatures in the heat exchanger with wavy micro-channels, vertical position, counterflow

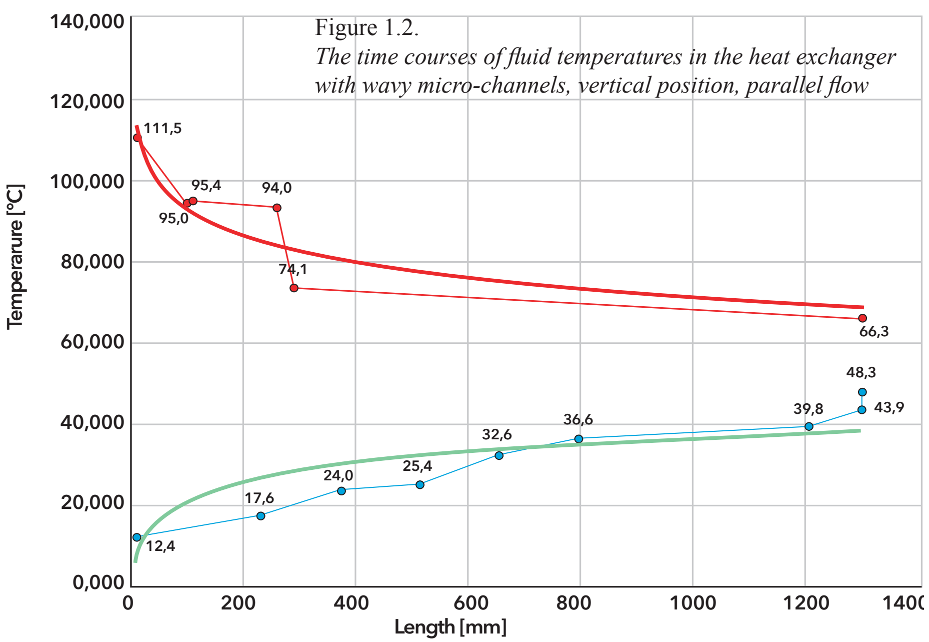


Figure 1.2.
The time courses of fluid temperatures in the heat exchanger with wavy micro-channels, vertical position, parallel flow

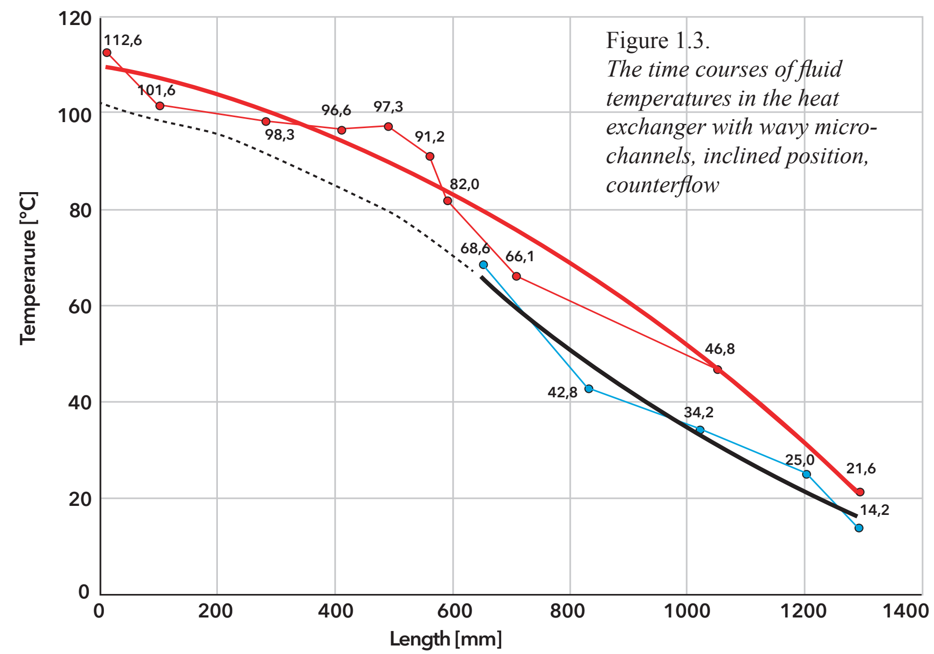


Figure 1.3.
The time courses of fluid temperatures in the heat exchanger with wavy micro-channels, inclined position, counterflow

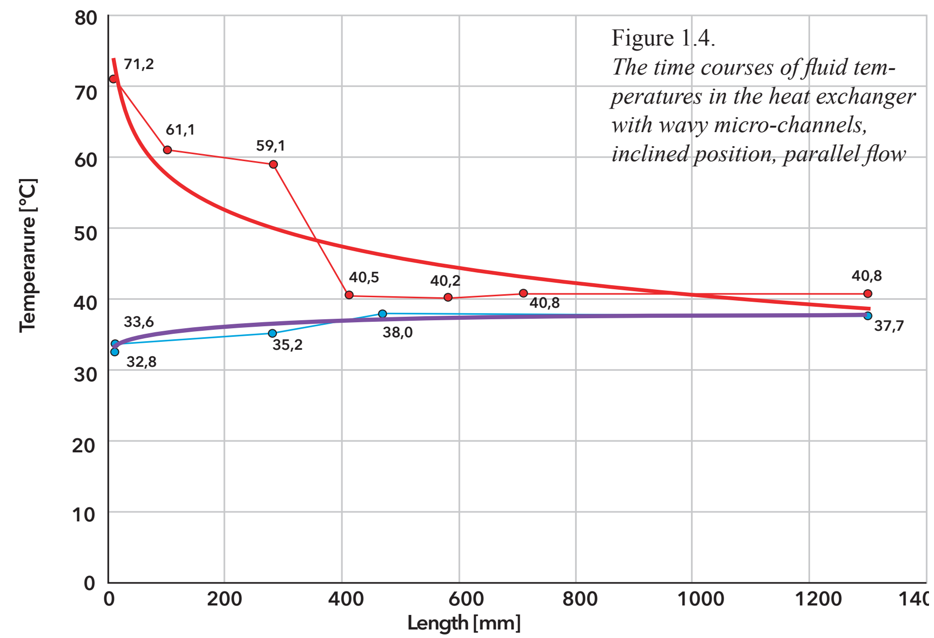


Figure 1.4.
The time courses of fluid temperatures in the heat exchanger with wavy micro-channels, inclined position, parallel flow

thick red line – modular curve of theoretical time course of temperatures (MCTTCT – vapour, condensate
thin red line – experimental time course of temperature (ETCT) – vapour, condensate
thick line – modular curve of theoretical time course of temperatures (MCTTCT) - cooling water
thin line – experimental time course of temperature (ETCT) – cooling water

Table 1.1.
The measured data in the selected time frame of the heat exchanger measurement with wavy micro-channels for the vertical position a) counterflow, b) parallel flow and for the inclined position c) counterflow, d) parallel flow, see Appendix

2. Solution methods

For many fluids, specific temperature profiles in energy equipment, including the heat exchangers in various positions (vertical, horizontal, inclined) are given in contributions, reviews and professional books, for example [19], [20], [21], [22], [23], [24] [25]. All the time courses of temperatures should be carefully checked before use because very often accuracy between different sources is not guaranteed. This paper compares the time courses of temperatures and selected temperature parameters in the condensation of water vapour in the heat exchanger in the vertical and inclined wavy micro-channels. The evaluation fluid is water, the inlet and outlet temperatures of the primer and the secondary are obtained from the interactive electronic 3D graphic tool INSION - UTZB, see Table 1.2.

Position HE	vertical		inclined	
	counterflow	**parallel flow**	**counterflow**	**parallel flow**
inlet temperature (°C)				
hot fluid T_i	118.1	111.5	112.6	71.2
cold fluid t_i	11.8	12.4	14.2	32.8
outlet temperature (°C)				
hot fluid T_o	75.8	66.3	21.6	40.8
cold fluid t_o	61.8	48.3	68.6	37.7

Table 1.2.
The inlet and outlet temperatures of fluids for different positions of the heat exchanger with wavy micro-channels

2.1. Parameters influencing the time course of temperatures

1. Heat Transfer Fluids (HTFs)

HTFs can be classified by their states of matter during normal operating conditions. Additionally to the three standard states (gaseous, liquid, solid), HTFs that undergo a phase change and supercritical fluids are also possible. Important thermo-physical properties of HTFs are low temperature limitation (solidification temperature), high upper temperature limitation (evaporation temperature/thermal stability limit) at low pressures, high thermal conductivity → receiver temperature close to HTF temperature, low viscosity → lower pumping power requirements, high density and heat capacity → enable use as storage medium, possibility of usage as working fluid, chemical compatibility (low corrosivity) with contact materials, low cost, high availability, low toxicity, flammability, explosivity and environmental hazard. [26]

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