Enhancing the boiling heat transfer

A V Dedov
National Research University "Moscow Power Engineering Institute", Moscow, Krasnokazarmennay 14
E-mail: dedovav@mpei.ru

Abstract. The main results obtained on boiling heat transfer enhancement over the past two decades are reviewed. The methods and ways to intensify the boiling heat transfer are traditional: influence on the internal boiling mechanisms; increase of the heat exchange surface; creation of conditions that suppress the least efficient processes during boiling. Today, the methods of influence have become much more selective and precisely tuned. The use of nanofluids and nanomaterials, femtosecond laser irradiation, plasma and ion processing allows obtaining a significant number of new results.

1. Introduction
The number of studies devoted to the issues of heat transfer during boiling increases every year. The increase in the number of publications can be explained by the emergence of new technologies and new tasks. Using the so-called nanofluids and nanomaterials, femtosecond laser irradiation, plasma and ion processing allow obtaining a significant number of new results and lead to a surge in relevant studies. Traditionally, most of the research was carried out for boiling under free convection, in order to establish the main influencing factors and to find common patterns. The results are then extrapolated to the channels of flow boiling and evaporation. Part of the modern work is related to the problems of the heat transfer intensification during boiling. The arguments for such research are as follows:
- the need to reduce overall dimensions, especially of compact heat exchangers (heat pipes, heat exchangers in electronics, etc.);
- the need to remove extremely high flux densities (more than 1 MW/m² when cooling power electronics components, thermonuclear installations, laser mirrors, etc.);
- the increase of critical heat fluxes (CHF). It should be noted that the tasks of the heat transfer intensification during boiling and an increase in CHF are not always the same;
- special boiling conditions (lack of a sufficient number of evaporation centers, special fluids and surfaces, etc.).

The methods and ways to intensify heat transfer upon boiling are traditional:
- influence on the internal mechanisms of the process (increase in the evaporation centers, control of the contact angle, increase in the inflow of liquid into the zone of evaporation of the microlayer, etc.);
- increase/development of the heat exchange surface;
The listed methods are often combined when implemented. For example, by changing/structuring the heat exchange surface, it is possible to exponentially develop the heat exchange surface, while creating artificial evaporation centers and increasing the inflow of liquid into the evaporation zone. The conditions of boiling heat transfer from a heated wall to the liquid volume a are determined by the nucleation of a bubble on the wall, the growth of its volume due to evaporation of the liquid near the contact line with the wall and the subsequent separation and entrainment of the vapor phase. The main process in bubble boiling is evaporation in a microlayer near the wall contact line.

The main results obtained when studying the intensification of heat transfer when boiling over the past two decades are reviewed in this article. It should be emphasized that most of the methods were tested in the 1960s and 1970s and it is probably impossible to set fundamentally new boiling tasks. So there is a repetition of earlier studies at a different technical and technological level, and the methods of influence have become much more selective and precisely tuned.

2. Influence on the internal mechanisms of the process and development of the heat exchange surface

The contact angle affects the formation of bubbles. Increase in the contact angle (deteriorating its wettability) allows reducing the temperature difference corresponding to the onset of nucleate boiling (ONB), intensifying heat transfer, improving the wettability, thus providing the liquid inflow into the zone of intensive evaporation and increasing the CHF. Initially, the change in wettability occurs through oxidation of surfaces (including natural oxidation of surfaces) and the deposition of other materials [1]. The influence at the low and subatmospheric pressures is especially effective. The emergence of technologies to deposit nanomaterials on the heat exchange surface (both electrochemical deposition and simple adhesives with heat resistances of up to 500 °C) [2], allowed obtaining surfaces with controlled wetting. So coating with nanoparticles of SiO2 on a part of the heat exchange surface [3-4] allowed alternating the zones of intensive vaporization and controlling the separation of bubbles, which in turn increased the heat transfer coefficient by 50%, reduced the heat buildup of the boiling point and increased the CHF. The application of a layer of nanoparticles of TiO2, ZnO [5-7] allows obtaining surfaces where the wettability increases with an increase in temperature. Initially, the surfaces are hydrophobic, which enables the reduction of the ONB temperature and intensifies the heat transfer, then, with an increase in wall temperature, it improves wettability, and the CHF typical for boiling on ordinary surfaces can be reached. Fig. 1 shows the boiling curves of subcooled water in a channel at mass velocity of 800 kg/m² s and a pressure of ~ 200 kPa [6] obtained by modifying the surface with particles of SiO2, TiO2, and ZnO. The contact angle of the water droplets on these surfaces at room temperature is 57, 83, and 90 degrees, respectively. The performed measurements of the characteristic irregularities (less than 50 nm) with such a modification exclude the influence on the number of vaporization centers.

A modification of the surface, leading to a change in the characteristics of boiling heat transfer is also possible through the deposition of particles on the heat transfer surface, forming microscale, usually porous structures. Previously, such surfaces were obtained by sintering microparticles on the surface and were rather well studied. Modern deposition methods are very diverse and allow obtaining unique three-dimensional structures: electrochemical methods (the formation of bi-porous copper structures [8-10]), plasma deposition [11], boiling of nanofluids [12], etc. For all such methods, the influence of several factors is characteristic: change in surface wettability; increase in the density of potential centers of vaporization; and more subtle mechanisms that determine heat transfer. In [8-10] there is a decrease in the temperature difference at boiling as a result of an increase in the heat transfer coefficient and an increase in the CHF up to 50-100% [10, 13]. It should be noted that, as a rule, the authors do not take into account the development of the surface due to its roughness. In the work [13], the shape of such surfaces is shown to be stable when heated to 500 °C in a gaseous atmosphere. A
typical result of the studies in the form of boiling curves showing a change in heat transfer at modified surfaces in comparison with smooth surfaces, for example, the data of the work [10] presented in Fig. 2.

![Boiling curves](image1.png)

**Figure 1.** Boiling curves for subcooled water [6].

![Saturated pool boiling curves](image2.png)

**Figure 2.** Saturated pool boiling curves for de-ionized water on composite porous surface (P1-P3) and plain surface [10].

Several works can be noted with similar results on the intensification of heat transfer and the increase in the values of CHF. Intensification, as a rule, tends to a decrease in the temperature difference at the ONB, with a similar behavior of the boiling curves, which emphasizes the conventionality of using the heat transfer coefficient for boiling.

Another popular method of surface modification is the use of short laser impulses (up to femtoseconds), leading to the ablation of the surface. As a result of the impact, a micro-relief of complex shape is formed. A hierarchical structure consisting of rough peaks, covered with a dense...
porous layer of nanoparticles is created. Such a surface is characterized by ultra-wetting and the action of capillary forces. Fig. 3 and 4 present data of the work [14], showing the surface profile (Fig. 3) and the results of the study of heat exchange in boiling water under conditions of free convection (Fig. 4). The results show a decrease in the temperature difference at the start of boiling and an increase in the CHF.

Figure 3. Laser confocal microscope images of the femtosecond laser processed surface

Figure 4. Heat fluxes with respect to surface superheat for both the laser processed and the polished stainless steel surfaces

Technologies using femtosecond laser action and subsequent surface treatment enable the formation of both ultrahydrophilic and ultrahydrophobic metal surfaces [15]. Formation of structured
surfaces with a complex relief occurs also with the use of pulse laser radiation. In the work [16], the action of nanosecond pulses on a surface of stainless steel produced samples with different regular microstructures, characterized by a change in wettability. Experiments on pool boiling showed a decrease in the temperature difference at the ONB on the treated surfaces in comparison with the polished ones, which was caused by a change in the wettability and an increase in the potential centers of vaporization. For laser exposure on metal surfaces, a durable change in wettability is characteristic, due to the surface oxidation and prolonged boiling.

When creating structured surfaces in our experiments [17], technological laser guns with a microsecond pulse were used, as well as pulsed plasma and electron beams. A change is noted in the contact angle only for oxidizing surfaces. The presence of graphite materials in the surface structure did not significantly change the value of the contact angles.

We can also note the successful use of traditional technologies for surface development by processing the metal. A noticeable improvement in the heat transfer at boiling was shown in the works [18-19] demonstrating also an increase in the CHF on micro-structured surfaces obtained through deforming cutting, which enabled the development of heat exchange surfaces up to 12 times.

3. Creating conditions that suppress the least efficient processes during boiling

Heat transfer at subcooled flow boiling attracts the unflagging attention of researchers. The largest values of the CHF are obtained at strongly subcooled flow boiling. This allows using subcooled flows for cooling devices exposed to high-density heat fluxes (more than 1 MW/m²). Among such devices there are elements of thermonuclear reactors, laser mirrors, etc. The density of heat fluxes permanently diverted in these devices can exceed 20 MW/m². The CHF values for subcooled water at moderate pressures and velocities exceed these values by a factor of two, and the use of the flow swirling for intensification allows reaching values exceeding 60 MW/m² [20].

An analysis of subcooled flow boiling [21] showed that in this mode an extremely high heat exchange efficiency is achieved, due to the joint action of the convective heat transfer and boiling mechanisms [22]. In the subcooled flow the unique formed conditions exclude the least efficient process at boiling - the need to evacuate steam from the wall. The current understanding of the heat exchange model is as follows [23-24]: the vapor bubbles present on the wall do not exceed the boundaries of the viscous sublayer without introducing additional hydraulic resistance, in some instances up to the CHF. Heat is transferred from the wall through evaporation of the liquid at the base of the bubble and condensation at the apex, followed by heat dispersion in the core of the flow due to forced convection. On the surface of the wall, not occupied by steam bubbles, convective heat transfer occurs. The natural limit for such a heat exchange model is the limited dispersion of heat from the upper boundary of a walled two-phase region, corresponding to the condition of equality of temperatures of liquid and saturation temperature in the core of the flow by forced convection. The limiting density of the heat flux taken can be expressed in terms of the Reynolds transverse mass flow [23]:

\[
q_*= \rho_l \omega c_p (T_\omega - T_f) \frac{\xi/8}{1-12\sqrt{\xi/8}}
\]  

Equation (1) represents, in the author's opinion, one of the most interesting results in boiling, unfortunately not properly evaluated, and generalizes all the data on CHF known in literature and corresponding to the concept of "high-speed subcooled flow": \( \rho_l \omega > 2000 \text{ kg/(m}^2\text{s}) \), \( x < -0.2 \) [25]. Such flow conditions are provided quite simply since the interval of operating wall temperatures is quite large, and boiling plays an appreciable role in rather large wall overheating (a few dozen degrees) relative to the saturation temperature.

The possibility of using the most effective heat removal mechanism during boiling-evaporation in a microlayer of liquid without actual boiling is shown in the work [26]. In the liquid films on the heating surface, evaporation occurs near the wall-liquid-gas contact line, and the steam evacuation is provided by blowing off the gas at a high flow velocity (up to 40 m/s).
4. Conclusion
The problem of heat transfer enhancement during boiling remains topical. Modern technologies were proposed to control heat exchange at boiling by applying nano-layers and surface structuring. It is possible to significantly reduce the temperature difference at the ONB and increase the value of the CHF. Technologies have practical implementation in compact heat exchangers. By preserving the purity of coolants, heat transfer can be intensified in industrial devices.

The use of subcooled flow boiling provides the dispersion of heat fluxes with a density of ~ $10^2$ MW/m$^2$.

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