Podtlaková zkušební komora pro hodnocení přestupu tepla na skrápěných trubkových svazcích v hlubokém podtlaku

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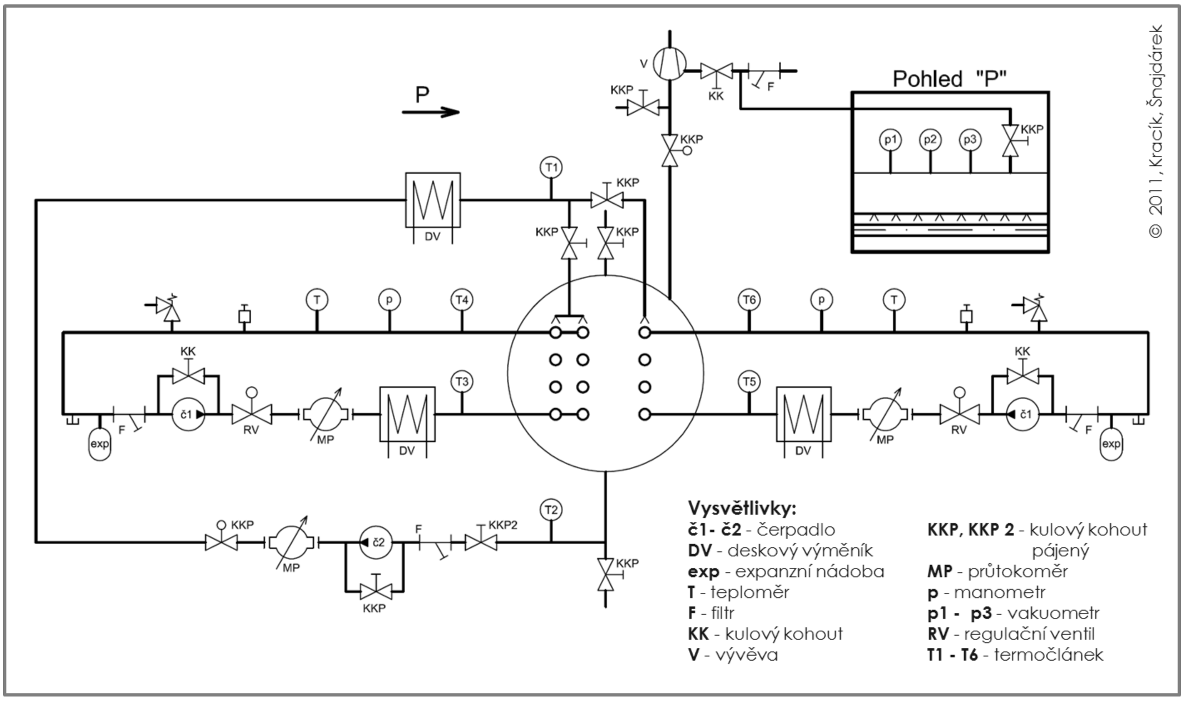
1. Úvod

Vyvinuto bylo experimentální zařízení určené pro výzkum přestupu tepla na skrápěných trubkových svazcích pracujících v hlubokém podtlaku, který je vytvářen vývěvou skrze ejektor. V komoře může být simulován var i kondenzace na skrápěném trubkovém svazku.

2. Popis zařízení



Obr. 1 Schéma stendu

Komora podtlakového stendu je válcová nádoba s třemi průzory, v níž je umístěn trubkový svazek. Na komoru jsou napojeny tři uzavřené smyčky. Dvě smyčky jsou navržené pro přetlak až 1,0 MPa a slouží pro dopravu chladicí/topné kapaliny. Třetí smyčka slouží pro dopravu skrápěcí kapaliny. Každá smyčka je osazena čerpadlem, regulačním ventilem, měřičem průtoku a deskovým výměníkem. Deskový výměník je možné napojit na boiler s horkou vodou pro ohřev kapaliny, nebo vodovodní řád v případě ochlazování. Přetlakové smyčky jsou navíc osazeny expanzními nádobami, které slouží pro vyrovnání dovolených tlakových diferencí, a pro případ nepřípustného navýšení tlaku slouží pojistný ventil, který část média může upustit. Pro vizuální kontrolu jsou smyčky také osazeny manometry a teploměry.

Teplotní stavy v jednotlivých smyčkách jsou měřeny termočlánky na vstupu resp. výstupu médií z nádoby a pro bližší přiblížení rozvrstvení tepla v trubkovém svazku jsou umístěny čtyři termočlánky po dvou v každé smyčce. Montážní plech trubkových svazků je rozdělen na dvě poloviny, kde v každé polovině jsou vrtány rozteče rozdílně pro velkou variabilitu uspořádání. Trubkový svazek je složen z měděných trubek o průměru 12 mm a ve skrápěcí trubce jsou otvory o průměru 1,0 mm s roztečí 9,2 mm na délce 940 mm.

Pro měření podtlaku slouží tři vakuometry. První je určen pro vizuální kontrolu a je rtuťový, druhý digitální měří v celém požadovaném spektru podtlaku, ale při velmi nízkých tlacích je značně nepřesný. Pro měření tohoto nízkého spektra (pod 20kPa absolutního tlaku) slouží třetí digitální vakuometr.

Na následujícím obrázku je uvedena fotografie finální podoby stendu.

Obr. 2 Podtlakový stend

3. Ukázka dosažených experimentálních výsledků prezentovaných na mezinárodní konferenci

The objective of the experiment described in this paper was to evaluate the effects of dynamic alterations of two physical quantities influencing the heat transfer coefficient at the outer tube surface in the evaporation mode, i.e. in the mode when hot water flows inside the tubes from the lower part of the bundle upwards and is cooled by the sprinkling liquid. The first monitored and altered variable is the sprinkling liquid flow rate and the second altered variable is the absolute pressure in the chamber. Both types of the experiment have been carried out at the right loop of the tube bundle where there are seven smooth tubes (including the distribution one) with the 25 mm span in two rows shifted by 10 mm. However, the calculation takes into account one row only as the flow rate is undivided and gradual from the bottom upwards.

3.1 The Sprinkling Liquid Flow Rate Alteration

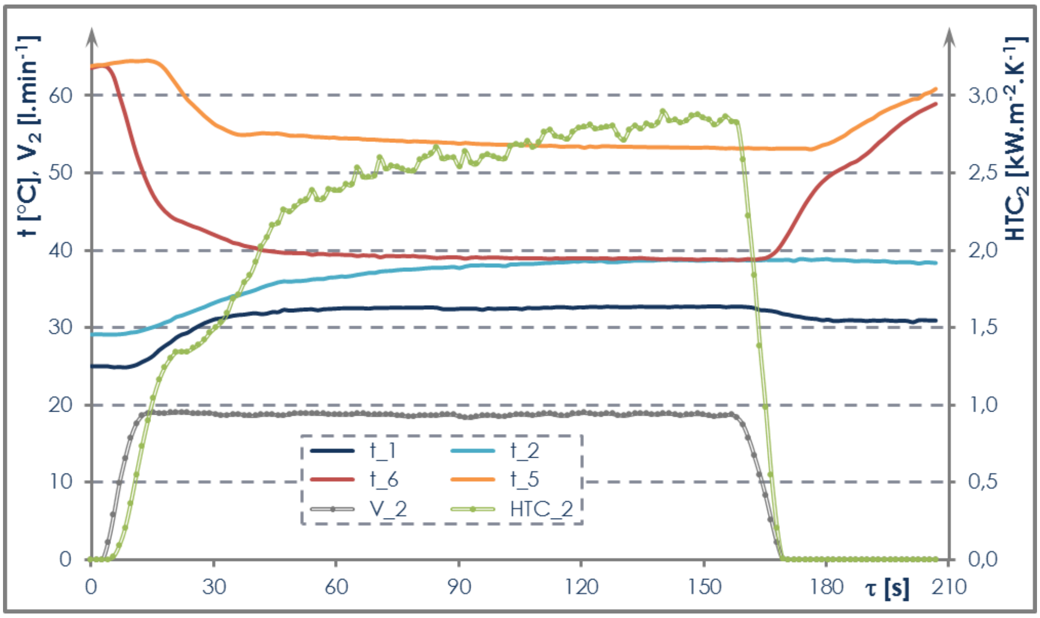
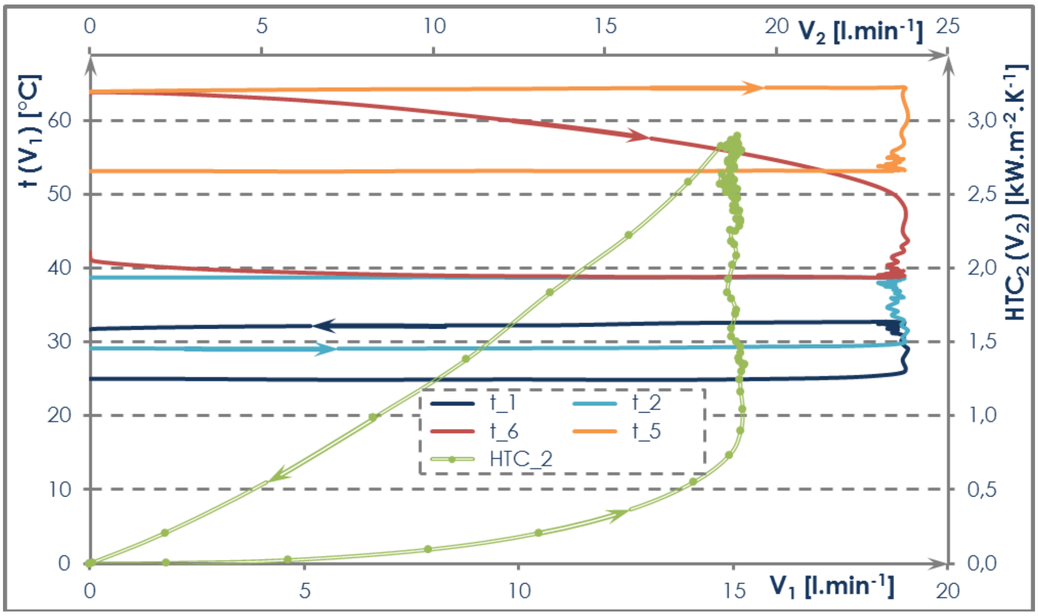
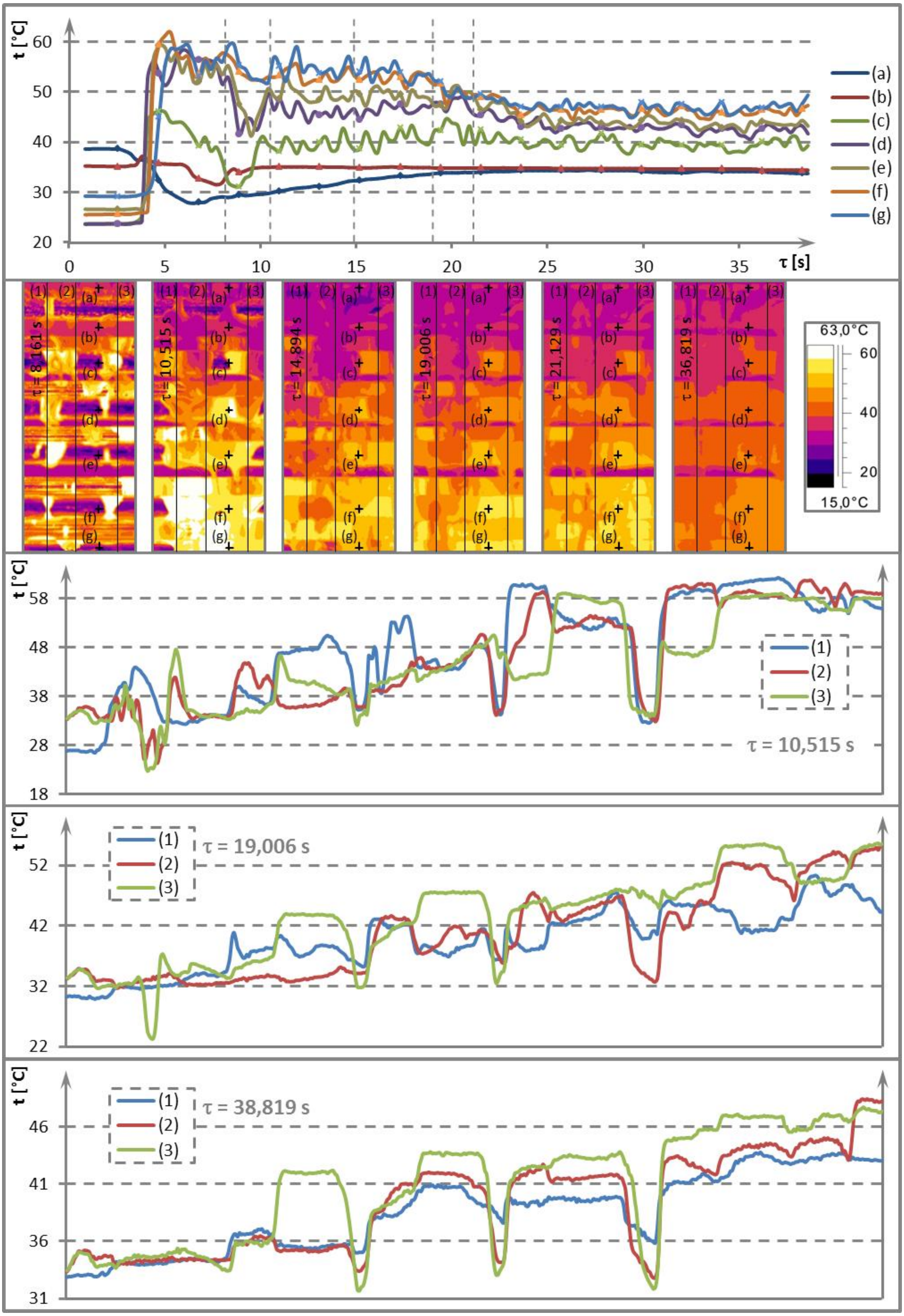


Fig. 3 Time chart of the "sprinkling liquid flow rate alteration"



During this experiment, the zero cooling liquid flow rate was rapidly increased to 18.8 litres per minute; this flow level was kept and then rapidly decreased to zero at the atmospheric pressure (the average value during the experiment was 97.8 kPa absolute), while the generated steam could escape from the vessel freely. The flow rate of the hot water inside the tubes was kept at the average value of 10.3 litres per minute. This experiment lasted for 168 seconds and the time chart is depicted in **Fig. 3**.



t [°C]
τ [s]
(a)
(b)
(c)
(d)
(e)
(f)
(g)
τ = 8,161 s
τ = 10,515 s
τ = 14,894 s
τ = 19,006 s
τ = 21,129 s
τ = 36,819 s
63,0°C
15,0°C
(1)
(2)
(3)
τ = 10,515 s
τ = 19,006 s
τ = 38,819 s

The temperature and the sprinkling liquid volume flow are shown at the left vertical axis while the right vertical axis represents the heat transfer coefficient at the outer surface of the tube. Looking at the shape of the sprinkling liquid flow rate curve and the heat transfer coefficient curve, a certain time lag is evident. This lag is caused among other factors by the increasing amount of water in the distribution tube and also by the evaporation and steam release from the vessel during the first drops' falling in the upper part of the bundle, which is also evident from the temperature 6 (thermocouple at the output from the tube bundle). Between the 18th and 25th second the desired temperature was stabilized (5) at the input into the tube bundle.

Projecting the values in relation to the sprinkling liquid flow rate at **Fig. 4** makes the observation more interesting. The bottom horizontal axis represents the volume flow rate of liquid inside the loop and relates to temperatures (going with the left vertical axis) and the diagram's top horizontal axis (the same flow rate, but in a different scale) relates to the heat transfer coefficient (going with the right vertical axis). The heat transfer coefficient slowly rises when the desired flow rate is being gradually approached. When the flow rate is achieved, there is an increase and a slow stabilization and with the rapid decrease there is a gradual fall corresponding with the trend, with a certain degree of inaccuracy compared to the stably measured points.

As mentioned in the introduction to this chapter, the vessel was not completely closed and the generated steam escaped freely through the middle look-through neck where the thermal imaging camera FLIR SC 660 was fixed. The whole sprinkling sequence was recorded with the resolution of 640x420 pixels and the frequency of 30 Hz. The analysis of the sequence can be found in **Fig. 5**. The top section of the figure depicts the waveform of temperatures scanned in seven points (marked with letters "a" to "g") during the sprinkling start-up and the beginning of the thermal gradient stabilization, i.e. approx. the first 38 seconds. The first point is situated in the area of the sprinkling liquid's outlet from the distribution tube and the other points are situated at the front part of the tube bundle successively from the top to the bottom. All the points are marked at the images below the

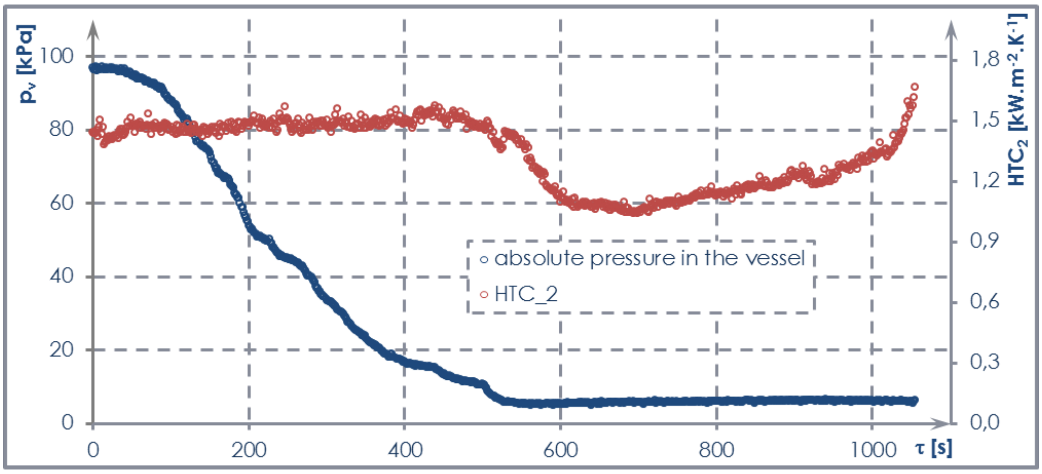


diagram which were extracted from the sequence record. These images also show the expanding steam cushion that was progressively getting larger. There are also three straight lines (marked with numbers "1" to "3") where the temperature was scanned along their whole length, which also represents the total length of the "x" axis in the diagrams below the images where the temperature is depicted in relation to the particular time duration specified at the legend.

3.2 Chamber Pressure Alteration

During this experiment all the input parameters were kept at a constant level with a certain degree of uncertainty of measurement except for the absolute pressure in the chamber. The liquid inside the tubes was cooled from the average temperatures of 47.0 °C to 35.3 °C and the average volume flow rate was 9.87 litres per minute. The sprinkling liquid was heated from the average temperatures of 28.8 °C to 38.3 °C and the average volume flow rate was 9.50 litres per minute. The time chart can be found at **Fig. 6.** Time is marked at the horizontal axis. The left axis represents the absolute pressure (in kPa) and the right axis represents the heat transfer coefficient. The measuring started at the atmospheric pressure in the vessel (the value during the measuring was 96.6 kPa absolute) and the pressure was gradually decreased until it reached its minimum which is nowadays possible using the modern technology of the Low-pressure stand. The calculated heat transfer coefficient is corresponding; it is rising with the decreasing pressure by the point of water saturation at the tubes' surface. Evaporation begins at the lower part of the bundle where the heated liquid reaches its maximum temperature at the average absolute pressure of 13 kPa. Water boiling at the tubes' surface is spreading and it appears predominantly in the time period between 515 and 513 seconds where a step change occurs. Generated steam is, however, conducted away by an exhausted, so it transfers its heat only while it is rising up through the tube bundle. The exhauster was removed in the 585^{th} second. Further fall of the heat transfer coefficient is caused by the time lag when the steam cushion was being produced above the tube bundle, but afterwards the generated steam transferred its heat to the sprinkling liquid as well which caused the heat transfer coefficient's increase. After the vessel had been closed, the absolute pressure inside increased by 0.8 kPa.

3.3 Conclusion

The introduction of the paper describes the topicality of the research on sprinkled exchangers for absorption circulations and the types of sprinkle modes. The sprinkled tube bundles placed in test apparatus at atmospheric pressure are currently in focus all over the world. The effects of various liquids, tubes' surfaces and insertions for the purposes of increasing the Reynolds number in tubes are examined. The paper outlined the effects of two physical quantities on the heat transfer coefficient. The data published by us were compared using similarity coefficients measured at atmospheric pressure by other authors, given the number of our own figures we decided not to publish these diagrams, but our measured values were within 15% error tolerance band.

The main part of the paper was devoted to testing the influence of sprinkling liquid flow rate alteration on the heat transfer coefficient; the effects corresponded with our expectations. The tests included a long-term measuring of several points with a constant sprinkling liquid flow rate and the generated curve copied the trend during the dynamic decrease of the flow rate, while the dispersion variance of the points determined by the long-term measuring was 8%.

The second part of the experiment consisted of measuring at the pressure fall in the vessel and monitoring the effects. According to our expectations, the heat transfer coefficient was rising until the boiling occurred at the tubes' surface. After the exhauster had been removed, the pressure was still slightly falling, but only by the moment when the vessel had been filled with sufficient amount of steam. Afterwards the increase of the examined heat transfer coefficient occurred. In order to monitor the heat transfer coefficient's development in longer time intervals the measuring apparatus would have to be adjusted.

3.4 Acknowledgement

This work has been financially supported by the Czech science foundation under the grant P101/10/1669.