Heat transfer under transition and film boiling of liquids at dimpled spheres and cylinders

V. M. Zhukov¹, Yu. A. Kuzma-Kichta², A. V. Lavrikov², K. I. Belov¹, and V. A. Len’kov¹

¹ Joint Institute for High Temperatures, RAS, Izhorskaya 13, bld.2, Moscow, 125412, Russia
² National Research University (Moscow Power Institute), Krasnokazarmennaya 14, Moscow, 111250

The paper is dedicated to the memory of prominent scientist and Laureate of State Prize Vladimir Zhukov

Abstract. The article presents the results of studies of heat transfer and film and transition boiling mechanism of nitrogen, Refrigerant R-113, and water at spheres and vertical cylinders, which surfaces are covered with spherical dimples. The data were obtained under the conditions of pool boiling and natural circulation in vertical 1.0 and 2.5 mm wide annular channels. Hemispherical dimples of 3 mm diameter (h/d = 0.17) were made on sample surfaces. The dimples occupied 45% of the sphere surface and 37% of the cylinder surface. In some tests, the dimpled surface was additionally covered with low-conductive coating (10 µm film). Minimal cooling time for the sphere with dimples and low-conductive coating took place under natural circulation in 2.5 mm annular gap and it was almost 2.5 times lower than that for a smooth sphere under pool boiling. It is shown that at pool boiling the presence of dimples and low-conductive coating leads to heat transfer enhancement at transition and film boiling regimes, while at natural circulation such an enhancement occurs at film boiling with high temperature differences. The tests at natural circulation in vertical annular channels of different width showed that in this case an intensity of boiling heat transfer is higher than that at pool boiling. High-speed filming of film boiling process on the surfaces with dimples was conducted.

1. Introduction and experimental method

Creating dimples on a heat transfer surface is one of efficient ways of heat transfer enhancement in channels. In recent years this technology was very popular [1-3]. The dimples provide intense heat transfer between a boundary layer and a flow core. There are many works devoted to heat transfer in single-phase flows using dimples. At the same time, an effect of dimples on boiling heat transfer has been poorly investigated. In this sense, we should point out the work [3], in which boiling crisis was studied under subcooled water boiling in annular channels having dimples, and the work [4], where high-pressure steam-water mixture heat transfer was investigated in a post-crisis zone of the annular steam-generating channel with dimples.

Boiling of liquid film usually appears in any system at an initial phase of cooling, and this phenomenon is just the main mechanism that determines total cooling time. Duration of cooling process strongly depends on an intensity of heat removal at film boiling. The interest in study of
nitrogen boiling is due by development of high-temperature superconductors, which are cooled by liquid nitrogen.

In particular, there is a certain interest in studying nitrogen boiling in slot channels under the conditions of natural circulation, which in some cases is accompanied by regimes of “enhanced” as well as “deteriorated” heat transfer [1]. Natural circulation of boiling cryogenic coolant in channels takes place due to buoyancy force, and when this happens, a velocity of the vapor-liquid mixture is determined by an equality of the driving head and the loop hydraulic resistance, and it is a function of a heat flux value and channel dimensions. The objective of the work is study of heat transfer and mechanisms of film and transition boiling regimes of different liquids on spheres and vertical cylinders having dimples on their working surfaces under the conditions of pool boiling and natural circulation.

Two experimental rigs were constructed for boiling heat transfer studying. The experiments in a low-temperature region are conducted in one rig, while the other one - at high medium temperatures. An unsteady-state method is used in all experiments. The samples preliminarily heated above Leidenfrost temperature are immersed into the liquid under study at atmospheric pressure. The tests with refrigerant R-113 and water were conducted at pool boiling [3], while the study of liquid-nitrogen boiling heat transfer - at free convection and natural circulation at the rig described in [4].

To conduct the tests copper spheres and cylinders with smooth and dimpled heating surfaces were fabricated [5]. They are shown in Fig. 1. The dimples on the sample surfaces were fabricated using special punches, at the end of which 5 mm sphere made of steel was fixed. An increase in the heat transfer surface area due to dimpled relief was not more than 5% compared to that of the smooth surface. Two cylinders were made of 18 mm diameter and 81.5 mm long solid copper rod. One of the cylinders had no dimples (it had technical roughness), while the other cylinder had dimples (Fig. 1). The lower parts of the samples had hemispheric shapes to provide better streamlining samples by a steam-water medium. On the cylinder 252 dimples were made in an order (18 rows with 14 dimples in every row, d = 3 mm, h/d = 0.17). The longitudinal pitch between dimple centers was 4 mm, while the peripheral pitch was 4 mm. An increase in the heat-transfer surface area due to dimpled relief was not more than 4%.

Using a thin-wall tube the samples were lifted up into the heating zone. Then, they were kept in this zone at a given temperature and immersed into the vessel with a liquid under study (R-113 or water). The vessel had windows for video filming. When using liquid nitrogen, the glass cryostat was applied. Synchronously with sample immersion the data acquisition and processing system was switched by thermocouples installed in samples, in liquid and in the heater.

The Chromel-Alumel or Copper-Constantan thermocouples were used to measure the sample temperature. The thermocouple wire diameter was 0.2 mm. Using VS 10T high-temperature glue hot junctions of these thermocouples were fitted in dead holes at a depth of 10 mm in spheres and 10 and 30 mm in cylinders at distance equal 2 mm from the surface. Thermocouple signals were transmitted
to E-24 L-Card analog-digital converter with 20 Hz interrogation frequency and then to personal computer. Special program was used for data processing. In addition, liquid and heater temperatures were measured. More thoroughly the measurement technique is described in [5].

The temperature and heat flux at the surfaces of spheres and cylinders were obtained by solving the inverse heat conduction problems using asymptotic methods developed in [2]. The final expressions for the temperature and heat flux at the surface of sphere are as follows

\[ T(R,t) = T(0,t) + \frac{2}{3} \frac{R^2}{a} \frac{\partial T(0,t)}{\partial t} \sum_{k=1}^{\infty} \frac{1}{k^2} \]

\[ q = \frac{\lambda R \frac{\partial T(0,t)}{\partial t}}{\pi a} \]

and that for the surface of cylinder

\[ q = \frac{R \lambda \frac{\partial T(0,t)}{\partial t}}{2a} \]

\[ T(R,t) = T(0,t) + \frac{R^2}{a} \frac{\partial T(0,t)}{\partial t} \] .

Special attention was paid to investigate of dimpled relief effect of the heat transfer characteristics in transition and film nitrogen boiling regimes.

To increase a two-phase flow velocity around the test sample, a tube was mounted coaxially outside. Thus, an annular channel was formed between the sample and the tube. This tube was made of stainless steel, its length was 110 mm. The inner diameters of the tube were 20 or 23 mm. The width of the annular gap was 1.0 and 2.5 mm. In tests with natural circulation of the coolant, three alternatives of the sample surface were applied: smooth surface without dimples, the same with dimples, and the dimpled surface coated by 15 µm low-conductive polymeric film. As it was shown in several works, in particular, in [2], a thin low-conductive coating on the heat transfer surface leads to a decrease in a local wall temperature, cold spot formation and early ceasing of the film boiling regime, thus heat removal intensity increase. In tests, an assembly comprising a tube and a sphere or cylinder mounted on it were heated in air and immersed into the bath with liquid nitrogen. At initial instant a film boiling regime developed on the sphere or cylinder, as well on both sides of the tube. Due to a difference in liquid nitrogen density in the cryostat bath and in vapor-liquid mixture in the tube a driving head provided two-phase medium flow. By low heat capacity of the stainless tube and its large cooling surface the boiling on it stopped in some time, while all boiling regimes took place in succession on the sample surface.

In the tests, high-speed 8-bite monochromatic MOCAM-4000 video camera was used for filming a boiling process. At a moment of camera stop a synchronizing signal came to the analog-digital converter. The video frames are correlated with thermocouple readings. Filming was made in passing light, with lightning from the side opposite. A frequency of filming was 2000 Hz with an exposure time equal to 1/50000.

2. Experimental results and data analysis

Boiling of nitrogen

To check a reliability of the experimental technique tests were conducted with nitrogen boiling at the smooth surface without dimples. The data on heat transfer intensity well agreed with the results

...
published in literature [7, 8]. Video filming of nitrogen film boiling on the sphere and cylinder with dimples under conditions of pool boiling showed that waves of different amplitude and shape with flattened leading and sharp rear fronts were observed at the vapor-liquid interface.

The time temperature changes are shown for the spheres and cylinders without dimples and corresponding dimpled samples under pool boiling condition on Figure 2. We see that the cooling time of dimpled samples decreases from 140 to 100 s as compared to smooth surfaces without dimples.

Fig. 2. Sphere cooling in liquid nitrogen. 1 – sphere without dimples, pool boiling; 2 – spheres without dimples, natural circulation; 3 – sphere with dimples, pool boiling; 4 – sphere with dimples, natural circulation; 5 – sphere with dimples and coating, pool boiling; 6 – sphere with dimples and coating, natural circulation.

To additionally enhance heat transfer the dimples were covered by a thin layer of low-conductive coating. In this case, the samples were cooled at pool boiling and under natural circulation conditions. Figure 2 shows the curves of sample temperature change in time from 280K down to the saturation temperature in nitrogen. From the figure we see that the combination of the dimpled relief and low-conductive coating at natural convection reduces a cooling time of spheres. For example, the cooling time for smooth spheres, which was equal to approximately 140 s (curve 1), was down to 60 s for the dimpled sphere with coating (curve 6), i.e. approximately by 2.5 times.

The data on pool boiling heat transfer on spheres with and without dimples (curves 1 and 2) show that the effect of dimpled relief is greater in the region of ceasing film boiling and in the zone of transition boiling. At natural circulation (curve 3), up to temperature difference ΔT ~ 140 K, an intensity of heat removal increases. Boiling process is accompanied by oscillations of the liquid flow rate and sample wall temperature. The vapor-liquid mixture was ejected from both ends of the cylindrical channel. Two-phase flow rate oscillations sharply weakened when the outer tube was cooled down to nitrogen saturation temperature and the following heat input was only from the dimpled sphere. The heat flux at film boiling regime increased approximately by two times as compared to the case of spheres without dimples (curve 1). The considerable increase in heat transfer coefficient values was observed in the range of temperature differences, which corresponded to a transition boiling regime.

The data in Fig. 3 demonstrates heat transfer on spheres with dimples with low-conductive coating and without coating under the conditions of natural circulation. The greatest increase in heat transfer coefficient values took place when the spherical dimpled surface was used in combination with this coating (curve 3). Such a situation was observed over the entire range of temperature differences typical for transition and film boiling zones of liquid nitrogen boiling.
Cylinder. Nitrogen boiling heat transfer at natural circulation

As it was pointed out above, the natural circulation of two-phase medium arises in annular channels and heat transfer grows. In commonly applied methods of studying a heat transfer in annular channels, at the experiment beginning, liquid wets annular channel walls and with an increase in heat flux a bubble flow regime originates, further transfers into slug flow. In the experimental technique used in the present study the channel is cooled after heating above Leidenfrost temperature. Therefore, a film boiling regime arises and a liquid is separated from the channel wall by a vapor film. Such a boiling regime is accompanied by flow rate oscillations and liquid-vapor medium ejection from both ends of the channel. Flow rate and temperature oscillations increased when critical heat flux point became closer.

With a decrease in wall temperature transition and bubble nitrogen boiling regimes appeared in succession. A sample temperature was practically constant along the tube length because of high heat conductivity of copper. The curves in Fig. 4 demonstrate this fact.

The tests conducted with annular channels showed that the cooling velocity of cylinders, both without dimples and those with dimpled relief, is noticeably greater than that under pool boiling conditions. From Fig 4, where the changes of cylinder temperature in time are shown for annular channels which have a width 1.0 and 2.5 mm one can see that dimples increase cooling velocity. In addition, these results demonstrate an increase in cooling velocity with an increase in annular channel width.

The data on heat transfer intensity from Fig. 4 for cylinders with dimples in the 1 mm wide annular channel demonstrate an efficiency of the dimpled relief under conditions of natural circulation.
Heat transfer intensity at the cylinder with dimples in annular channels, especially in 2.5 mm wide channel, is also higher than that during pool boiling. The difference is equal to 50% at film boiling and up to 100% in transition boiling.

When approaching the maximal heat flux point, a growth of the net vapor content in the channel sharply increases. This leads to two-phase flow chocking and deteriorated heat transfer regime with lowered intensity of heat transfer removal from the sample surface. This regime is unstable through ject of vapor bubbles to the lower end of the annular channel. Two-phase mixture ejection is described in literature as liquid nitrogen boiling in a channel. Assessments based on the data on nitrogen boiling in annular channels [9] show that the void fraction value reaches 0.9-1.0 while a mass-averaged flow velocity tends to 0.5-0.6 m/s. An increase in channel transversal dimension leads to a decrease in friction losses, an increase in two-phase flow velocity and in enhancement of heat removal intensity. Peaks that correspond to maximal velocity of the flow in the channel core are seen on boiling curves.

Refrigerant R-113. Sphere

The dependences of heat transfer coefficient on temperature difference for spheres with dimpled relief are shown on Fig. 5. The presented curves show that the effect of dimples is especially strong in the range of small temperature differences and decreasing vapor film thickness, i.e. near the zone of a ceasing film boiling regime. The heat transfer intensity for this dimpled relief geometry is approximately 15-20% higher than those for the smooth sphere without dimples. Visual observations showed that on the dimpled surface, a vapor film coming-off sometimes arises at the lower part of the sphere, in contrast to the case of using smooth spheres without dimples, when such film coming-off always in upper part of sphere. In the range of nucleate boiling, the presence of dimples on the sphere surface has no effect on heat transfer intensity because adding a limited amount of dimples does not considerably increase a number of active nucleation sites.

Fig. 5. Heat transfer R-113 film boiling at spheres with different surface treatment
Key: 1- smooth sphere; 2- dimpled sphere; 3 – sphere with porous coating;

The strongest effect of dimples is the change of film boiling ceasing boundary and this is especially so when liquid is subcooled relative to the saturation temperature. With an increase in subcooling value a vapor film thickness decreases and this leads to film boiling ceasing at larger \( \Delta T_{cr2} \) and \( q_{cr2} \) values. The dependences of critical heat flux \( q_{cr2} \) on subcooling \( \Delta T_{sub} \) both for dimpled spheres and those without dimples. They demonstrate the stronger effect of dimples on film boiling ceasing at larger subcooling values.

If we compare film boiling heat transfer obtained at dimpled spheres, those without dimples, and spheres with porous copper coating [5], we recognize that the dimpled spheres occupy intermediate position (Fig. 5). We should note that at all spheres with different surface treatment, heat transfer intensity sharply increases in the range of small temperature differences, i.e. when approaching the zone of film boiling ceasing. The relatively weak effect of the dimpled relief on heat transfer at film
boiling regime, as compared to that in the case of porous coating, can be explained by a low spatial density of dimples (~12%) on the heat transfer surface. In addition, the dimple configuration being studied (h/d = 0.164 < 0.2) belongs to a class of small dimples, at which vapor flow occurs without separation from the heating surface, and heat transfer enhancing effect is lower than that for deep dimples (h/d > 0.2) [2].

Figure 6 shows the heat transfer coefficient under film boiling of refrigerant R-113 on the dimpled sphere. It recognized that heat transfer considerably grows with an increase of subcooling.

![Figure 6](image1)

**Fig 6.** Effect of subcooling on R-113 film boiling on dimpled spheres. 48 dimples, D= 20 mm, h = 0.5 mm, d = 3mm, h/d = 0.17, n = 27%. Key: 1 – subcooling 26 K, 2 – subcooling 13 K, 3 – saturation.

**Cylinder**

The heat transfer studies of Refrigerant R-113 were conducted on cylindrical surfaces with dimpled relief and without dimples within the temperature difference range up to 170 K, which included all boiling regimes at the liquid saturation temperature.

Figure 7 shows the video filming of the film and transition boiling of the saturated Refrigerant R-113 on the vertical cylinder with dimples. Typical profiles of waves on the interface are shown as well.

![Figure 7](image2)

**Fig. 7** R-113 film and transition boiling on vertical dimpled cylinder and typical wave profile on the interface

The analysis of the temperature change in time for cylinders without dimples and those with dimpled relief shows that the cooling time of the dimpled sample in R-113 is lower as compared to that for cylinders without dimples.

The data on the wavy flow of the vapor film are similar to the results obtained by Borishanskii and Fokin in the studies of hydrocarbons and water boiling on a vertical tube [10]. In their work the wave amplitude reached several millimeters. With an increase in heat flux density, while reaching the point of maximal critical heat flux, an amount of heat sharply increases. A decrease in heat flux density reduced vapor void fraction and formation of single vapor bubbles.

In the case the sphere with dimpled relief described earlier, nonlinear three-dimensional waves with amplitude alternating in time were noted on the vapor-liquid interface. These amplitudes were comparable in size or even greater than the mean thickness of the vapor film. From typical photos,
presented in Fig. 7 for cylinders with smooth surface and dimpled ones, one can see the existence of a complex system of waves on the liquid-vapor interface [9]. At the frontal spherical part of the samples the smooth interface and laminar vapor film flow, which transfers into turbulent one at the cylindrical part of the samples arises. The wavy flow on the cylindrical part of the dimpled sample is more complex. To a certain extent, it repeats the dimpled relief.

The dependences of q on ΔT for cylinders with dimples is shown on figure 8 in the range of ΔT from 50 to 170 K that corresponds to the transition and film boiling. They show a considerable effect of the dimpled relief on ΔTcr2 and qcr2 values as well as on heat transfer intensity in transition and film boiling regimes. At the dimpled cylinder the crisis occurs at ΔTcr2 values equal to 80 K, while at the cylinder without dimples the crisis occurs at ΔTcr2 equal 65 K. For cylinders with dimpled relief the value qcr2 increases by 1.5 times. In addition, the data presented in this figure show that the effect of the dimpled relief on heat transfer intensity is more pronounced in the range of small temperature differences near the film boiling crisis. This is occur through a decrease in the vapor film thickness. For example, at ΔT= 170 K the heat flux density increases by 20%, while at ΔT = 72 K, by 120%, as compared to the case without dimples.

![Fig. 8 Heat transfer at transition and film boiling of Freon R-113 on the dimpled cylinder (1) and on cylinder without dimples (2)](image)

**Water**

The water boiling heat transfer on surfaces with dimpled relief and without dimples is investigated in the temperature difference range that embraces all boiling regimes.

Figure 9 shows the video filming of film and transition boiling of water on the dimpled sphere and cylinder. At the frontal part of the samples a laminar flow of the vapor film is seen. The wavy flow of the vapor film is more complex, and it repeats the dimpled relief.

![Fig. 9 Subcooled water film and transient boiling at dimpled sphere and cylinder](image)

The data presented in Fig. 10 show that the dimpled relief provides an increase in critical heat flux qcr2 value and increases heat transfer intensity in transition and film boiling regime by three times.
3. Conclusions

The results of studying heat transfer at film and transition boiling regimes of nitrogen, Refrigerant R-133, and water on dimpled spheres and vertical cylinders are presented under conditions of pool boiling and natural circulation in vertical annular channels with a gap width by 1.0 and 2.5 mm. Semispherical dimples of 3 mm diameter and h/d = 0.17 were made on the sample surfaces. The density of dimples distribution on the surfaces of sphere was 45% and that on the surfaces of cylinder was 37%. In some tests, the low-conductive film of 10 µm thickness was deposited on the dimpled surface.

Under natural circulation of nitrogen in the 2.5 mm wide annular channel the cooling time of the sphere with dimples and low-conductive coating was almost 2.5 times smaller than that under pool boiling on the sphere without dimples.

At film and transition water pool boiling the presence of the dimpled relief provides increase in heat transfer intensity.

Acknowledgments

The work was supported by the Russian Foundation of Basic Research, Grant N 15-08-00775. The authors are thankful to Professor Yuri Zeigarnik for his help in preparing of the paper.

References

[1] Kiknadze G I, Krasnov Y K, Podymaka N F and Khabenskii V B 1986 Self-organization of vortex structures at water flow upon semispherical dimples Doklady of the USSR Academy of Sciences vol. 291 no. 6 pp 1315-1318
[2] Shchukin A V, Kozlov A P, Agachev R S and Chudnovskii Y P 2003 Heat transfer enhancement by spherical dimples under impact of disturbing factors (Ed. by V.E. Alemasov. Kazan. KGTU Publishing) p 143 (in Russian)
[3] Dzyubenko B V, Kuzma-Kichta Y A, Leont’ev A I et al. 2008 Heat transfer enhancement on macro, micro, and nanoscales (Ed. by Yu.A. Kuzma-Kichta. Moscow. FGUP TsNIAAtominform) p 532 (in Russian)
[4] Kiknadze G I, Kryuchkov I I and Chushkin Y V 1989 Self-organization of tornado-like structures in a coolant flow. Preprint IAE-4841/1 (Moscow, TsNIIAtominform) p 29 (in Russian)
[5] Mostinskii I L, Geshele V D, Goryainov D A and Raskatov I P 2001 Heat transfer from a surface with spherical dimples under water boiling and steam-water mixture flow in post crisis region IFZh 74(3) 13-19 (in Russian)
[6] Kuzma-Kichta Y A, Zhukov V M and Agal’tsov A M 2008 Heat transfer at cooling dimpled spheres in boiling liquids. VI Minsk International Forum. Theses of reports (ITMO Publishing, NANB) vol. 1 pp 111-113 (in Russian)
[7] Shumakov N V 1979 Method succeeded intervals in heat flux metering at unsteady processes (Moscow, Atomizdat) p 216 (in Russian)
[8] Kirichenko Y A, Kozlov S M, Rusanov K Vet al 1992 *Heat transfer at nitrogen boiling and problems of high-temperature superconductors cooling* (Kiev, Naukova dumka) p 278 (in Russian)

[9] Zhukov V M, Kazakov G M, Kovalev S A and Kuzma-Kichta Y A 1974 *Heat transfer under liquid boiling on surfaces with low-conductive coatings* In *Heat Transfer and Physical Gas Dynamics* (Moscow, Nauka) pp 116-129 (in Russian)

[10] Borishanskii V M, Maslichenko P A and Fokin B S 1964 *Studying of vapor layer at film boiling on vertical surface. In convective heat transfer in single-phase and two-phase flows* (Moscow, Energia) pp 243-248 (in Russian)