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TRANSIENT HEAT TRANSFER INTO LIQUID HELIUM UNDER CONTROLLED HEAT GENERATION

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INTRODUCTION

The transient experiment performed by Jackson [1] shows that the use of steady-state heat transfer rates results in an unwarranted margin in thermal stability of helium-cooled devices. Besides, as demonstrated by many investigators later (see Funaki et al. [2] and references therein), an adequate simulation of a superconductor behaviour in the conditions of thermal transients requires the consideration of a "thin structure" of time-dependent heat removal. Thereby transient helium heat transfer represents still a topical problem. Since many variables are displayed in heat transfer, we restrict ourselves to the case of heating a solid placed in saturated HeI under ambient pressure by a single pulse. All previous studies may be conventionally classified as follows:
i) relatively full-scale tracing of transient heat transfer;
ii) registration of a certain event in the course of the process.

Type i) data afford a basis for the development of the map of transient heat transfer modes, i.e. assist to understand the regularities of thermal processes and the shifts of heat transfer regimes. The mode map plotted on the basis of the data given in Refs. [3,4] is shown in Fig. 1. (For convenience we introduce the term "mode map" by analogy with "flow pattern map".) Owing to certain difficulties, the number of similar works is far from being large. Type ii) data go to demarcate different modes, i.e. provide information on the boiling-up point and on the crisis moment (see Ref. [5] and Ref. [6] respectively and references therein). Despite the abundance of similar works, no unified procedure for determination of these characteristics has been established. Further, according to Lue et al. [7] "... the stability margin is strongly dependent on the details of energy input to the conductor (i.e. time history and spatial extent)". However, the majority of experiments has been performed with a step pulse heat load input. Somewhat different shape of loading is described only in a few works: the experiment by Giarratano and Frederick [8] with a linearly growing superheat and semi-transient experiments with a linearly increasing electric current through a

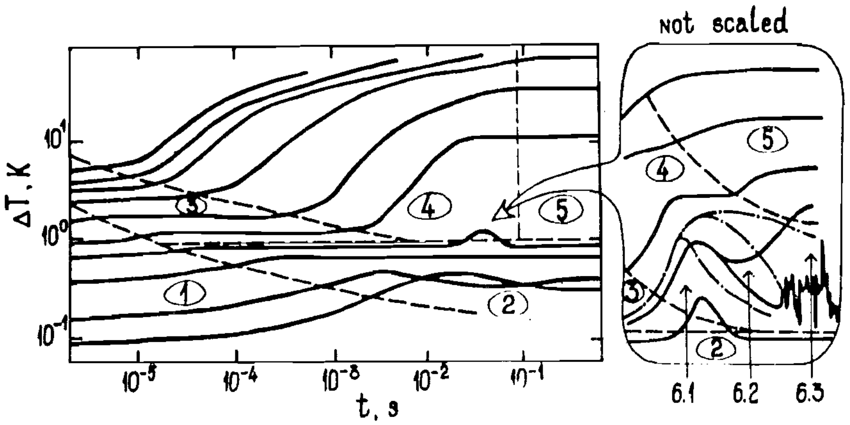

Fig.1. The map of modes after Steward [3] and the region of unstable boiling after Miklayev et al.[4] Solid lines - data; dashed lines - boundaries of regimes. Modes: 1 - transient heat conduction, 2 - steady nucleate boiling, 3 - metastable nucleation, 4 - transition to film boiling, 5 - steady film boiling, 6 - unstable boiling (6.1 - peaks, 6.2 - branchings, 6.3 - oscillations of superheat).

heater (e.g. see Grigoriev et al.[9]). Thus, blanks in the data on transient helium heat transfer are evident. Our opinion is that to fill in some of these blanks it is more convenient to examine a trapezoidal pulse heating.

EXPERIMENTAL SYSTEM

Experimental equipment has been described earlier [4,10]. Now we shall dwell upon a few important aspects. Test sample is a stoppered and pumped-off polished ceramic tube of 11.5 mm e.d., 1.75 mm thick, and 61 mm long. Deposited on the specimen is a carbon film less than 1 μm in thickness and 54 mm in length, which serves both as a heater and a thermometer (HT). Due to thermometric requirements, the characteristic of HT resistance as against temperature is rather steep. Therefore, if the voltage (or current) applied is stabilized on HT, then the intensity of the Joule heat generation will essentially vary with temperature during the period of load application. For this reason the heat input is maintained by a special system which stabilizes just the thermal power. Besides, this system controls the thermal power in accordance with a preset rule W(t), i.e. it loads HT with a heat pulse of a desirable shape. The results described in this paper are for single trapezoidal pulses:

$$W(t) = \begin{cases} u \cdot t, & 0 < t \leq \tau \\ Q, & \tau < t \leq 6.4 \text{ s} \\ 0, & t > 6.4 \text{ s}, \end{cases}$$

where Q is the pulse power, t - time, τ - the leading edge time, u = Q/τ - the rate of the power increase at the pulse edge. Voltage drops across HT and standard resistor are measured by two 12 bits x 30 μs ADCs with a frequency range 10 Hz to 33 kHz. For every value of power Q, from several hundreds to several thousands measurements were taken. The control-measuring apparatus is made to CAMAC-standards and operates on line with a microcomputer. The data are processed as dependences of superheat vs. time, $\Delta T(t)_Q$. Uncertainty in the determination of ΔT, as estimated, amounted to about 10 mK for T $\leq$ 5 K and to 0.5% all over the remaining range. Error in measurements of W constituted 1-4% where large values correspond to smaller W-values.

RESULTS AND DISCUSSION

The data are obtained when such parameters as - orientation of specimen is vertical, helium is saturated, the bulk fluid temperature equals 4.23 K, duration of the pulse is 6.4 s - are fixed; and other parameters are variable: heat pulse power ranges from 0.3 to 17W (which corresponds to the heat flux from 0.15 to 8.5 kW/m^2), duration of the pulse leading edge is 20 μs, 1 ms, 2 ms, 10 ms, 100 ms, 200 ms, 1s. Due to the fact that the measuring system used has a dead time of 30μs, the case of τ = 20μs may be considered as a step pulse load input.

Quasistationary Regime

Characteristic results are plotted in Fig.2, showing that the pattern of transient heat transfer with a trapezoidal pulse heat load input is qualitatively the same as for a step pulse input. All regimes indicated in Fig.1 are also clearly traced

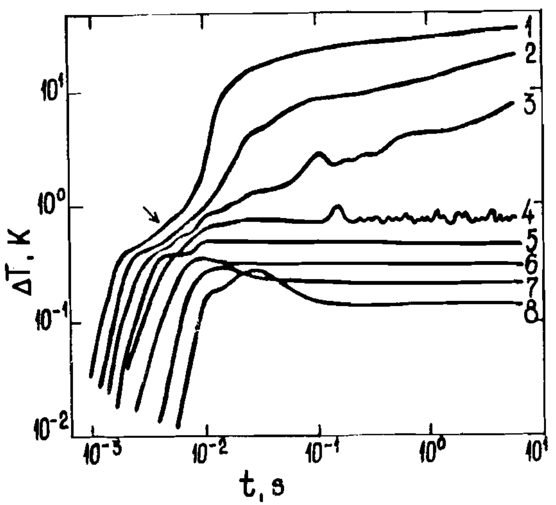

Fig.2. Superheat versus time histories for various pulse power at leading edge time equals 10 ms. 1 – Q = 16.7 W; 2 – 10.9; 3 – 8.54; 4 – 6.40; 5 – 3.48; 6 – 1.34; 7 – 0.63; 8 – 0.33.

here; however, essential differences may be denoted. First, as it could have been expected, instantaneous values of $\Delta T(t)_Q$ changed. Second, the regime of metastable nucleation is almost degenerated. Third, at $t < \tau$ and large Q (curves 1-5) a new regime arose characterized by a linear dependence of lg(ΔT) on lg(t). In Fig.2 this regime is marked by an arrow; and its interpretation is not difficult. Since at $t < \tau$ the power is linearly related with time, then from the a.m. proportionality it follows that power dependence of the superheat on heat load, $\Delta T = C_1 \cdot W^n$. The exponent n and coefficient C_1 are close to m and C_2 respectively which appear in the approximation $\Delta T = C_2 \cdot q^m$, of the nucleate boiling section of the steady-state boiling curve. Besides, the range of superheats covered by that regime agrees with the interval of ΔT in which a steady-state nucleate boiling occurs. Then it is obvious that this new regime is the nucleate boiling when the system "a solid - a liquid" adapts immediately to the variation in the intensity of heat release. This regime can be reasonably called as *quasistationary nucleation.* In view of the above it is natural that the quasistationary nucleation is disposed in the area of the metastable nucleation on the mode map. Exact determination of the boundaries of this new regime follows from subsequent analysis.

Modified Mode Map

Influence of the pulse leading edge time on the dynamics of heat transfer can be estimated by comparing the experimental data at different τ. In Fig.3 we present the results of comparison only for two series of experiments in order not

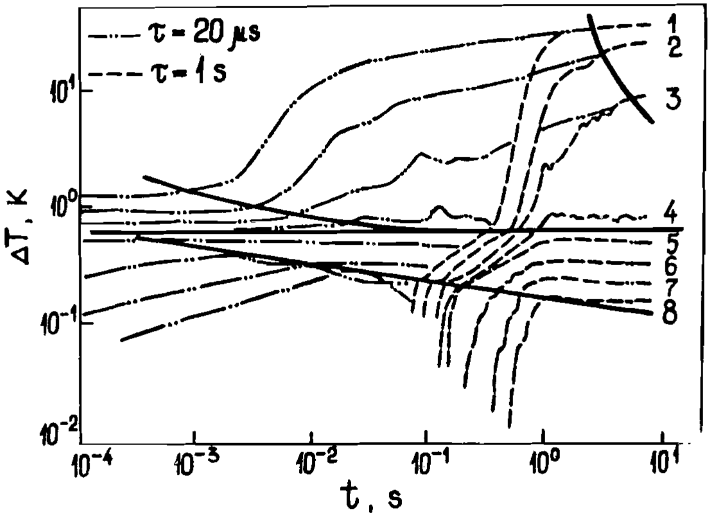

Fig.3. Superheat versus time histories for pulse pairs at equal powers and different leading edge times. Powers 1-8 are approximmately the same as those in Fig.2.

to overload the graph; however, the information which follows, is based on comparison of all data obtained. Figure 3 shows that the influence of τ on instant values of $\Delta T(t)_Q$, and consequently on the transient characteristics of the process, is rather substantial. Also, for $\tau > 20$ μs there exists a new regime, the quasistationary nucleation, that is not observed for a step pulse load input. Thereby the generalization of the transient data may seem hardly attainable. Fortunately, it is not true to fact. The matter is that though the dependences $\Delta T(t)_Q$ "shift" to the right along the time axis with growing τ, and hence, the times of boiling-up and crisis rise with τ at a constant power Q, the corresponding boundaries, *transient boiling-up* and *transient crisis*, in ΔTvst coordinates remain fixed; i.e. if these boundaries are given by

$$\Delta T^i = \mathrm{Func}^i(t), \quad i = \begin{cases} b \text{ (boiling-up)} \\ c \text{ (crisis)} \end{cases},$$

the functions Func^i are invariant with respect to τ. The same is valid for two other important boundaries, *the nucleate boiling limit* (the line bounding from above the regime of stationary nucleate boiling) and *the film boiling limit* (the line bounding from below the regime of the stationary film boil-

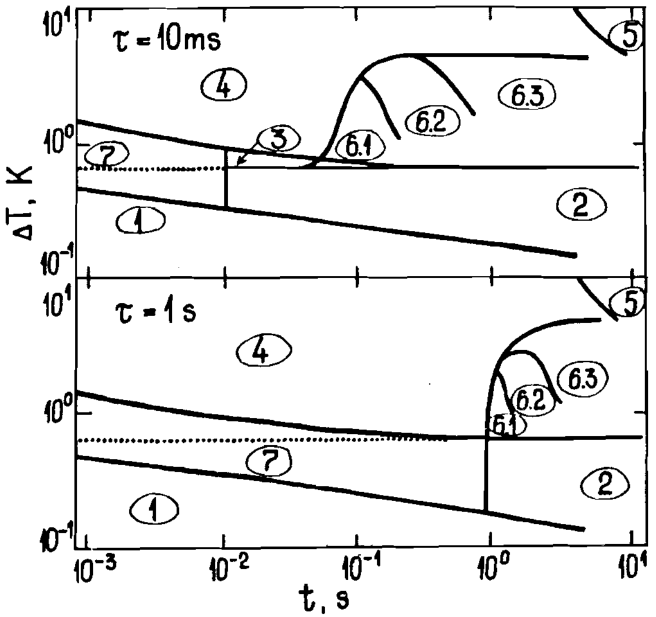

Fig.4. Modified mode map for two values of leading edge time, 10 ms and 1 s. Modes 1-6 are the same as in Fig.1. Mode 7 - quasistationary nucleation.

ing); their positions are obviously independent of τ. In other words, the "skeleton" of the mode map is constant. As to the quasistationary nucleation, from the point of view of its nature and experimental data it follows that the corresponding region of the mode map is contoured by three boundaries: $\Delta T^{b} = \mathrm{Func}^{b}(t)$, $\Delta T^{c} = \mathrm{Func}^{c}(t)$, and $t = \tau$. And finally, let us consider the boundaries of the region of instabilities. These are: from below, the nucleate boiling limit, from above, the film boiling limit, and from the left, the curve of unstable boiling onset. As has been mentioned, the positions of the first two boundaries do not depend on τ; as to the third boundary, its position may be approximately considered to be also independent of τ. At large τ exceeding the time of unstable boiling development a part of the region of instabilities is "cut off", and the third boundary is the line $t = \tau$. Figure 4 shows modifications of the mode map for τ of "short" and "long" duration. By comparing these data with the map for $\tau \to 0$ (Fig.1) one can see that if the leading edge time of the

heat pulse is taken into account, only one additional boundary appears, $t = \tau$, the remaining boundaries do not shift. Thus, we can state that the map of transient heat transfer modes displays the property of universality.

Methodological Problems

In view of the universality of the mode map, its boundaries are of special interest. Unfortunately, at present there is no unified approach, to the determination, for instance, of the moment of transient crisis which is of particular importance for practical applications. As a matter of fact, this is a separate problem; below we plot only a draft for the concept of exact determination of regimes boundaries. It includes the representation of the transient data in the form of q vs ΔT, and therefore all our data, $\Delta T(t)_Q$ and $W(t)$, were accurately recalculated to the form of q vs ΔT. Some results are plotted in Fig.5, the steady-state boiling curve is also plotted thereon. As it is expected, transient and stationary curves coincide within the sections of nucleate and film boiling. The part of transient data that corresponds to the regime of unstable boiling is placed here within a curvilinear tetragon ABCD*.

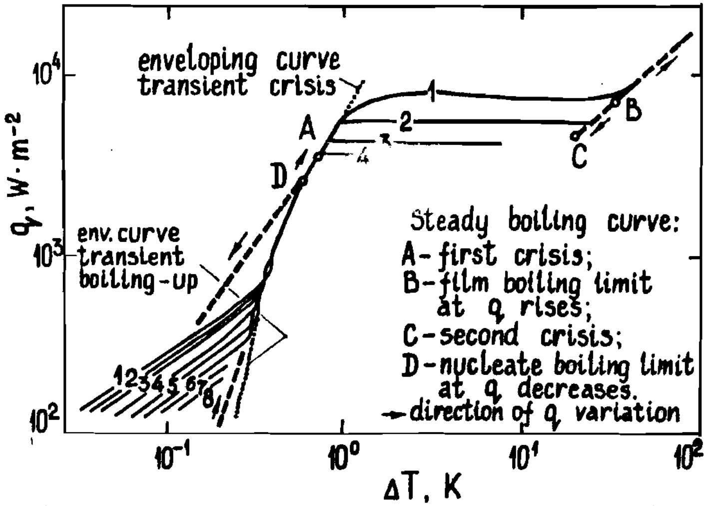

Fig.5. Transient data recalculated comparing to steady-state data.

* *τ rises, curves 1-8 trend to approach the stationary curve, the tetragon shrinking.*

From this fact one may understand the nature of the superheat branchings and oscillations observed earlier[4] and plotted in the insertion to Fig.1. The most important thing is that the graph q vs ΔT displays very clearly the traces of the mode boundaries. In particular, it is obvious that point A in Fig.5 is the boundary of *the nucleate boiling limit;* whereas point B, is the boundary of *the film boiling limit.* In addition it is possible to construct two enveloping curves: the first envelopes the local maxima of curves 4-6 (the maxima along the axis ΔT) in the range of $0.2 < \Delta T < 0.4$ K, the second envelopes those sections of curves 1-3 that represent the extrapolations of the part of nucleate boiling in the range of $0.7 < \Delta T < 1.0$ K. It is clear that these enveloping curves represent loci, respectively, of the *transient boiling-up* and *transient crisis* in q vs ΔT coordinates. Thus, on the graph q vs ΔT it is possible to construct projections of mode contours devoid of arbitrariness or uncertainty. It is relevant to make use of this approach for accurate calculation of the regime boundaries, e.g. transient crisis. To begin with, we should make a proviso: as the crisis is preceded by the quasistationary or metastable nucleation, the power released in HT is dissipated into helium in full, i.e. $W(t^c) \propto q$. Taking the value of q as specifying, one finds the corresponding point ΔT^c on the enveloping curve of transient crisis on graph q vs ΔT. Then passing over to graph ΔT vs t one finds point ΔT^c on curve $\Delta T(t)_Q$ which corresponds to the given value of Q and determines the moment t^c. Thus, the computation scheme is as follows: $Q \to q^c \to$ Fig.5, $\Delta T^c \to$ Fig.2, t^c. As a result, one obtains a block of points that determines both boundary $\Delta T^c = \mathrm{Func}^c(t)$ and the well-known dependence $t^c = \mathrm{func}(q)$. The advantage of the technique decribed above lies in the fact that when it is applied to process transient data for various pulse powers and leading edge times, it assures high accuracy along the whole range of Q and, in particular, at Q close to the steady-state critical heat load. It should be noted, that results of calculations according to a.m. procedure well agree with the results cited in Ref.[6] when pulse powers are high. (Thorough description of such results will be presented in a separate paper.)

COMPARISON WITH DATA OBTAINED BY OTHER AUTHORS

Among a great variety of publications devoted to transient helium boiling, we have chosen papers by Steward[3] and Giarratano and Frederick[8] to compare with our results for the following reasons: first, constructions of experimental samples are similar (of course, to a certain extent), and second, these data are quite exhaustive and still actual in spite of the fact that a ten-year period has passed. As to the results obtained under a step pulse heat load input and described in Ref.[3] we may compare only the part of our data that corresponds to the least value of the leading edge time, $\tau = 20$ μs. We have made this comparison earlier[4] and therefore we do not present here the corresponding Figure (instead, data shown in Figs.1 and 3 can be made use of). The comparison shows that quantitative and qualitative differences exist, but no contradictions are observed, i.e. the process pattern and dynamics are similar. The differences are caused by the geometry of the experimental samples, their sizes, and the manner of heat load input. The main difference lies in the fact that no unstable boiling process is evident in the results of Ref.[3]. To analyse it, let us consider Fig.6, where among other things we plotted the steady-state boiling curve for the Steward sample taken from Ref.[8]. The curve has a specific feature: points of the first and the second crisis coincide. And, as shown above, the region of unstable boiling on the graph lies between these points (tetragon ABCD in Fig.5). Hence, it

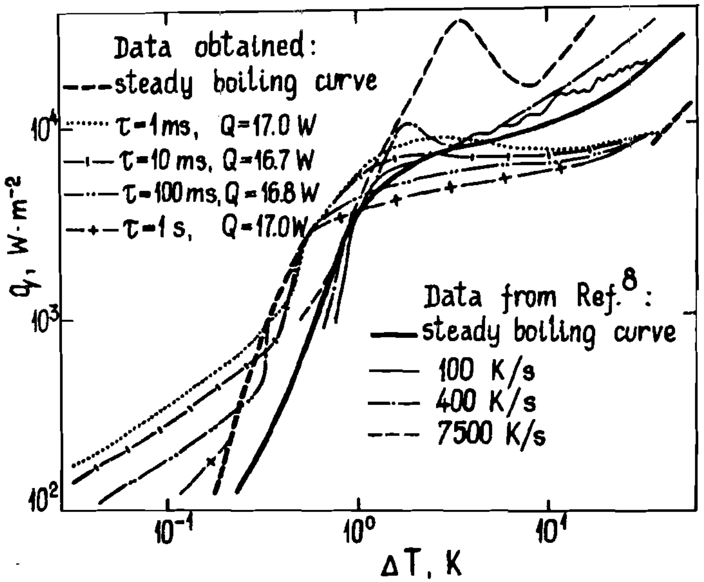

Fig.6. Comparison with data[8] *(as long as the test sample in works*[3,8] *is the same, compared to data*[3]*, we use the steady-state curve*[8]*).*

is clear now why in Ref.[3] no branchings and oscillations of superheat at powers close to the stationary critical load were observed. Figure 6 also shows the results of our data recalculation to the form q vs ΔT, which allows the comparison to be made with data of Ref.[8]. The reasons for the observed discrepancies are the same as mentioned above. However, there is an important coincidence. It consists in the tendency of curves to change their shape with the growth of heating velocity found by Giarratano and Frederick and with shortening of the leading edge time found by us. This is one more evidence in favour of the universality of the transient heat transfer pattern, which takes place disregarding the differences in experimental conditions.

CONCLUSIONS

Duration of the leading edge of the heat pulse inputed to a solid greatly influences the instantaneous values of superheat of the solid surface, and as a result, the characteristics of transient heat transfer into helium. Under certain conditions it is possible to realize the regime of quasistationary nucleation. This regime is naturally included after some modification into the map of transient heat transfer modes. The mode map reveals a universal nature, and for this reason it is a powerful tool for generalizing transient data. The representation of data in the coordinates "heat flux into helium - superheat of a solid" allows for clear interpretation of transient experimental results. Processing of transient data obtained for different leading edge times in accordance with the scheme

$$Q \longrightarrow q^c \xrightarrow{\text{plot } q\,vs\,\Delta T} \Delta T^c \xrightarrow{\text{plot } \Delta T\,vs\,t} t^c$$

assures an accurate determination of the boundaries of regimes most important for practical applications.

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