Heating surface thermal stabilization for pool boiling on porous coverings

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Abstract. The paper presents the results of comprehensive research of boiling on heating surfaces covered with copper fibrous capillary-porous structures (CPSs) used as fillings in heat pipes. The studies involved experimental and theoretical investigations, including development of technologies related to lab-scale manufacturing of sintered structures. Application-related problems such as the use of boiling in heat transfer control were also taken into account. Experiments were carried out for pool boiling of distilled water, ethanol, R–113 and R-123 on coverings of porosity of 40, 70 and 85%. The scope of the paper includes the description of the experimental setup, the methods used and the study results for pool boiling with various hysteresis types. In addition, possible applications of boiling on CPSs porous coverings to heating surface temperature stabilization are proposed.

1. Introduction
One of the substantial concerns of today’s technology is transfer of high heat fluxes, which is often connected with the necessity to maintain a steady temperature of the heating source. Precise temperature control is essential in developing new materials and thermal processes in energy conversion, nano-particle research, and advanced electronics. Most electronic devices are subject to a complex combination of internal and external transient thermal loads. The situation becomes even more conspicuous when the device experiences a sudden surge of heating power, which can have detrimental effects on its components. A number of studies have been presented in the literature for the design of effective thermal control [1].

There are two major reasons to maintain the operating temperature of a device at a certain level [2].

1. It is a well-known fact that the reliability of electronic devices (microprocessors, transistors) is exponentially dependent on their operating temperature. As such, small temperature differences, the order of 10–15°C, can result in a double shortening of the device lifespan.

2. The other factor is the speed of the microprocessor. At lower operating temperatures, due to reduced gate delay, microprocessors can operate at higher speeds.
The devices which emit high heat fluxes use the following controllable heat pipes for temperature stabilization: a) variable conductance heat pipe with a non-condensable gas reservoir (VCHP), and b) pressure controlled heat pipe (PCHP). Main disadvantages of those solutions consist in relatively big sizes of cooling elements and inability to apply them to variable thermal loads. Such issues do not occur in the cooling systems which use the properties of a pool boiling process on capillary porous structures.

2. Capillary and porous covering on a heat transfer surface

Capillary-porous structures (CPSs) as heat transfer surface coverings offer significant boiling heat transfer enhancement, Figure 1. However, when the heat transfer surface is covered with a CPS, hysteresis manifests itself much more clearly than in boiling on a technically smooth surface.

![Figure 1. Correlation between heat transfer coefficient \( \alpha \) and heat flux \( q \) in pool boiling.](image)

In the years 1995-2010, the authors conducted comprehensive research related to heat transfer for pool boiling on metal, fibrous capillary-porous coverings of the heat transfer surface. Such covering is a layer of sprinkled wires sintered to one another and to the surface, Figure 2. The main structural parameters of the covering, most often made of copper or steel, are as follows: wire diameter \( d_w \) (10 - 100 \( \mu m \)), wire length \( l_w \) (1-100 mm), layer porosity \( \eta \) (40 – 85%) and layer thickness \( \delta (0.2 – 2 \text{ mm}) \). For metal, fibrous sintered coverings, unlike for ones obtained by other methods, e.g. thermal spray technique, we can plan the parameters that we want to obtain.

The studies involved experimental and theoretical investigations, development of technologies and the issues of lab-scale manufacturing of porous sintered structures. The application-related problems were also investigated, including the use of a boiling process in heat transfer control.

![Figure 2. Metal, fibrous porous structure.](image)
3. Experiment

3.1. Experimental stand

Figure 3 presents a diagram of the experimental stand and its basic module. A specimen (1a, Figure 3) with a porous covering was mounted on a copper cylinder (1b). A heater coiled around the cylinder (1c) was charged via autotransformer. The cylinder was thermally isolated with a ceramic pipe (1d) and insulation fillings. A compensation heater (1e) mounted on the exterior of the ceramic pipe (1d) provided additional protection against heat loss. Type K thermocouples (1f) were mounted underneath the specimen, along the axis of the cylinder and in the boiling liquid.

![Diagram of the experimental stand and auxiliary systems](image)

**Figure 3.** Diagram of the experimental stand and auxiliary systems: 1 - basic module (details in the text); 2- heat loss compensation system; 3 - heating module with input power reading; 4 - measurement of pressure in the liquid tank; 5 - low pressure generating and measuring module; 6 - vapor cooling and condensate recovering module; 7 - digital high speed camera; 8 - excessive temperature signaling module; 9 - temperature measuring module; 10 - data collecting and processing module; p - pressure; Q- electric power; T- temperature.

The temperature of the heating surface was determined by extrapolation of temperatures measured along the axis of the cylinder, Figure 4:

$$ T_w = T_p - \frac{ql}{\lambda} $$

(1)

where: $q$ – heat flux, $T_w$ – temperature underneath the porous layer, $T_p$ - temperature under the specimen, $l$ – distance between the thermocouple under the specimen and the porous layer; $\lambda$ - thermal conductivity of copper.
The heat flux was calculated based on measurements of power supplied to the main heater, with heat loss to surroundings taken into account. The dependence below was used for calculating thermal power supplied to the specimen:

\[
q = \frac{4CQ}{\Pi d^2}
\]  

(2)

where: \(Q\) - electric power wattmeter reading, \(d\) - diameter of the sample with the porous covering.

The correction factor of heat loss to environment \(C\) was determined experimentally from the thermal balance of the experimental stand, \(C = 0.918\).

3.2. Experimental uncertainty

The error evaluation was conducted in accordance with the principles of the measurement accuracy analysis for experimental studies [1]. The absolute error value for estimating the heat flux was calculated from the dependence:

\[
\Delta q = \sqrt{\left(\frac{\partial q}{\partial Q}\Delta Q\right)^2 + \left(\frac{\partial q}{\partial C}\Delta C\right)^2 + \left(\frac{\partial q}{\partial d}\Delta d\right)^2}
\]

(3)

where: \(\Delta Q = 0.5\) W - electric power measurement error; \(\Delta C = 0.026\) – measurement error of constant \(C\); \(\Delta d = 10^{-4}\) m – specimen diameter measurement error. The relative error as the ratio of the absolute error to the minimum value measured was \(\delta_q = 12\%\).

The relative error of the measurement of the heating surface temperature was found using the dependence:

\[
\Delta T_w = \sqrt{\left(\frac{\partial T_w}{\partial T_p}\Delta T_p\right)^2 + \left(\frac{\partial T_w}{\partial q}\Delta q\right)^2 + \left(\frac{\partial T_w}{\partial l}\Delta l\right)^2 + \left(\frac{\partial T_w}{\partial \lambda}\Delta \lambda\right)^2}
\]

(4)

where: \(\Delta T_p = 0.2\) K – temperature measurement error; \(\Delta q = 3.2 \times 10^3\) Wm\(^{-2}\); \(\Delta l = 10^{-4}\) m – measurement error of the distance between the thermocouple and the porous layer; \(\Delta \lambda = 0.25\) Wm\(^{-1}\)K\(^{-1}\) – error of

![Figure 4. Arrangement of measurement points.](image)
thermal conductivity calculation. The relative error for temperature differences $\Delta T$ was 9%.

3.3. Results
Experiments were performed for pool boiling of distilled water, ethanol, R–113, and R–123. In comparison with a technically smooth heat transfer surface, copper fibrous porous coverings were found to substantially increase heat transfer coefficient $\alpha$, Figure 5.
The boiling curves were determined by increasing and decreasing the heat flux, which for certain sets of structural parameters of the coverings and the physical properties of the liquid, induced heat flux hysteresis. Three different types of hysteresis were observed, Figure 6.

**Figure 5.** Example of the dependence of the heat transfer coefficient $\alpha$ versus $q$ for the structures with porous covering thickness from 0.2 to 2 mm, and porosity of 85%, $\alpha_{\text{porous}}/\alpha_{\text{smooth}} \sim 5$.

**Figure 6.** Examples of three types of hysteresis.

Figure 6a presents the specific experimental boiling curve for *type - I hysteresis* characterised by the decrease in heat transfer coefficient after the decrease in heat flux. Figure 6b presents a specific experimental boiling curve for *type - II hysteresis*, where the heat transfer coefficient increases as the heat flux diminishes, prior to the latter reaching its maximum. The particular feature of *type - III hysteresis*, Figure 6c, is the decrease followed by the increase in heat transfer coefficient.
4. Application of porous structures to heat transfer control
The attributes of boiling on CPSSs were used for heating surface temperature stabilization, both for surfaces where hysteresis does not occur and those with type-II hysteresis.

4.1. Method for heat transfer control
Stability and repeatability of the boiling curves with type-II hysteresis help present a new approach to boiling heat transfer control on heat transfer surfaces coated with porous layers. Those two features of type-II hysteresis decide about its name “controlled hysteresis”.
The described phenomenon seems suitable for controlling the heat transfer surface temperature. The heat source, to which the control refers, is cooled with the use of boiling on the surface coated with a CPS. Specially selected characteristics of the structure facilitate type-II hysteresis similar to that presented in Figure 6b. The procedure of heating surface temperature control is presented in Figure 7.

\[ q_1 \rightarrow q_2 \rightarrow q_3 \rightarrow q_{ad} \]

**Figure 7.** Heat transfer control technique.

At the unwanted change in the heat flux emitted by the source (for instance from \( q_1 \) to \( q_2 \)), it is possible to find such point \( B \) on the curve \( b \) that after another heat flux decrease to the certain value \( q_2 \), we can obtain the desired temperature difference between the heat transfer surface and liquid saturation \( \Delta T_n \). An additional heating source emitting heat flux \( q_{ad} \) must be used for the time necessary to reach point \( B \). The procedure of heat transfer surface temperature control has been patented [4].

4.2. Method for heat transfer surface temperature control under high and variable thermal loads
The method uses the attributes of the boiling process on the CPS with additional nucleation sites (along with pores) in the form of cavities developed as a result of the so called hydrogen corrosion of copper [5]. The boiling curve plotted for such a structure typically has a nearly vertical section for nucleate boiling region without hysteresis, Figure 8, section I.

The heat transfer process for that section of the boiling curve may occur in a wide range of heat flux changes \( \Delta q_n \) (also under dynamic conditions) at the maintained, almost steady wall superheat \( \Delta T_w \).

4.3. Method for temperature equalization on the heat transfer surface under varied thermal loads
The need for higher performance and an increased scale of microprocessor integration leads to preferential clustering of higher power units on the device. This in turn entails diversification of local heat flux values resulting in large temperature gradients, see Figure 9.

Heat transfer surface coverings in the form of porous layers can provide different boiling curves depending on their porosity and thickness, Figure 10, covering-1, covering-2, covering-3. Therefore, for various heat fluxes, Figure 10, \( q_1 \), \( q_2 \), and \( q_3 \), superheat \( \Delta T_n \) can be held constant if the proper choice of boiling curves is made. For that purpose the parameters of heat transfer surface covering need to
correspond to the selected boiling curves. The heat transfer surface temperature equalization for the case presented in Figure 9 is discussed at length in [6].

Figure 8. Maintaining surface temperature under conditions of variable heat flux $\Delta q_n$.

Figure 9. Example of heat flux distribution on the computer processor surface [2].

Figure 10. Equalization of heat transfer surface superheat $\Delta T_n$ under varied thermal loads.
Figure 11 presents sample parameters of the covering (porosity and thickness) which allow maintaining constant surface temperature for variable heat fluxes.

![Graph showing porosity and thickness parameters](image)

**Figure 11.** Capillary-porous structure application to temperature equalization of computer processor.

5. Conclusions

The results of longstanding experimental studies of boiling on porous layers let the authors propose the application of boiling process properties for temperature stabilization on heat transfer surfaces. All forms of boiling heat transfer hysteresis are generally regarded as disadvantageous phenomena. In this work, the authors advocate a novel approach to the problem. It consists in an attempt at the practical application of type - II hysteresis to heat transfer process management. According to the presented idea, type - II hysteresis could be applied to maintain constant temperature of the heat transfer surface in spite of an uncontrolled increase in the heat flux.

The properties of boiling on porous structures with additional nucleation sites resulting from copper corrosion were used for thermal stabilization on surfaces under variable thermal loads. The custom-tailored capillary porous covering with properly adjusted thickness and porosity distribution across the heating surface is recommended for temperature equalization of non-uniformly heated computer processors.

References

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