HEAT TRANSFER DURING BOILING OF LIQUID NITROGEN AT COILED HEAT EXCHANGERS

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An experimental study was made of the heat transfer during the boiling of liquid nitrogen at various types of immersed heat exchangers. The values of the heat-transfer rate are given for various temperature differences and heat load levels.

Test data published in [1-12] indicate that the process of heat transfer during boiling depends not only on the physical properties of the boiling liquid and of the heat emitting surface, but also on the geometry of the heat-exchanger surfaces, their structural design, their finish, their disposition in the boiling liquid, and various other factors. There are no universal formulas for calculating the heat transfer during boiling, and the available semiempirical relations have been checked only on similar apparatus models with serious restrictions arising from the necessity of knowing the values of many empirical factors for every specific case. Thus, the heat transfer in boiling liquids must be studied experimentally in every specific case. Furthermore, an accumulation of test data on heat transfer during boiling, especially pertaining to cryogenic liquids, is desirable for the purpose of their theoretical generalization. This article deals with such a study of the heat transfer and with the determination of the heat-transfer coefficients when liquid nitrogen is boiling at the heat-exchanger surfaces of liquid-medium heat exchangers used in liquefaction apparatus.

Cooling in liquid-medium heat exchangers of liquefaction apparatus is usually effected either by immersing the heat-exchanger surface in the boiling liquid or by means of the vapor–liquid stream flowing through a separate channel [13, 14]. Sometimes liquid-medium heat exchangers are built by coiling a tube for the cooling gas so as to maintain a thermal contact around the pool of boiling liquid [15]. The authors have studied the heat transfer in immersible liquid-medium heat exchangers (as in those most often encountered in cryogenic apparatus). They constitute, in effect, tubes for high-pressure cooling gas, variously wound into spiral or helical coils (Fig. 1).

In such heat exchangers there is always a temperature gradient along the tube with cooling high-pressure gas, and there is a possibility of interaction with the heat-transfer process in adjacent heat-exchanger tube segments as well as in nearest coil turns, i.e., all boiling modes coexist here: convective, bubble-, transition-, and film boiling, the interplay of which cannot but affect the character of the heat transfer in a heat exchanger. Earlier experimental studies of the heat transfer during boiling of liquid nitrogen in a large volume refer, generally, to the case where the entire heat emitting surface is at the same given temperature and is disposed in the boiling liquid so that any incidental effect may be as far as possible eliminated.

It is plausible that the performance of immersible liquid-medium heat exchangers will largely depend on the separation between adjacent coil turns, on the spatial orientation of the heat exchanger (vertical or horizontal), on the direction in which the temperature gradient in the heat exchanger changes ("from the bottom up" when the hotter coil turns are on the bottom or, the other way, "from the top down"), and on the rate of regulation (increase or decrease) of the heat load; in other words, the heat-transfer process in such heat exchangers may be determined also by these technological and structural factors.

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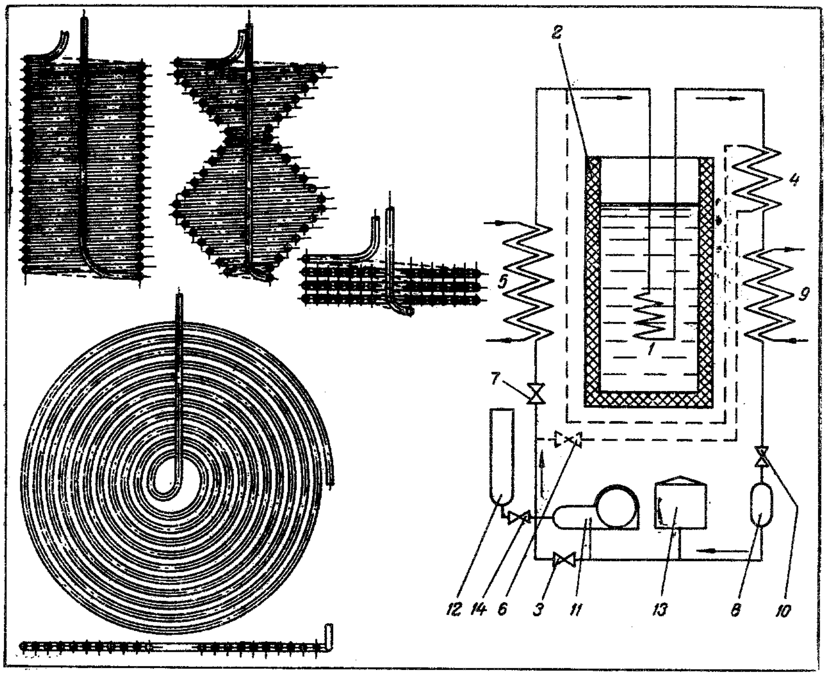

Fig. 1. Schematic diagram of the test apparatus and tested shapes of immersible liquid-medium heat exchangers: 1) tested heat exchanger [a) helical coil; b) spiral coil with a variable winding radius, in extended and in compressed position; c) flat spiral]; 2) nitrogen bath; 3, 6, 7, 10, 14) valves; 4, 5, 9) heat exchangers; 8) flow meter; 11) compressor; 12) storage bottle; 13) gas meter.

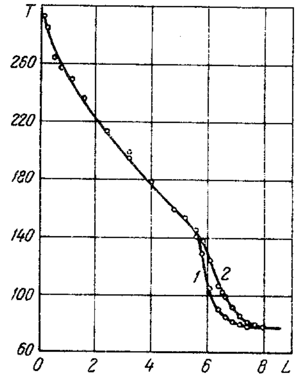

Fig. 2. Temperature profile along a heat exchanger, under conditions where the high-pressure hydrogen enters at room temperature and leaves at the "nitrogen" temperature (78°K): 1) smoothly increasing heat load; 2) decreasing heat load. Temperature T (°K); distance along the tube L (m).

The apparatus for studying the heat transfer during boiling of liquid nitrogen in the heat exchangers to be tested (a, b, c) is shown schematically in Fig. 1. A heat exchanger 1 was placed for the test in a thermally insulated container 2 with liquid nitrogen (a vessel with approximately 150 liters capacity), the level of the latter held constant during a test. A heat load on the heat exchanger was produced by a stream of hydrogen circulating in a closed cycle under a pressure of 100 atm. The circulation system used here made it feasible to vary the heat load over a wide range. The heat load was defined by the temperature and the flow rate of the gas stream in the heat exchanger 1. The gas stream was regulated by means of a bypass valve 3, while the temperature of the high-pressure hydrogen entering the heat exchanger 1 was set in heat exchangers 4 and 5. The amount of circulating hydrogen was determined by a flow meter 8, after the hydrogen had been "heated up" in heat exchanger 9 to the calibration temperature and pressure of the flow meter (by throttling through valve 10).

Heat exchanger 1 was made of industrial-grade copper tubing 6 mm in diameter, 1 mm wall thickness, and 8 m long, bent into various spirals (Fig. 1). Carefully calibrated thermocouples were soldered to the heat-exchanger tube at definite distances (0.5-0.2 m). The solder joints were thermally insulated with glass wool subsequently soaked with grade BF adhesive for surface hermetization. This thermal insulation covered 10 mm of the tube length on both sides of each joint. At 4-6 mm from the insulation edges the walls of the heat-exchanger tube underneath this insulation became equal to the temperature of the circulating gas, because of the high coefficient of heat transfer from that high-pressure gas.

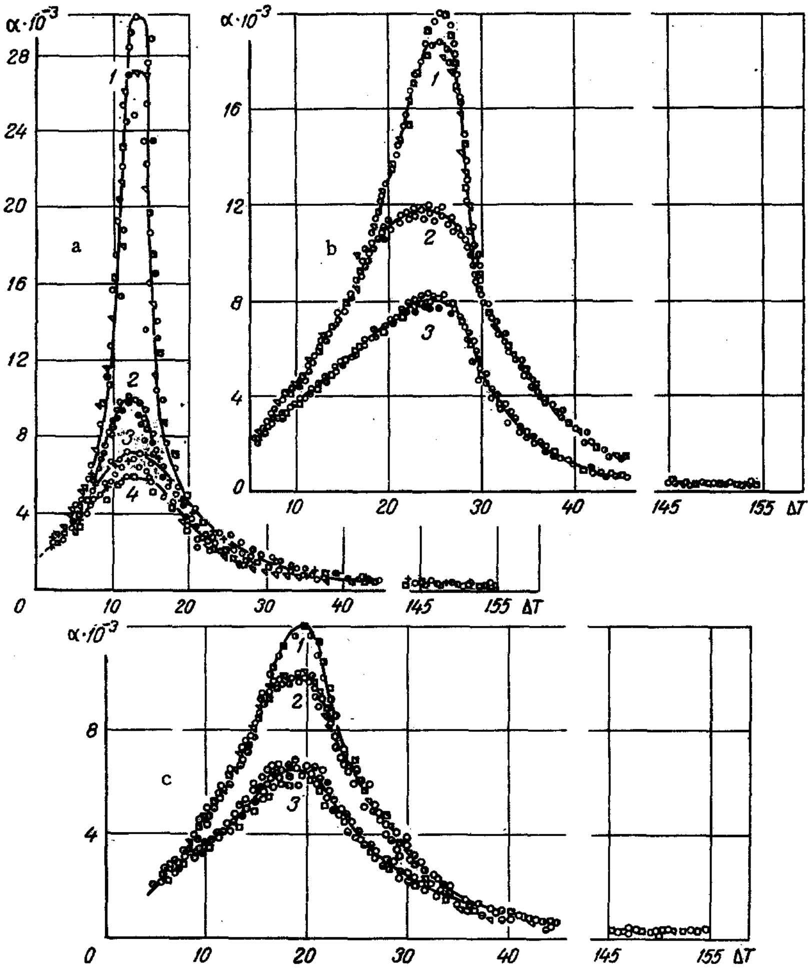

Fig. 3. Relation $\alpha = f(\Delta T)$ for heat exchangers a, b, c during boiling of liquid nitrogen at their surface. Heat-transfer coefficient $\alpha \cdot 10^3$ kcal/m$^2 \cdot$h$\cdot$deg; temperature difference ΔT, °K.

During each test we measured the flow rate of hydrogen W and recorded the temperature profile along the heat exchanger $T = f(L)$ (Fig. 2). From these test data, with the aid of state diagrams based on well-known formulas [13, 16], we determined the thermal transmittivity k and the heat-transfer coefficient α. This procedure enabled us not only to study a specific boiling region but also to determine the mean thermal transmittivity for a tested heat exchanger as well.

The heat-transfer coefficient α during boiling of liquid nitrogen at heat exchangers a, b, c (Fig. 1) has been plotted in Fig. 3a, b, c, respectively. Curves 1 indicate the trend of α during boiling of liquid nitrogen at those heat exchangers when the heat load is smoothly increased from zero up (rise time t $\geq$ 5 min). The trend of α during a fast increase of the heat load (smooth, instantaneous, intermittent, stepwise) is indicated by curves 2. Curves 3 correspond to a decreasing heat load, from much above the critical level. These curves apply to a vertical position of heat exchangers a and b with the heat load transmitted from the top down (i.e., with the temperature of the top coil turns higher than that of the adjacent lower coil turns), and to a horizontal position of heat exchanger c regardless of the direction of hydrogen feed. In the case of a heat load transmitted from the bottom up on the vertical heat exchangers a and b, during a smooth increase of the heat load (almost at any heating rate) the values of α are close to those according to curve 2. For heat exchangers a, b, c in the horizontal position under a smoothly increasing heat load, the values of α are close to or below those of curve 2. For an instantaneously increasing heat load, the $\alpha = f(\Delta T)$ curve can in this case run anywhere between curves 2 and 3. Curves 3 and 4 correspond to a decreasing heat load on the heat exchanger in any position.

These $\alpha = f(\Delta T)$ curves shown here correspond to an approximately 6-10 mm separation (clearance) between adjacent coil turns for heat exchangers made of 6.0×1.0 mm and 8.0×1.0 mm tubing. As the clearance between coil turns decreases, α decreases even below curves 2 during a smooth increase of the

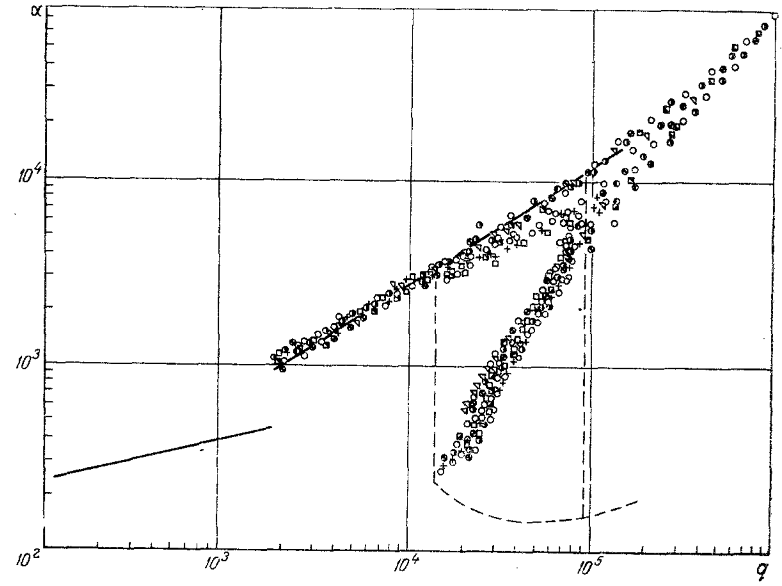

Fig. 4. Heat-transfer coefficient α (kcal/$m^2 \cdot h \cdot deg$), during boiling of liquid nitrogen, as a function of the heat load density q (kcal/$m^2 \cdot h$).

heat load with small deviations of ΔT_{cr} near the values referring to heat exchangers b and c. We note that ΔT_{cr1} and ΔT_{cr2} almost coincide for each heat exchanger in each specific case. Here ΔT_{cr1} and q_{cr1} denote the critical temperature difference and the critical heat load during transition from bubble to film boiling; ΔT_{cr2} and q_{cr2} denote those corresponding to the reverse transition from film to bubble boiling.

As the clearance between adjacent coil turns of a heat exchanger is increased, during a smooth increase of the heat load α decreases to values close to curve 2 (but not below 8000-9000 kcal/$m^2 \cdot h \cdot deg$) and, moreover, in the case of heat exchangers b and c the peak of the $\alpha = f(\Delta T)$ curves gradually shifts toward lower ΔT_{cr} values approaching the well-known published values for a helical coil [5, 8]. A drop in the heat load does not produce significant changes in curves 3, as also does not an increase or a decrease of the clearance between adjacent coil turns.

The differences between the α-values are sometimes due to hysteresis in the nitrogen boiling process, which is manifested by the occurrence of one or another boiling mode under a given heat load depending on the rate at which it is approached and from which side. Bubble boiling continues up to high values of q_{cr} when the heat load is increased from low values up; a transition to bubble boiling corresponds to lower values of q_{cr} when the heat load is decreased from much above critical values down. Analogous, but of somewhat different character, hysteresis effects in the boiling process within this range were noted earlier [3, 7]. There is no precise explanation for this phenomenon known as yet [7, 11]. One may hypothesize that it is related to the kinetic state of the liquid during bubble and film boiling, respectively. Such a hysteresis should occur if the energetical state of the liquid is more favorable during film boiling. Evidently, the magnitude of the hysteresis during boiling of liquid nitrogen at heat exchangers a, b, c depends not only on the velocity and the direction of the heat load but also on the disposition of the heat exchanger in the boiling liquid and on the size of the clearance between adjacent coil turns. Such variations in the magnitude of the hysteresis are, apparently, due to appreciable differences in the conditions of wetting of the tubing coils in each specific case considered here. During a smooth slow increase of the heat load there forms a current of bubbles sufficiently strong to produce a solid gas cushion around part of the perimeter of the heat-exchanger tube.

The heat-transfer coefficient α as a function of the heat load q during boiling of liquid nitrogen is shown in Fig. 4 for all the cases considered here (test points) and in the published technical literature (solid and dashed lines), with the heat-exchanger surface heated electrically [3]. It can be seen that the character of the hysteresis here is somewhat different than before. There is no sudden jump from bubble to film boiling and back. Moreover, the critical heat load levels q_{cr1} and q_{cr2} are high above those in [3, 5, 8], due to the design and the construction of the heat-exchanger surfaces.

It is to be noted that, in the range of high-temperature differences ($\Delta T \approx 180$-200°C), the heat-transfer coefficient increases fast (several times, in some cases by an order of magnitude) when the liquid nitrogen level in the bath approaches the top coil turns of a heat exchanger. This phenomenon is particularly noticeable when heat exchanger a or b is in a vertical position and the heat load is transmitted "from the top down" (ΔT larger at the top coil turns than at the adjacent lower ones). Such a rapid rise of α in this range of temperature differences has, apparently, to do with the hydrodynamics of the process in the top coil region during slight fluctuations of the liquid nitrogen level near those turns. The boiling here resembles a torrent of atomized evaporating liquid (a stream of atomized liquid droplets) forcefully and frequently striking the top coil surface of a heat exchanger. This phenomenon, obviously, must be further studied very carefully.

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