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SOME TECHNICAL NOTES ON LN_2 BOILING

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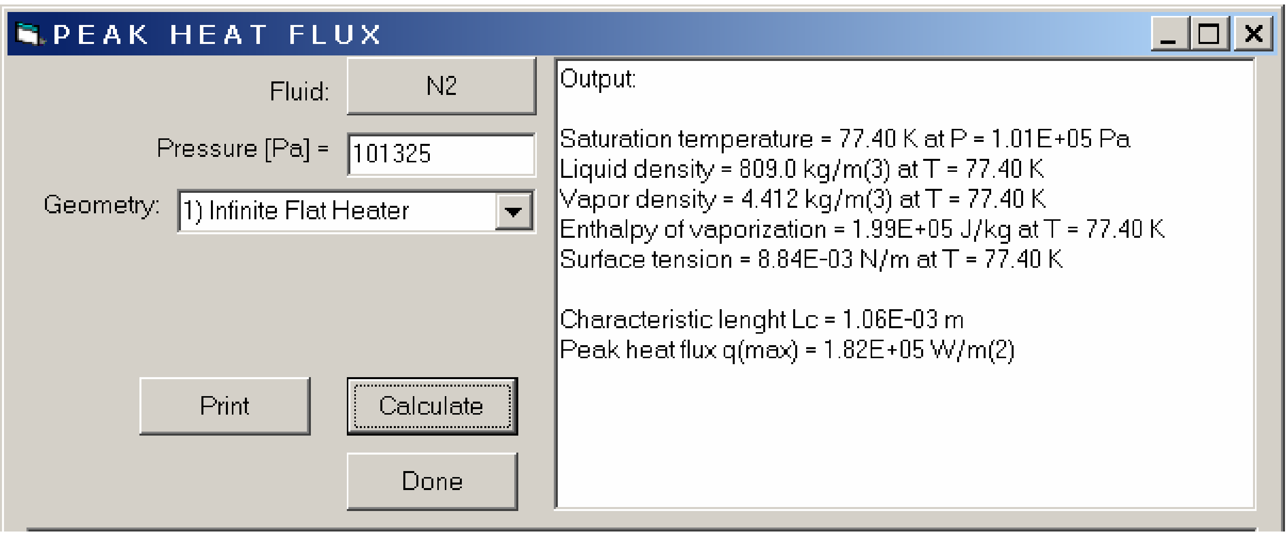
These technical notes aims to give a theoretical support on the liquid nitrogen boiling heat transfer in order to guide the design of the new research apparatus which must be realised at VIRGO centre. In particular these notes are the first attempt to understand the causes of a noise signal, which is characterised by a frequency of about 60 Hz, which is revealed during the test running of a cryostat, located at Virgo laboratory.
The apparatus mainly consists of a hollow inox steel cylinder 85.6 cm long and with a diameter of 15.5 cm. The external surface of the cylinder is wetted by saturated liquid nitrogen at 1 atm (77.4 K) and the internal surface is heated by a radiation coming from a black body at 300 K.

1. LN2 boiling main topics

Some relevant features of boiling heat transfer are reported in Appendix A.
From the early 60's the study of the boiling heat transfer of cryogenics fluids has hold a wide interest. Many studies have been carried out on different LN_2 boiling topics, which can be collect in three main group:

- steady state boiling;
- transient boiling;
- bubble diameter and nucleation frequency.

The relevant properties of liquid nitrogen at 77 K are reported in the frame below. The Critical Heat Flux on a flat plate is also evaluated (about 180 kW/m^2). The characteristic length L_c (termed also Laplace or capillary length) is about 1 mm, and is of the some order of magnitide of bubble size.

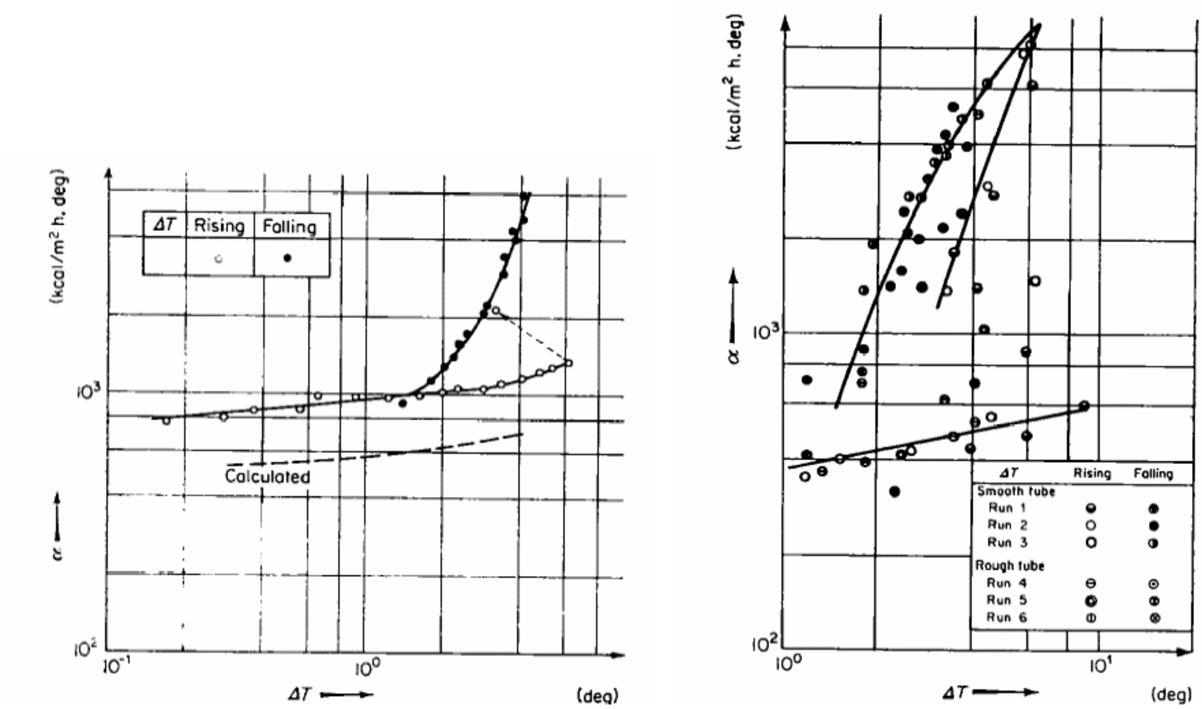


Steady-State Boiling

The study of the steady state heat transfer regime in the case of a boiling liquid nitrogen is a problem which has been analysed since 1966. In 1966 Bewilogua et al. [1] have experimentally studied the boiling heat transfer of four different cryogenic fluid: argon, nitrogen, hydrogen and neon. They tested two different heat transfer surfaces; a capillary wire and a tube. In both the cases they noted a delay of the onset boiling as the heat flux increases, but no discontinuity as the heat flux decreases. This hysteresis effect has been observed just only for neon and nitrogen. This effect suggests that heat transfer is dependent on the preliminary state. A simple explanation of hysteresis is possible on the assumption suggested by Stephan, Hsu and others (heterogeneous nucleation theory) the formation of bubbles is originated by gas or vapour residues which are entrapped in the surface pores (nucleation sites). The minimum and maximum diameter of active sites depends on surface overheating. Figure 1 a and b shows the measured heat transfer coefficient [1] in the case of capillary and tube, respectively. Table 1 show the measured ΔT of boiling onset for different surface roughness.

Table 1

	Nitrogen		*Argon*	
	σ(dyn/cm)	ΔT_c(deg)	σ(dyn/cm)	ΔT_c(deg)
Smooth capillary	8·9	6·1	12·6	6·2
Smooth tube	8·9	9·0	12·6	9·0
Rough tube	8·9	4·1	12·6	7·7
Rough tube, 4·85 atm	5·5	≃0	8·3	5·8



(a) (b)

Figure 1: Boiling curve in the case of nitrogen over capillary wire (a) and a tube (b).

In 1975 Ackermann et al. [2] reported experimental results obtained with identically finished and prepared copper, German silver, and aluminium surfaces in boiling nitrogen under atmospheric pressure. No big difference in the boiling curves has been observed.

In 1980 Stephan and Abdelsalam [3] analysed a large set of experimental data of different boiling liquid and material surfaces, fitting a general boiling correlation on them. They observed that the data could be best represented by subdividing the substances into four groups (water, hydrocarbons, cryogenic fluids and refrigerants).

For cryogenic fluids where the heat-transfer coefficients proved to depend also on the material of the heater surface, the best-fit equation to predict the heat transfer coefficient h is given by:

$$h = c_3 \cdot q''^{0.624} \cdot \left(\rho \cdot c_p \cdot k\right)_c^{0.117}$$

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where *q"* is the heat flux, ρ is the density of fluid in kg/m^3, c_p is the specific heat in kJ/kg K and lastly *k* is the thermal conductivity in W/(K m). All the thermal physical properties are evaluated at the saturation temperature of the boiling liquid. If the constant c_3 is so modified:

$$c_3' = c_3 \cdot \left(\rho \cdot c_p \cdot k\right)_c^{0.117}$$

It possible find for the atmospheric pressure and for different combinations of heater surface and boiling liquid, the values of this constant. They are shown in Table 1 and Figure 2.
in Table 2.

Table 2

Combination Heater surface/boiling liquid	C_3'
Copper/nitrogen	12.65
Stainless steel/nitrogen	7.6

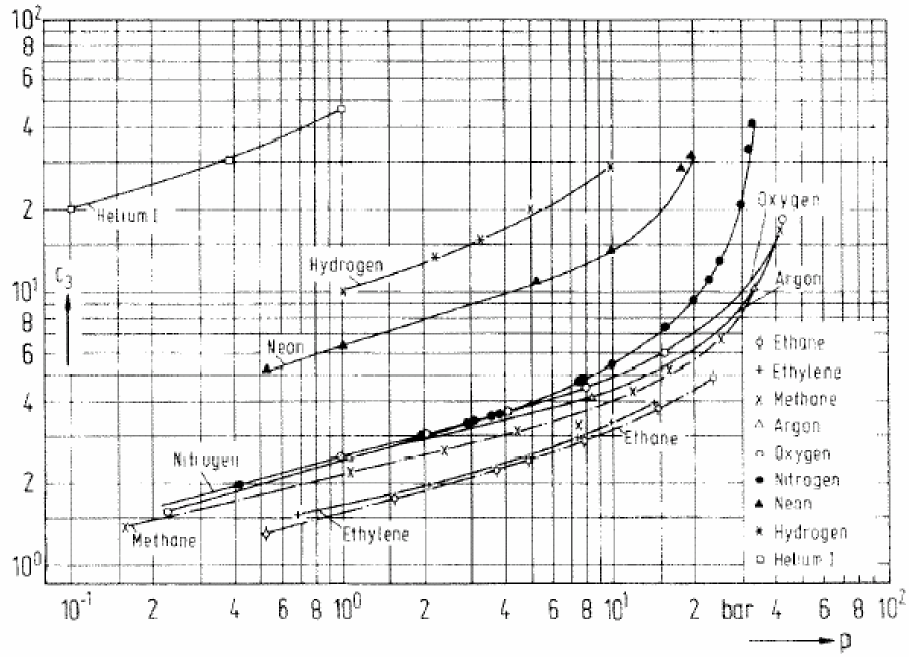


Figure 2: Constant c3 for different heater surface and different cryogenics boiling liquid [3].

In 1990 Mirza [4] analysed the behaviour of a aluminium heating surface on boiling nitrogen. In particular the effect of vertical channel was evaluated. The onset of turbulence was observed at a distance of about 30% up to 50% of the total length of the plate. He proposed experimental correlation to predict the vapour quality and the heat transfer coefficients.
In 1996 Duluc and Francois analysed the nitrogen boiling on a wire. They observed, from the experimental data shown in figure 3, which all the classical boiling steady-state regime were present: natural convection (AB), transition boiling (BCD) and film boiling (DE).
For natural convection regime they observed that it is possible to maintain a laminar natural convection regime for high temperature differences between wire and fluid (15 - 25 K) as shown on part AB of figure 3. In this regime the heat flux is linked by the equation: $q'' \propto \Delta T^{1.2}$.

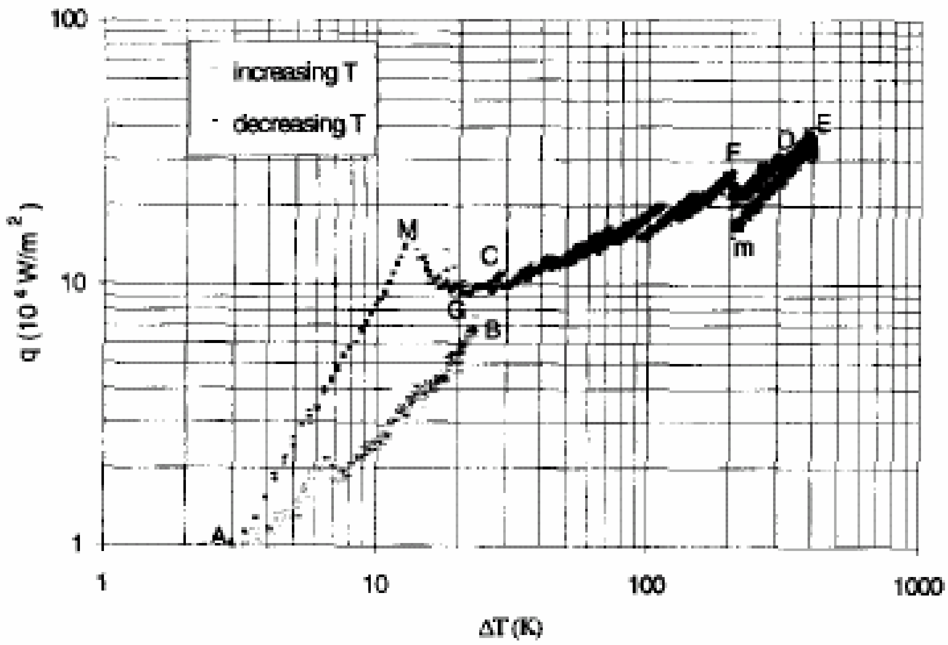


Figure 3: Boiling curve for a wire immersed into a boiling nitrogen at atmospheric pressure [7].

For the nucleate boiling regime the experimental exponent of the previous equation was observed between 2.5 and 3.5, in good agreement with the ones of Stephan and Abdelsalam [3], who gave for a value of 2.66. The discrepancy around this value is probably due to the surface finish, whose role has been reported by many authors. The mean value obtained in these experiments for the peak heat flux (Critical heat flux) was 142 kW/m^2, in good accordance with the equation of Kutateladze and Borishanskii (CHF on wires occurs at different value than on plates).

Unsteady Boiling

If the heat fluxe on the heating surface rapidly changes with time, it is possible to observe an unsteady regime which has a number of different characteristics with respect to the steady one. Unsteady boiling of liquid nitrogen has been studied in the literature.

In 1992 Malkovsky et al. [5] affirmed that there is a period of deteriorated heat transfer at the beginning of the boiling process if a stepwise change of heat flux is supplied. The duration of this period was a random quantity and the time period differences between values of at the same controlling parameters of the experiment are rather high, as shown in figure 4. They found that the duration of the deteriorate heat transfer period scattered almost a factor of 1.5 under the same experimental conditions. However, during the period of deteriorating heat transfer, minimum values of transient to steady heat transfer coefficients, $\alpha(t)/ \alpha s$ were close to 0.5 (figure 4).

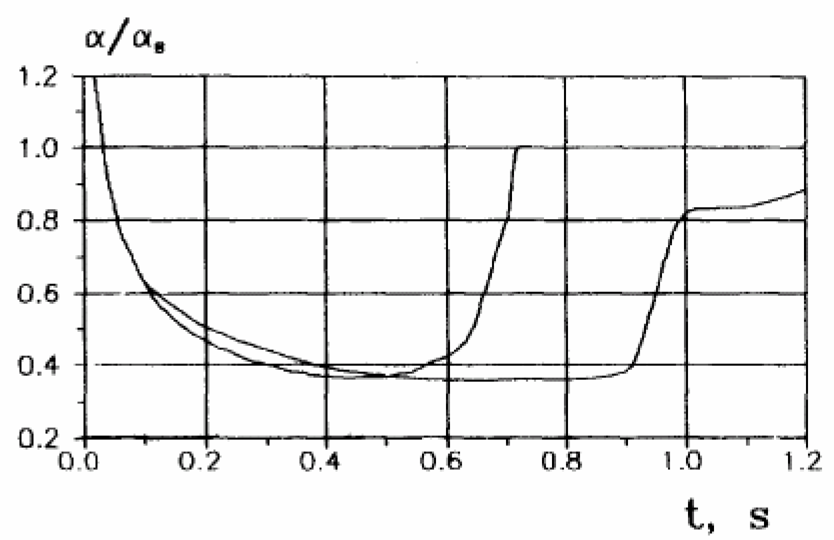


Figure 3: Evolution of the rate between a transient and steady state heat transfer coefficient measured for two test with the same experimental conditions.

Several researchers had reported unfavourable heat transfer characteristics of liquid nitrogen: in transient heat transfer, a rapid transition from the non-boiling regime directly to film boiling occurs for a step heat input whose height corresponds to only 40% of the steady-state critical heat flux. They call this phenomenon premature transition to film boiling. In 1992 Sakurai et al. [8] made experiments on horizontal cylinder in liquid nitrogen, for heat inputs with various increasing rates under pressure.
Figure 5.a shows the temperatures of the surface measured in [8] for the transition process from non-boiling (single-phase) to film boiling or nucleate boiling on a horizontal cylinder of 1.2 mm in diameter in liquid nitrogen caused by exponential, rampwise, and stepwise heat inputs with various increasing rates. The transition temperature increases as the period of the heat input decreases. The effect of the unsteady boiling is however well highlighted by Sakurai et al. and shown in Figure 5 [8], which shows the boiling processes for exponential heat inputs with various periods, in which transitions from non-boiling heat transfer to film boiling or to nucleate boiling occur at atmospheric pressure. The period of 100 s can be considered as a steady-state nucleate boiling.

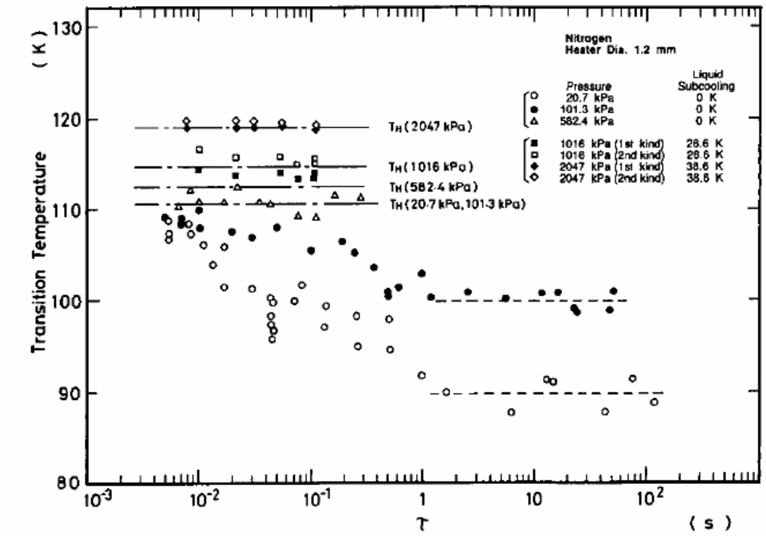
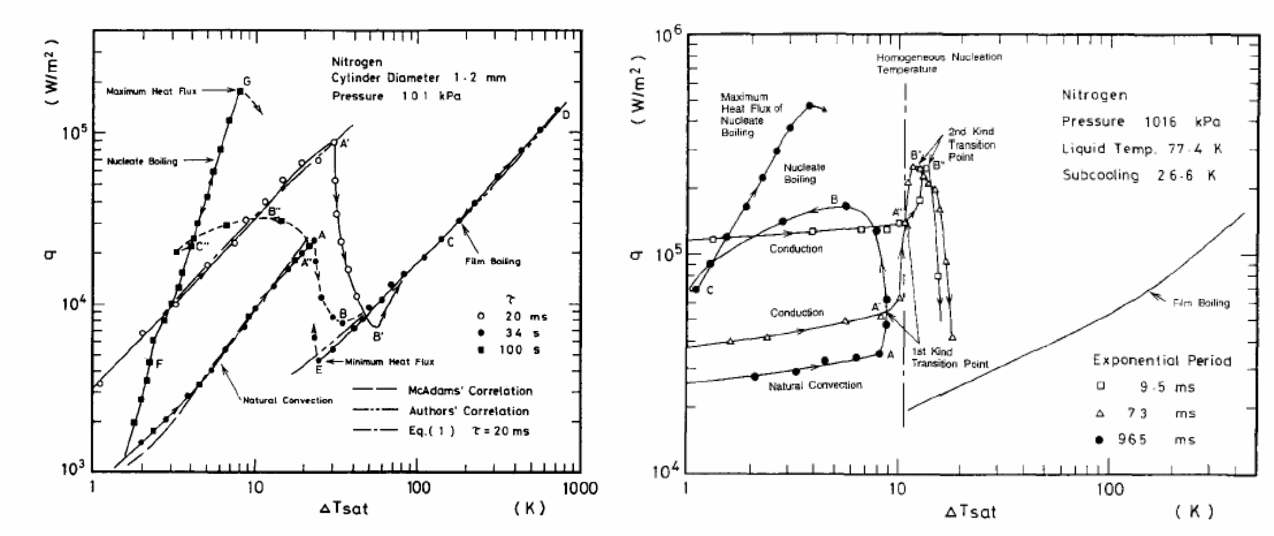


Figure 4: Relation between the surface temperature at which direct transition from non-boiling heat transfer to film boiling occurred and exponential period of the heat input [8]



(a) **(b)**

Figure 5: Heat transfer processes for exponential heat inputs with various periods in which transitions from non-boiling heat transfer to film boiling or to nucleate boiling occur at atmospheric pressure in saturation (a) and subcooling conditions (b) [8]

Bubble detachment diameter and nucleation frequency

The diameter of the bubble and the frequency of nucleation have been studied by many researchers. In 1970 Bewilogua et al.[1] presented the bubble frequency plotted as function of the diameter for several cryogenics liquid (figure 6). They found which for the nitrogen fluid the bubble frequency f and the bubble diameter D are correlated by the equation:

$$f \cdot D^2 = 7.6 \quad mm^2 / s$$

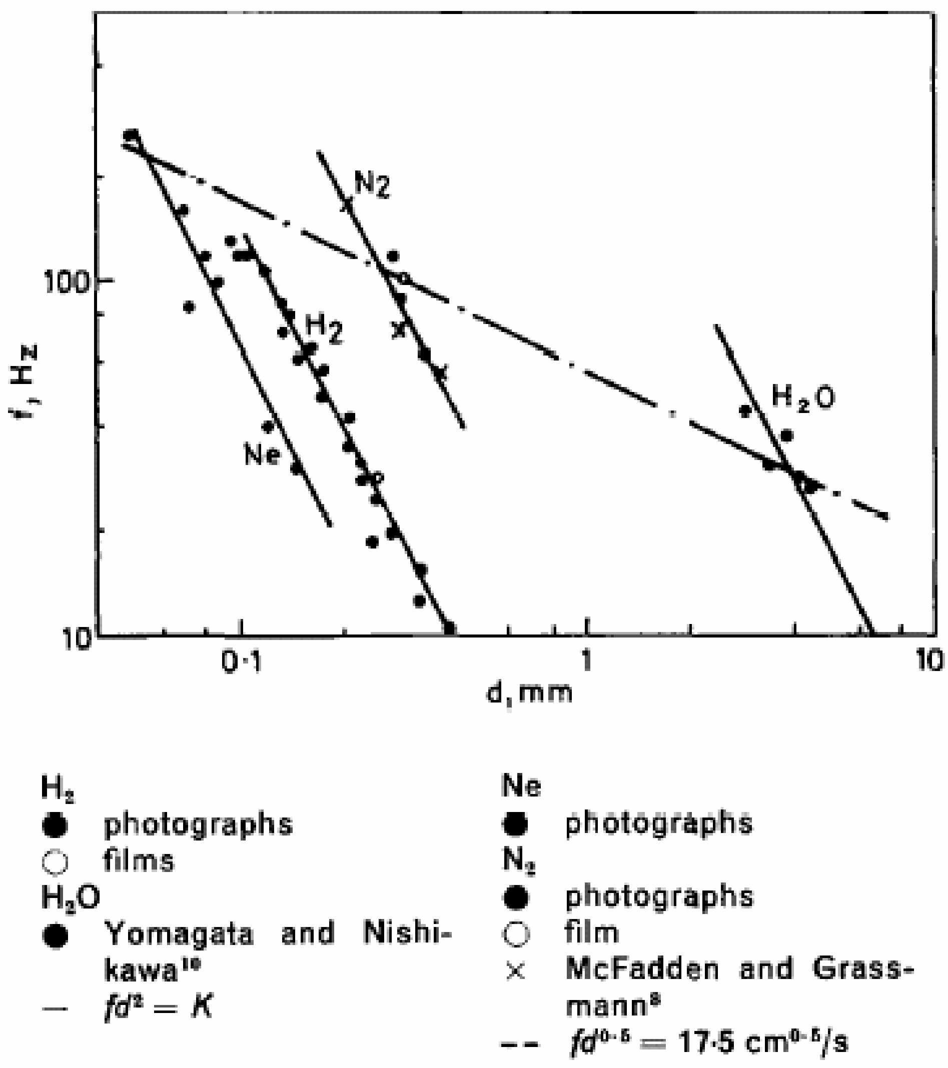


Figure 6: Bubble frequency and bubble diameter for different fluids [1]

Fuchino et al. in 1996 [9] found that the correlation proposed in [1] is weakly influenced by the roughness of the surface and heating power in the case of boiling liquid nitrogen, as shown in figure 7.

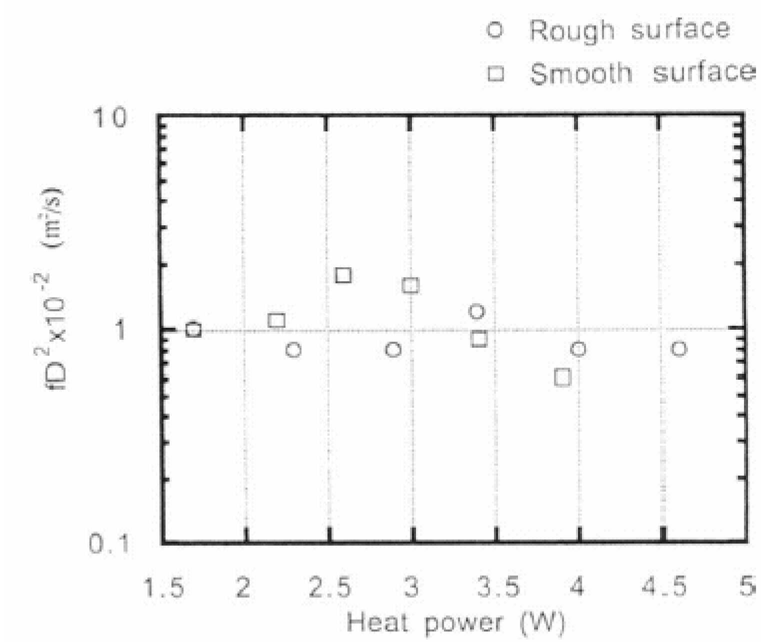


Figure 7: Bubble diameter and frequency for liquid nitrogen at different input power and rough surface. [9]

In 1996 Duluc et al. [7] showed visual observations of boiling nitrogen. The measured diameters are between 250 and 600 μm. Considering Bewilogua's relation, this gives a detachment frequency around 50 Hz.

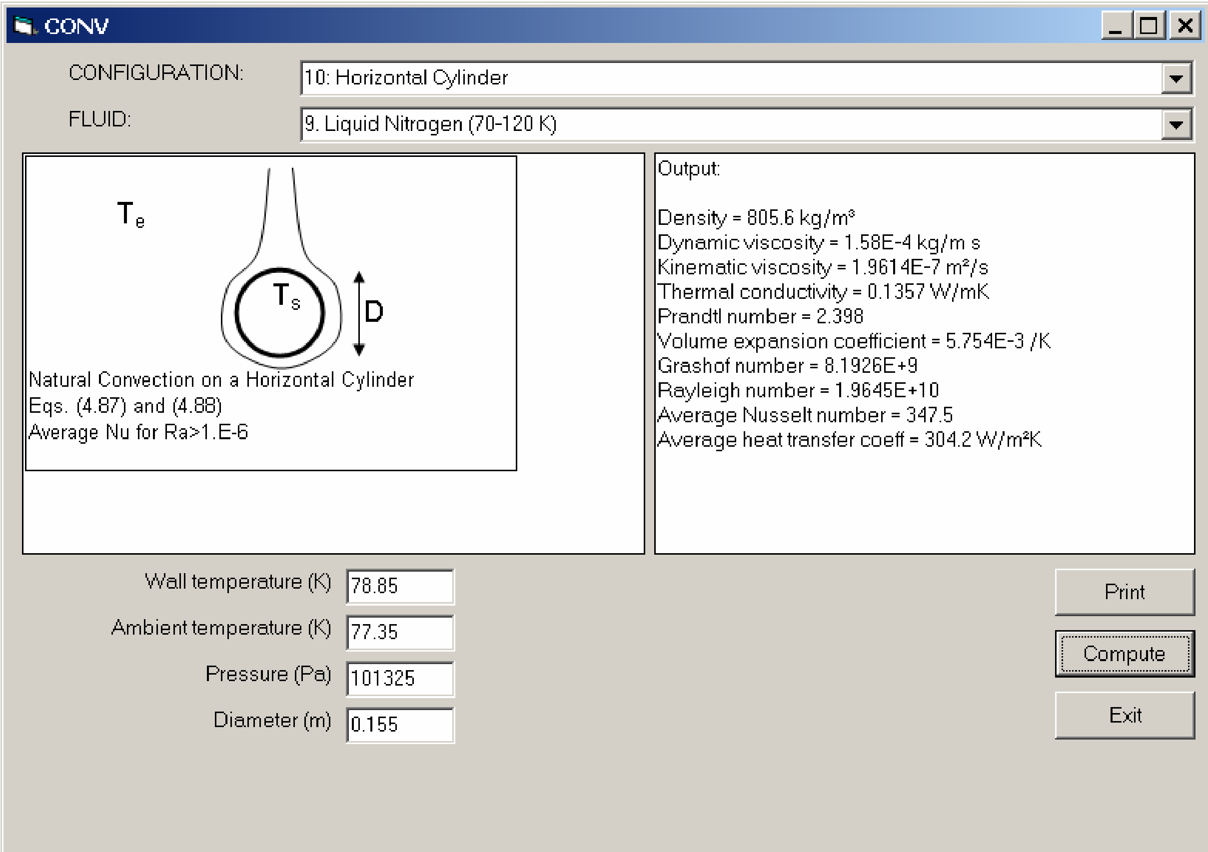
2. Geysering boiling

At low heat fluxes and high heat load, the geyser boiling occurs, and a big bubble is expanding very quickly. If the heat flux is insufficient to cause steady-state nucleate boiling, the temperature of the liquid pool increases until it becomes superheated. At this point, a vapour bubble appears somewhere in the liquid pool, and its size grows quickly due to the reduction of the hydraulic head. The bubble is explosively lifted to the separation surface. This sudden surge causes the vapour above the liquid to collapse with a smocking sound, suppressing boiling. After a period of time the liquid pool is again superheated and the geyser boiling phenomenon occurs again.
In 1983 Hegishi found the period of geyser boiling depends on the liquid column height and the input power. As the heat load increases the geyser boiling period decreases, but frequencies are generally much lower than 60 Hz.

3. Working hypotheses

The assumed boundary on the internal of the pipe is uniform heat radiation heat flux from a black body at 300 K, yielding about 450 W/m^2. Of course, the hypothesis of uniform heat flux can be refined with more accurate radiation calculations, taking into account view factors and surface emissivity, however the order of magnitude is not expected to vary significantly.

From the collected data, the possibility that stable nucleate boiling occurs on the entire surface is highly unrealistic. Direct transition from natural convection to film boiling can occur only under a considerable stepwise or rampwise heat input, which does not appear to take place in this case. Conversely, as demonstrated by the following picture, single-phase natural convection can hold with a limited surface overheat (1.5 K). Therefore, if boiling occurs, it must be intermittent or localized in some region of the pipe (hot spots, thermal bridges).



Since natural convection can be easily established with sufficient heat rate, intermittent boiling located on the whole surface seems to be excluded. This is confirmed also by a first analysis of the time constants of the heating surface, which are much higher than the ones required to produce disturbing frequencies of 60 Hertz.

On the contrary, a first analysis of the bubble detachment diameter and of the related detachment frequency seem to be compatible with a frequency of 60 Hz or a bit higher, see e.g. Fig.6.

A possible line of investigation is thus that steady localized boiling is established at some hot spot on the surface, originating the disturbance. The spot can be originated by a concentration of heat flux or by an anomalous amount of appropriate nucleation sites, or both of them. The number of active nucleation sites could be limited to few ones. On the other hand, considering the value of heat flux (if confirmed), a thorough design of the container, associated with computer detailed analysis of heat transfer, could ensure the total suppression of boiling with no detriment in performance.
These considerations are, of course, very preliminary and must be confirmed by a more detailed analysis.

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Appendix A - Main features of pool boiling

Boiling Overview. In any heat transfer process between a solid surface and a fluid, the heat rate Q is commonly expressed using Newton's law of cooling:

$$Q = hA\left(T_w - T_{ref}\right) \quad (1)$$

where h is the heat transfer coefficient, A is the heater area, and (Tw-Tref) is the difference between the temperature of the surface and a convenient reference one taken in the fluid; in boiling phenomena, the saturation temperature Tsat is generally adopted for Tref. Both the heat transfer area and the temperature difference should be kept as small as possible, the former to minimize weight and investment costs, and the latter to minimize entropy generation and avoid surface overheating, which in turn may lead to equipment failure. Consequently, the heat transfer coefficient is desired to be as high as possible to accommodate large heat fluxes.

Pool boiling. Following the approach originally developed by Nukiyama [**Errore. Il segnalibro non è definito.**3] in his early experiment, heat transfer performance in pool boiling is commonly reported as a plot of heat flux vs. wall superheat ∆Tsat = Tw – Tsat (boiling curve). The curve generally exhibits the trend shown in Figure A1. Several heat transfer regimes can be identified. Between A-B no boiling exists and heat transfer is by natural convection even though the wall is above the saturation temperature. When the temperature at the surface exceeds the saturation value by a certain amount, bubbles are generated in surface cavities by heterogeneous nucleation and boiling starts. This implies a strong increase in heat transfer performance, and the superheat is suddenly decreased, path B-C. The temperature overshoot

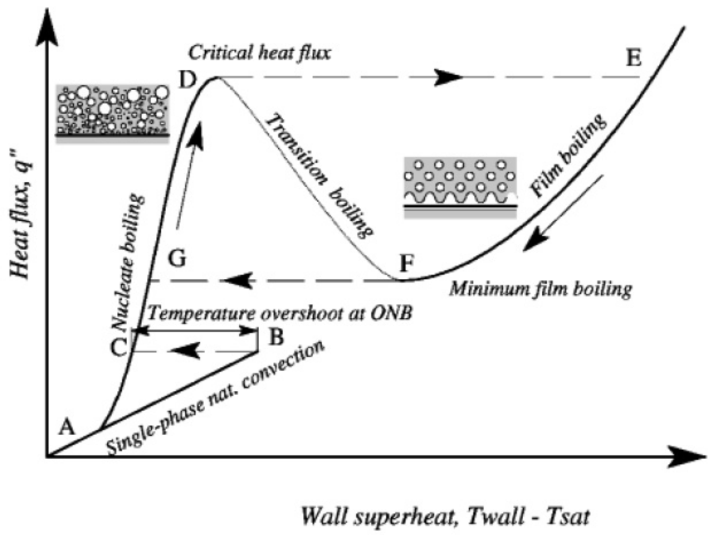

Figure 1. Pool boiling curve.

(point B) may be so high as to compromise the operation of temperature sensitive equipment such as electronic devices. Along the path CD (nucleate boiling), the nucleation site density increases and the heat flux q" increases steeply with superheat; this heat transfer mode is termed nucleate boiling and is the most important regime for industrial applications due to its high efficiency. However, it cannot be sustained indefinitely: beyond a maximum value referred to as the critical heat flux (CHF, point D), it is suppressed. Two paths can be followed depending on the controlling variable. If the variable is heat flux, as in electric or nuclear equipment, a small rise in q" causes a transition from point D to E with a very large increase in wall temperature which often leads to the destruction of the heater (the so-called burnout phenomenon). Beyond point F the curve has a much smaller slope than CD and the heat transfer regime is termed film boiling. In film boiling, the surface is completely blanketed with vapor and at most sporadic liquid contacts may occur. An unstable vapor film covers the heater, with bubbles detaching periodically from the film surface; radiation contributes significantly to the total heat transfer in this regime, especially at high superheat. If heat flux is now progressively reduced (see the arrows), this curve is followed down to point F, the minimum film boiling heat flux (MFB), where a further decrease takes the system back to G (hysteresis loop). On the other hand, if the wall temperature is the controlling variable, as in heat exchangers, the unstable path DF (termed transition boiling) can be covered, by increasing or decreasing the wall superheat.

To summarize, although nucleate boiling is a very suitable heat transfer regime, care must be taken in establishing it from cold conditions without damaging the equipment due to temperature overshoot, and the heat flux must always be maintained well below the critical heat flux value.