Influence of controlled pulsations of a liquid flow on the surface temperature of heater with a high heat flux

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Abstract. The removal of high heat fluxes from 100 W/cm² to 1000 W/cm² for microelectronics components is one of the difficult tasks in the field of applied thermal physics. One of the important parameters in the task of cooling the intensely heated surfaces of the elements of microelectronics is the temperature depending on the operation time. This work is an experimental study of the influence of controlled pulsations of a liquid flow in a two-phase system on the temperature of the heater surface depending on the heat flux. It is shown that for a heat flux of more than 80% of the critical heat flux, the temperature change on the surface of the heater can reach up to 15 °C, which can adversely affect the operation of the cooled chip. In the case of less than 80% of the critical heat flux, the temperature change is less than 4 °C, allowing the cooled chip to work in a stable mode. It is shown that in the case of controlled pulsations of the liquid flow, subregimes are formed with different duration of existence.

1. Introduction
In the field of rapidly developing microelectronics, there are problems of diverting high heat flux from the surfaces of various electronic components (chips, microprocessors). Great attention is paid to highly efficient cooling systems capable of removing heat fluxes from 100 W/cm² to 1000 W/cm² and higher [1]. Two-phase systems with stratified and annular flow regimes have enormous potential for solving problems of removing high heat fluxes [2–4]. In [5–7], studies of the heat and mass transfer of a two-phase system in mini/micro channel were carried out, and the efficiency of removing high heat fluxes using a thin film of liquid moving under the action of a gas flow was shown.

One of the potential modifications of two-phase systems with stratified and annular flow regimes is the addition of periodic perturbations in the form of liquid flow pulsations into the system [8, 9]. These works show that with an increase in the frequency of pulsations of the fluid in the system, the heat transfer coefficient begins to increase. At the same time, pulsating additives to the system have a negative effect on the heat and mass transfer in a two-phase system. For large periods of pulsations, the heat transfer coefficient can deteriorate significantly compared with the regime without pulsations. Pulsating additives lead to a temperature gradient on the surface. This may lead to the impossibility of the technical application of such systems in the field of cooling microelectronic components.

The main objective of this work is an experimental study of the influence of controlled periodic pulsations of a liquid flow on the surface temperature depending on time. In the course of the work, the phenomenon of flow regime transitions from the stratified to annular regime due to fluid pulsations was investigated.

2. Experimental setup
A schematic diagram of the evaporative cooling research system with controlled pulsation is shown in Figure 1. To create a fluid flow with pulsations, two liquid pumps were used. First is Grundfos DDE 15-4 (LP) pump for pumping a working liquid with a constant flow. Second is Etatron BT MA/AD diaphragm pump (MP) for pumping the working liquid with pulsations. The gas circuit contains a MVNK membrane vacuum pump-compressor (CG), which produces up to 100 l/min of working gas. To control the gas flow rate, the Bronkhorst F-111AC-70K flow rate regulator (CV) is used. At the exit
from the working section, the vapor-gas mixture is condensed in a ACH16-14H-F (C) plate heat exchanger. After condensation, the gas and liquid enter the separator (S), from which they again begin to circulate in the prototype of the cooling system (TS). The test fluid is ultrapure water, created using a Merck Millipore Direct-Q 3 UV water treatment system.

**Figure 1.** Schematic diagram of the experimental prototype of evaporative cooling system:

TS – testing section; C – condenser; S – separator; R – receiver; CV – control valve; LP – liquid pump; CG – gas vacuum pump-compressor; BWS – building water supply, MP – membrane pump.

A high-speed camera was used to visualize heat transfer processes.

A channel of rectangular section 10x1.1 mm$^2$ is realized in the working section. The channel is oriented horizontally. At the inlet, the temperature of the liquid and gas does not exceed 25°C. A copper heater is installed in the middle of the channel creating local heating in a two-phase system. The size of the heater is 10x10 mm$^2$ and it is equivalent to a channel width of 10 mm.

### 3. Experimental results

The roughness of the walls of a rectangular channel is about 900 nm. Studying the surface wettability of the heating element was carried out using a KRUSS DSA 100 device. The hysteresis of the angle is 70°.

Experiments on heat and mass transfer in a two-phase system with controlled pulsation of the liquid were conducted. In the course of the experiment, the temperature on the heater surface and the heat flux were determined using thermocouples embedded in the heater. The total average flow rate is 150 ml/min, the flow rate of the fluid is approximately 20% of the total flow rate. The superficial liquid velocity ($U_{sl}$) is 0.23 m/s. The superficial gas velocity ($U_{sg}$) is 45.5 m/s. Figure 2 shows the dependence of the temperature of the heater surface on time for different values of heat flux within one pulsation period. Heat fluxes are given taking into account heat losses, which are not more than 10%.
Figure 2. The dependence of the surface temperature of the heater in a two-phase system with fluid flow pulsations on time for different values of heat flux. \( U_{sg} = 45.5 \text{ m/s}, U_{sl} = 0.23 \text{ m/s} \). 1 – 402.1 W/cm², 2 – 422.7 W/cm², 3 – 452.8 W/cm², 4 – 581 W/cm², 5 – 625.2 W/cm², 6 – 685 W/cm² (heat transfer crisis). The liquid inlet temperature is 25 °C.

It is seen that for heat flux below 80% of the critical heat flux, the change in temperature of the heater surface \( T_s \) over time is from 3 °C to 4 °C. At the same time, at heat exchange crisis in the system approaches, the temperature of the heater surface change can reach more than 15 °C (at heat flux, \( q = 625 \) W/cm²). Before the crisis itself, the surface temperature can change to 40 °C. The surface temperature was determined using the equation (1):

\[
T_s = T_1 - \frac{q l}{\lambda}
\]  

(1)

\( T_1 \) – the temperature of the thermocouple located close to the surface, \( q \) – local heat flux, \( \lambda \) - thermal conductivity of the heater material, \( l \) - distance from thermocouple to heater surface. The equation (1) follows from the Fourier thermal conductivity law:

\[
q = \lambda \frac{dT}{dt}
\]

(2)

Using high-speed camera imaging, photographs of a two-phase flow in a heated rectangular channel were obtained (Figure 3).

Figure 3. Photographs of the heater surface for different subregimes. Heat flux is 685 W/cm². \( U_{sg} = 45.5 \text{ m/s}, U_{sl} = 0.23 \text{ m/s} \). (a) – the annular regime, (b) – transitional regime from the annular regime to the stratified regime, (c) – the stratified regime.

Two phase flow is directed upwards in the pictures.
The flow regime with pulsations can be divided into 3 parts. The first part is the annular flow regime, which occurs when a pulsating fluid additive begins to cross the heater. The top wall channel is completely wetted with liquid. This regime lasts less than 1 second (Figure 3 (a)). During this period of time (annular regime duration), the surface temperature begins to decrease until the second part of the flow regime occurs. The second part of the flow regime is transitional from the annular to the stratified regime, when the pulsating additive almost completely crossed the heater boundaries (Figure 3 (b)). The top wall channel is only partially wetted with liquid. The photo shows rivulets on the top wall of the channel. During this period of time (about 2 seconds), the surface temperature begins to rise, but the surface temperature of the heater is still less than in the third part of the flow regime. The third part of the flow regime is the stratified regime (Figure 3 (c)). The top wall channel is not wetted with liquid. The temperature at this flow regime continues to rise until the next pulsation of the fluid arrives and reaches maximum temperatures in the system depending on heat flux.

Figure 3 (a) shows that the heater surface and the top of the channel wall are completely covered with liquid. Figure 3 (b) shows that the surface of the heater begins to dry. Liquid rivulets are formed on top of the channel wall. Under the stratified flow regime (figure 3 (c)), the liquid only flows on the heater surface and the heater surface is almost completely drained, indicating that the heat exchange crisis is approaching.

Conclusions

In this study, the effect of periodic fluid pulsations on the temperature of the heater surface for different values of the heat flux at fixed values of the superficial liquid and gas velocity has been studied. It is shown that with heat flux from 402.1 W/cm² to 581 W/cm² the temperature change on the heater surface is not higher than 4 °C. Such a temperature change on the heater surface may not affect the stability of the chip, microprocessor. For heat flux over 80% of the critical heat flux, the temperature change can be 15 °C, reaching 40 °C before the crisis. Such a high temperature change can adversely affect the operation of microelectronics elements. The intensification of heat transfer processes in a two-phase system with controlled pulsation of liquid flow can be applied without restriction for applications where there is no effect of temperature changes on the operation of the device (power transistors). It is shown that with controlled pulsations of a liquid flow in the system, a sub-regime consisting of an annular (duration less than 1 second), transitional from annular to stratified (2 seconds long) and stratified flow regime (3 seconds long) is formed.

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