Nucleate pool boiling on microstructured surfaces

Alexander Ustinov

Novel surface microstructure for nucleate pool boiling has been developed and used in extended experimental studies. It consists of cylindrical pins as basic elements, having diameters of 0.1 μm to 25 μm, height ranging from 10 μm to 100 μm, and the number density of the pins can be varied from 1×10^4 cm^{-2} to 1×10^9 cm^{-2}. Inclination of micropins can be varied as well, and it is possible to create simultaneously several sets of pins with different inclinations on the same surface. Such microstructures can be easily generated on cylindrical specimens like tubes in almost all electrochemically depositable materials. Besides of the significant heat transfer enhancement, the microstructure demonstrates several unique features. Main of them is the independency of the surface temperature on the heat flux over a wide range. This property is attributed to very large lengths of TPL, provided by great number of micropins piercing the growing bubbles. In several boiling modes the TPL lengths were so long that 2 K – 3 K decrease of surface temperature was detected with the increasing heat flux.

Eleven microstructured surfaces with different geometry were tested with refrigerants R141b, R134a and highly wetting electronic liquid FC-3284 at pressures from 0.5 bar up to 9 bar in single and tandem tube configurations. Microstructured surfaces show a heat transfer enhancement ranging up to the factor of 20, largely independent of the heat flux. At most effective boiling modes the boiling inception occurred as a front, moving at a high speed along the tube length. The heat transfer performance of the tested structure remains unaffected by long time operation under the strongly changing conditions.

The original classification system of enhanced surfaces was proposed in the work, basing the common properties of different enhancement methods and consideration of basic physical principles governing the nucleation. Majority of existing enhanced surfaces for nucleate boiling were considered with pro and contra using the proposed classification system. Modified surfaces can enhance the boiling heat transfer either supporting the initial nucleation which is a probabilistic phenomenon, or by enlarging the length of three phase line (TPL) after a vapor bubble had been created and started to grow. To judge about certain way of enhancement, a characteristic micro geometry scale of structure is proposed to calculate using the fractal dimension. This quantity seems to be the universal and applicable for different kind of microstructures, unlike the roughness parameter.

For boiling on surfaces with two different sets of inclined pins (bi-cavity pattern), wall superheat experiences a sharp step-alike change, later remaining unaffected by the heat flux. This process is called in the work “boiling re-establishing”. First, smaller cavities are activated at a certain superheat. Later, when surface reaches the activation temperature for larger cavities, they become activated as well. As cavities of both sizes are formed by the same near by pins, only a larger one acts. Thus the larger bubbles occur on the surface, what was observed visually.

The heat transfer efficiency of the microstructured surface in comparison with a technically smooth tube under idem conditions was found to be by the factors ranging up to 20 in several boiling modes. The enhancement factor depends on the geometry of the microstructured surface, system pressure and properties of the boiling liquid. The enhancement factor decreases with increasing pressure: at lower pressures the critical bubble radius increases, therefore, even more nucleation sites can be activated, as their sizes become large enough to support density fluctuations and form a vapor bubble.

Appearance of the bubble chains on the microstructured surfaces was observed in all boiling modes. It confirms the correctness of the nucleation criteria, given in the work: it is easier for a new bubble to arise near an existing vapor rest. This phenomenon also sets thinking about boiling as a chaotic process with deterministic behavior. The order of bubbles chains appears in the chaos of the fluid density fluctuations.

Temperature oscillations of the surface were detected experimentally near the crisis during boiling of the highly wetting fluid FC-3284. The amplitudes and the frequencies of oscillations rise significantly right before the crisis, because large vapor masses are formed and detached from the surface. Both amplitudes and frequencies of temperature oscillations depend on the microstructure geometry. For microstructures with larger number of pins the decrease of amplitudes of temperature oscillation was noted. The phase portrait (attractor) was constructed after measured data, showing that some time after the beginning of observations the amplitudes and the frequencies of surface temperature oscillations tend to tighten near a narrow phase area. This allows recommending this method for detection and prevention of boiling crisis in industrial apparatus.

Boiling hysteresis was found to be expressed stronger for structures with higher micropins density due to their better vapor trapping abilities. Higher pressures suppress the hysteresis as well as the surface temperature gradients.

Tandem tube experiments have shown high compactness of results of measurements for different boiling modes. The independence of the surface superheats on the heat flux applied to the test tube has been observed for all pressures. This is attributed to the great number of vapor bubbles, produced by the microstructured surface, same as for a single tube. Weak dependence of the upper tube superheats on the heat flux of the lower tube was observed. For industrial practice it means no significant temperature gradients in a heat exchanger, and simultaneous stable and effective work of all microstructured tubes, regardless their positions in the bundle, entering position of fluids into the heat exchanger, and pressure. Higher heat transfer coefficients for R134a have been found for the upper tube, than for lower tube, what has good agreement with data from literature. Presence of the lower tube generally promotes heat transfer of the upper tube, as vapor bubbles generated by lower tube are trapped by the microstructure of the upper one, helping to create new bubbles. For FC-3284, however, the increase of surface temperature of the upper tube in comparison with single tube at 2 K was measured. Effects of boiling reestablishing, hysteresis and, most important, the constancy of the wall superheat, were detected for the tandem configuration in the same degree as for the single tube experiment.

The microstructured surfaces have demonstrated very high effectiveness in tandem configuration, stability of the performance, very low superheats and independency on non-stationary effects. The microstructured surfaces can be recommended for use in industrial heat exchangers with the corresponding liquid, so its critical heat flux would be large enough. As soon as boiling occurs on a single tube from the bundle, the rest of the tubes becomes activated as well, so no great inception superheats are required for the bundle of microstructured tubes.

A model was proposed in the work, based upon the statistical information of a surface micro geometry and properties of liquid. The proposed model is universal and is not limited to a single class of enhanced surfaces. The only surface specific information required is a function of distribution of cavities on their sizes. The proposed model gives correct principal dependence of the heat flux on the surface superheat for a real surface, microstructured surface with mono-cavity pattern and bi-cavity pattern. Modeling results show that the superheat of a mono-cavity pattern surface is independent on the heat flux – a fact confirmed by numerous experiments. For bi-cavity pattern the re-establishing is obtained as results of calculation. It happens when all cavities of a smaller characteristic size are active. In subsequent process, surface temperature “jumps” up, activating the rest of the cavities. Modeling results show that boiling crisis starts when there are no more cavities available on the surface and the number of active nucleation sites is equal to the number of potential nucleation sites. As distance between neighboring nucleation sites is about several micrometers, vapor, created by them, immediately forms a film. Principally the mechanisms of boiling crisis and boiling re-establishing are the same.

Varying model parameters (number of distinguished cavities, diameter of these cavities, dispersions of cavities sizes around their diameters, and percent relation between the distinguished cavities) one may obtain any shape of a boiling curve. It seems possible to manufacture a surface with pre-programmed boiling curves.

Result of this work were reported at several international conferences, and published in corresponding proceedings and journal articles [1-5].

References

1. Mitrovic J., Ustinov A.: Nucleate boiling heat transfer on a tube provided with a novel microstructure // *Journal of Enhanced Heat Transfer*, 13(3) 1–18 (2006).
2. Mitrovic J., Ustinov A.: Boiling features of a novel microstructure // *Proc. of 13th International Heat Transfer Conference,* Sydney, Australia, August 13 – 18, 2006
3. Ustinov A., Mitrovic J.: Highly effective surfaces for boiling applications // Paper MJ2. *Proc. of 5th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*, 2007, Sun City, South Africa.
4. Ustinov A., Mitrovic J.: Special boiling effects of novel microstructured surface // Paper THP-19. *Proc. of 5th European Thermal-Sciences Conference*, 2008, Eindhoven, Netherlands.
5. Ustinov A., Mitrovic J.: Pool boiling heat transfer from a bundle of tubes provided with the novel microstructure // *Proc. of ECI International Conference on Heat Transfer and Fluid Flow in Microscale,* Canada, Whistler, 21-26 September 2008. (Invited in the special issue of International Journal of Heat and Fluid Flow).