

EVALUATION OF SODIUM INCIPIENT SUPERHEAT MEASUREMENTS WITH REGARD TO THE IMPORTANCE OF VARIOUS EXPERIMENTAL AND PHYSICAL PARAMETERS

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Abstract—The published results of the various laboratories on the parameters having an influence on superheat are not definite. There has even been inconsistent and conflicting experimental evidence on the effect of some parameters.

The most consistent agreement in the trend is seen in the influence of oxide impurity and gas entrainment. In both cases superheat decreases with increasing gas entrainment and oxide level.

The most inconsistent and conflicting experimental evidence concerns the effect of heat flux and of temperature ramp. The data of bulk superheat as far as the trend is concerned are in good agreement. The bulk superheat definitely decreases with increasing velocity. An influence of the heating wall material on the superheat is uncertain. Experiments on materials compatible with sodium did not exhibit significant effects. Most of the experiments in which the influence of the operation time has been observed were short time tests. It is supposed that the effect of operating conditions was masked by the degassing of the heating surface during heating up or boiling. There is experimental evidence that for given test conditions a characteristic threshold superheat range is not exceeded. The threshold superheat level is presumably determined by the heating surface finishing, the oxide level and the gas loading of the sodium.

A general evaluation of the results of loop experiments shows an average value of superheat for technically clean sodium of $80 \pm 30^\circ\text{C}$ (O_2 -impurity of about 5–10 ppm) and for sodium with impurity of about 40 ppm of about $25 \pm 20^\circ\text{C}$.

NOMENCLATURE

T_{sat} ,	saturation temperature;
T_w ,	wall temperature;
ΔT ,	superheat of the liquid, $= T_w - T_{\text{sat}}$;
P_{sat} ,	saturation pressure;
P ,	system pressure;
C ,	O_2 concentration;
σ ,	surface tension force;
r_c ,	radius of wall cavity mouth;
V ,	coolant velocity;
B ,	empirical constant.

INTRODUCTION

IN THE past 10 years an increasing number of research papers have appeared on the subject of incipient boiling (IB) superheats in alkali metals.

Mainly experimental work has been performed and is still underway. The results published show gross scatter and those from different laboratories no explicable gross disagreement. In the present paper is reviewed the research work performed to analyse the factors influencing the IB. The conditions under which experiments have been performed are examined in order to get a common reference or at least to explain the discrepancy.

DISCUSSION ON THE PARAMETERS VARIED IN THE EXPERIMENTS

Theoretical analysis indicate already a number of factors influencing the amount of superheat. However, by theoretical analysis only a rough estimation on the importance of the various factors can be obtained.

More complex are the real operation conditions where a combined action of the various factors has to be assumed, and for which theoretical methods of evaluation are unknown.

In various laboratories pool- and forced convection experiments have been performed with the aim of the validation of the various factors. The experiments revealed the following parameters being important: gas entrainment, O_2 -impurity, surface condition, material of the heating surface, operation history, heat flux ramp, temperature ramp, velocity, and conditioning of the surface by chemical treatment.

The relative importance of the quoted factors would be understood and would be adequate for the reactor safety analysis, if the experiments of the various laboratories would not show contrary results.

GAS ENTRAINMENT

The simplest nucleation-mechanism is the passage of gas bubbles through a superheated region. A bubble circulating with the liquid metal with a radius greater than about $10 \mu\text{m}$ will nucleate boiling at any superheat greater than a couple of degrees. The superheat depends on how much superheat can build up before a gas bubble comes along [1]. There is experimental evidence that in a 0.9 cm radius pipe at 1.8 m/s flow velocity argon bubbles injected through a 0.4 mm dia orifice with a frequency of 20 bubbles/s suppressed bulk superheat completely (Fig. 1).

Nearly all the loops used for boiling experiments have an expansion tank behind the boiling test section. Since the solubility of inert gases in liquid metals

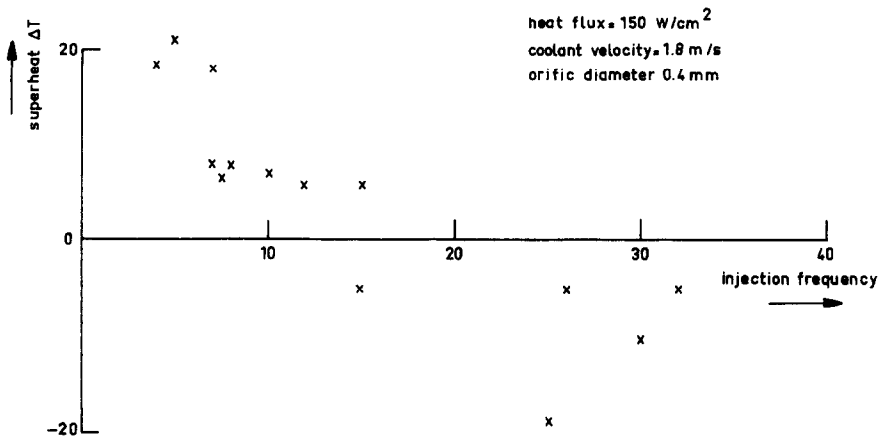


FIG. 1. Bulk superheat vs bubble injection frequency [1].

increases with temperature the sodium will be supersaturated in the cold part of the loop and the argon will precipitate in the hot part. The inert gas mass transfer and the formation of gas bubbles on the wall to a critical size (about 100 μm radius) is described in [2]. Assuming reasonable values for a typical experimental loop, the time taken to reach a steady state is found to be several hours. Loops are normally operating under conditions of equilibrium in the inert gas mass transfer. Isothermal operation between the runs seems likely. On the other hand superheat measurements imply a temperature rise ranging from less than one degree to some tens of degrees of centigrade per second. Both these factors will influence the gas precipitation, so that evaluating the literature, the presence of bubbles in the flow is likely.

As far as the influence of undissolved gas is concerned the results reported by the various laboratories do not disagree. It seems that for most of the experiments the entrained gas might determine the incipient boiling event and overshadow the other factors. The effect of undissolved gas is not only limited to gas bubbles carried in the fluid. The most important factor in this frame is the gas diffusion into the fluid from the blanket gas and the gas entrapped in wall cavities. Singer and Holtz [11] made an analysis "on the role of inert gas in incipient boiling experiments". Their conclusion is that the non specification of the inert gas partial pressure in the gas cover blanket can cause an uncertainty in the incipient superheat as large as 100°C.

The important role of inert gas on the IB under conditions approximating reactor operation demonstrate the experiments performed at Argonne [3]. Based on experimental results (Table 1) it was judged that in a loop type system operating at steady state for a period of time (operation time > 30 h) the superheat at boiling inception following a system transient is zero (see test series A1–A26). The significant influence of the inert gas was demonstrated by the same authors especially for pool type LMFBR-conditions, which were realized by test facility operation with the test section by pass open (Table 1 run number B1–E1). The test section flow was mixed with the cold by pass flow

in order to lower the coolant temperature especially in the plenum vessel. The test series C and E indicate the influence of low gas concentration in the coolant due to the lower desolution capacity at low temperature.

The test series B was conducted with all parameters identical to those of test series A. The only procedural difference was that the incipient boiling run was

Table 1. Pretest history and superheat data (ANL) (mass flow rate ~ 1.5 m/s, $T_{\text{inlet}} \sim 315^\circ\text{C}$)

Run number	T_{Plenum} (°C)	Time from loop fill (h)	Maximum test section superheat (°C)	Incipient boiling superheat (°C)
A.1	482.6	30.5	0	0
A.2		34.8	↑	↑
A.3		45.8		
A.4		54.3		
A.5		58.7		
A.6		76.7		
A.7		79.7		
A.8		79.8		
A.9		79.9		
A.10		80.0		
A.11		80.1		
A.12		80.2		
A.13		80.3		
A.14		80.4		
A.15		86.0		
A.16		86.1		
A.17		86.2		
A.18		93.7		
A.19		104.2		
A.20		104.4		
A.21		104.5		
A.22		106.8		
A.23		106.9		
A.24		107.4	↓	↓
A.25		108.4	0	0
A.26	482.6	108.5	0	0
B.1	482.6	0.8	66.7	0
B.2	482.6	1.5	83.4	33.4
C.1	371.4	34.0	22.2	11.2
C.2	371.4	42.0	55.6	0
D.1	482.6	20.0	0	0
D.2	482.6	20.1	0	0
E.1	371.4	24.0	16.7	16.7

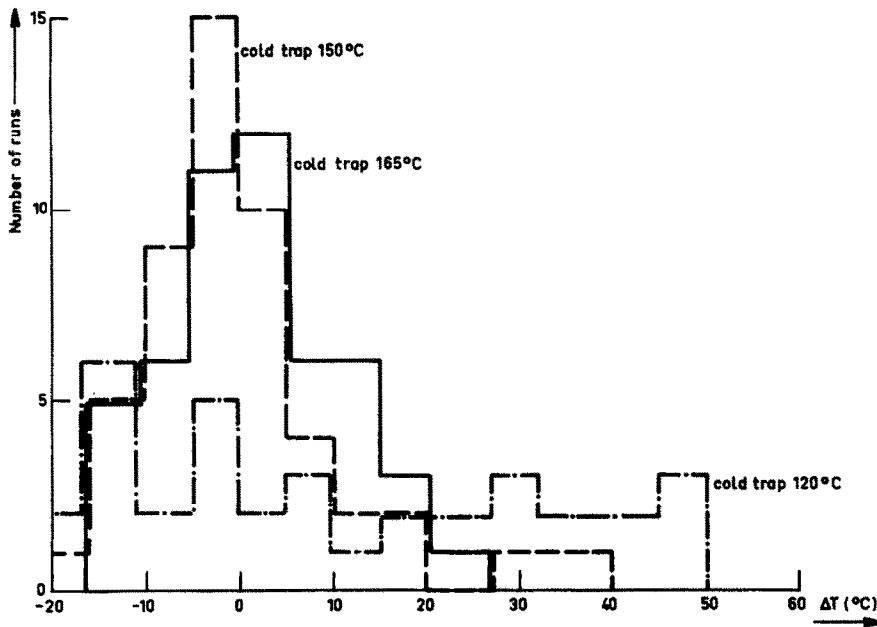


FIG. 2. Superheat histogramme "AI" evaluation (bulk superheat) [8].

performed after 0.8 h of steady state operation subsequent to sodium fill instead of 30.5 h prior to test A1. In consequence, test series B was performed with far less Argon dissolved in the sodium. For test series C and E the test section inlet temperature was $\sim 315^\circ\text{C}$ and the plenum temperature $\sim 371^\circ\text{C}$ (Table 1). The system was filled and operated at steady state for 34 h prior to test C1. Test C2 was performed 8 h later. Moderate superheat was observed although the system was operating at steady state conditions similar to test series A. Series D was similar to series A in all respects. The superheats were zero. Test E was performed after test D establishing the test conditions of test C. Here we met again superheat.

These experiments indicate the influence of operation mode. The physical factor which appears being varied by the operation mode seems to be the solution rate of inert gas. More experimental and theoretical effort should be given to study this phenomenon.

OXIDE LEVEL

One of the possible contributions to the variation in the boiling initiation superheat values is the presence of oxides in the sodium. Several laboratories [4–8] performed stagnant and forced convection experiments especially to study this effect on the incipient superheat. AI and ANL report some hundred boiling initiation tests made with oxide concentrations established by cold trap temperatures of 165, 150 and 120°C . In all these runs, the velocity was about 0.90 m/s, system pressure 0.34 bar, and the inlet subcooling of about 83°C . The histogram of the oxide (cold trap temperature) effect is shown in Fig. 2.

The distributions for the two higher cold trap temperatures are seen to be quite similar. The distribution for the lower oxide level (150°C cold trap) shows somewhat lower superheat and a greater

superheat range. However, since the oxide levels are not very different, no firm conclusion can be drawn. The distribution for the 120°C cold trap data shows a strong influence. Weak peaks are at superheat of about 5 and 15°C , but otherwise the range of superheat is much greater (up to about 70°C).

The CCR Ispra laboratories report [5] also some hundred of boiling initiation tests performed with oxide concentrations of 17, 18.5, 30 and about 40 ppm. The oxide level was determined by chemical analysis. The tests have been performed at a system pressure of 0.8 bar and velocity of 1.4 m/s (17 and 40 ppm)* and 1.8 m/s respectively (18.5 ppm, 30 ppm).

The oxide level was maintained constant at the indicated values and scrupulously controlled during the tests. The distribution for the lower oxide concentration (17 ppm and 18.5 ppm) displays the same trend, as shown by Logan *et al.* The range of superheat is up to 75°C (Figs. 3 and 4).

The difference in the histogram is due to the smaller number of experiments at 17 ppm O_2 . The strong influence of the oxide on the superheat is seen in Fig. 5. The oxide concentration was increased to 30 and 40 ppm respectively. Boiling inception occurred already at 5°C superheat. The range of superheat is lower (up to 55°C). The trend of the decrease of the superheat (wall and bulk) with increasing oxide impurity is shown in Fig. 6 and Fig. 7. Figure 6 represents the Ispra experiments of local wall superheat vs oxide impurity. The dots are mean values of ten runs. Figure 7, however, shows mean values of bulk superheat measurements, reported by AI and ANL. The trend of the influence of the oxide level on the wall and bulk superheat seems evident.

A comparison of the absolute values becomes

* ppm = mg O_2 per g Na.

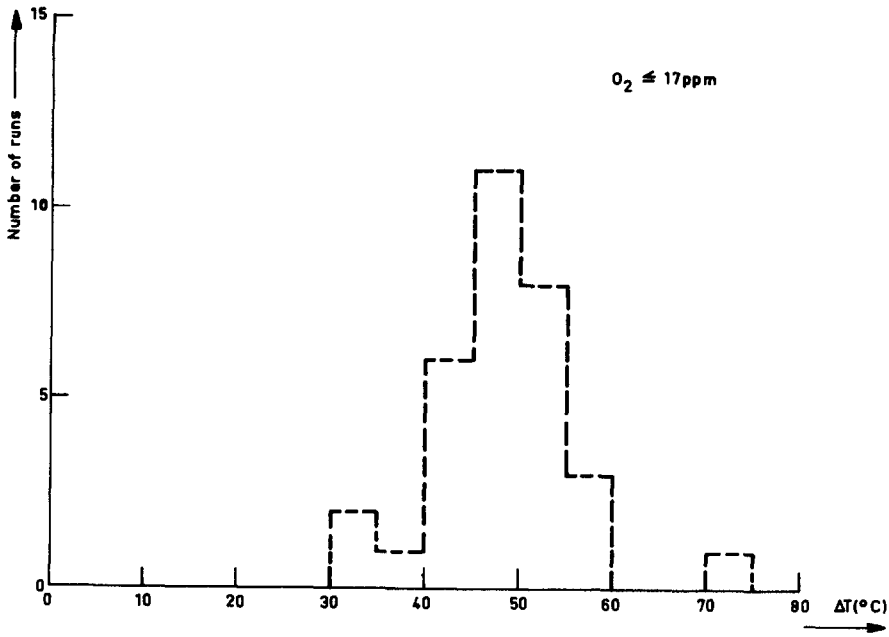


FIG. 3. Superheat histogramme (wall superheat) [5].

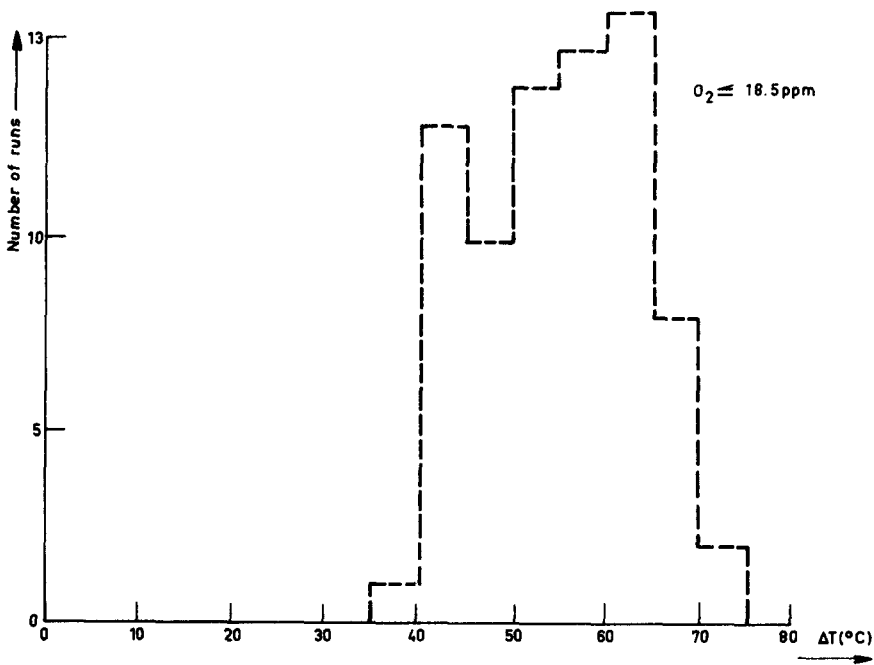


FIG. 4. Superheat histogramme (wall superheat) [5].

difficult because of the uncertainty of the different methods of oxide determination. The Ispra oxide-concentrations correspond *approximately* to cold trap temperatures of about 120°C, 165 and 175°C. It has to be noted that there is a good qualitative agreement between the measurements independently performed.

Systematic experiments in pool boiling conditions were made in the Karlsruhe Laboratories (GfK) [7]. Various materials of the heating wall have been investigated in the presence of different oxide concentrations. Stainless steel (DIN 4571), Ni, Cr and pure iron have been used as test surface. The nucleation of

boiling was triggered on artificial cavities of 0.4 and 0.2 mm dia and extension of depth of 0.4, 1, 2 and 5 mm. The test facility and test surface were cleaned carefully before filling with sodium.

The Na_2O (note the difference in the "oxide" definition) concentration of the sodium, when filled into the test vessel was lower than 0.4 ppm. Impurities like carbon, nitrogen and hydrogen were removed by a zirconium trap. The Na_2O concentration was determined by the cold trap temperature (CTT). It was found that for the low Na_2O concentration (0.4 ppm) the Laplace-correlation between cavity size and

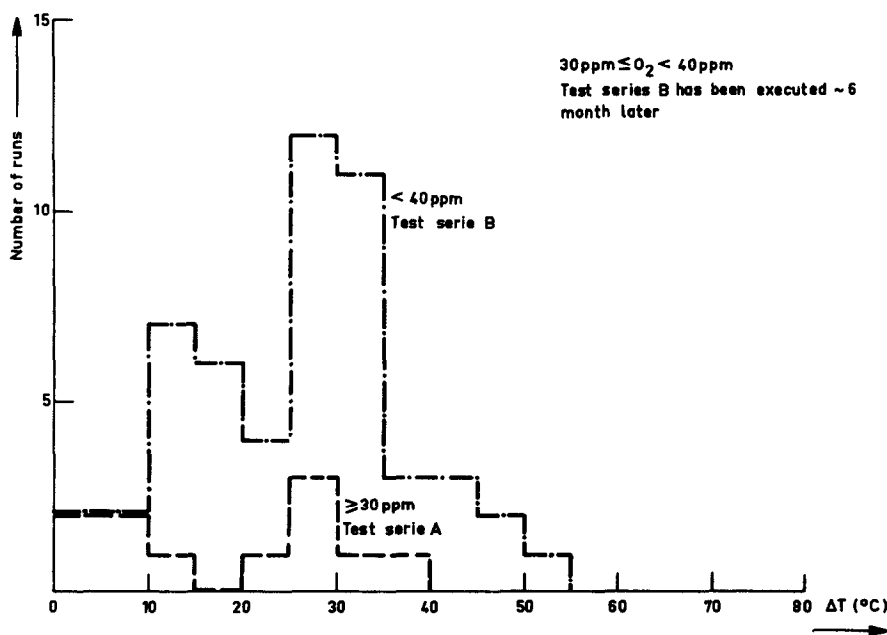


FIG. 5. Superheat histogramme (wall superheat) [5].

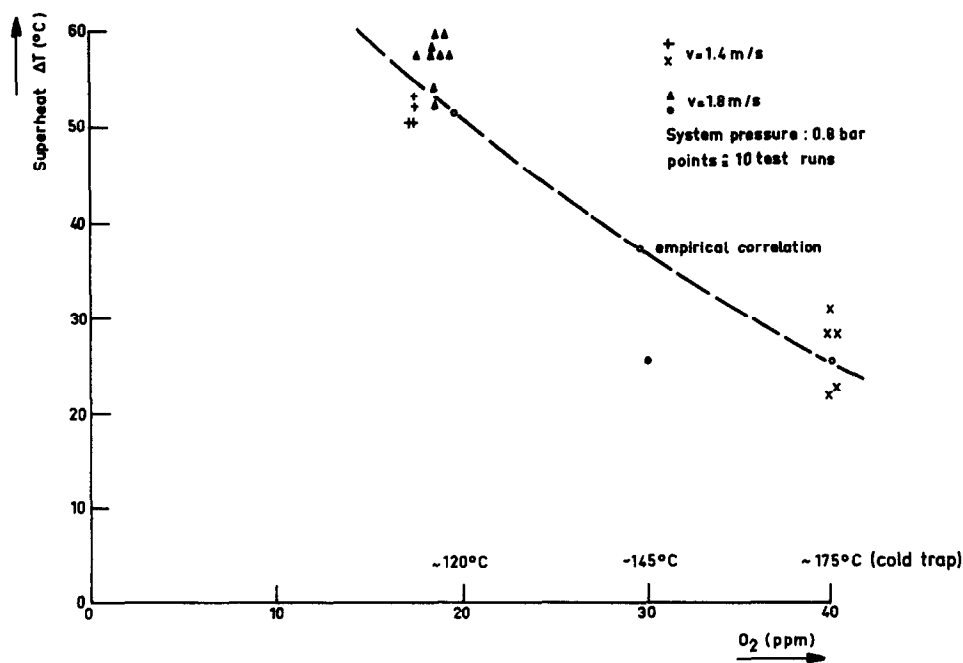


FIG. 6. Influence of oxide on wall superheat [5].

superheat was in good agreement with the experiments. Beside the influence of oxide concentration on the superheat, especially on the stainless steel test specimen a "hysteresis" effect was observed.

The first results published by Schultheiß display a maximum value of superheat as a function of Na₂O concentration. Figure 8 shows these measured data. The peaking of the superheat, however, was not observed on test specimens of Fe or Ni (Fig. 9). This peaking behaviour was initially explained as an effect due to the free energy of formation of chromium oxide and temperature. New experiments, however, iden-

tified this effect as a kind of "hysteresis" of surface cleaning. Figure 10a shows clearly this effect on a new mounted test specimen when starting with the experiments. The data connected through lines were performed in the sequence indicated by the arrows. After an operation time of about three hours the "hysteresis" disappeared and the superheat was decreasing monotonously with increasing Na₂O concentration (Fig. 10b).

Comparing the results of the various laboratories we get the following picture:

The oxide concentration seems to overshadow the

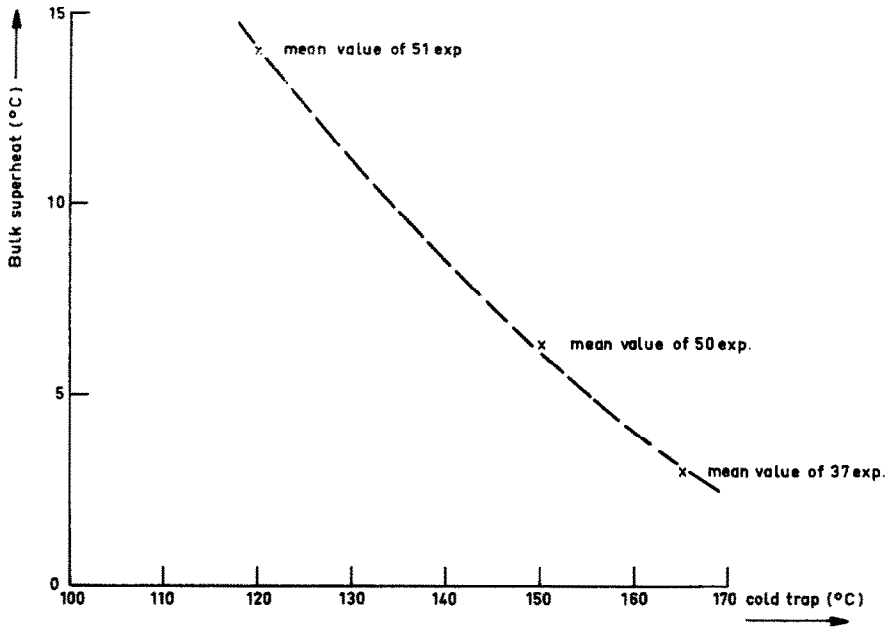


FIG. 7. Bulk superheat vs cold trap temperature [8].

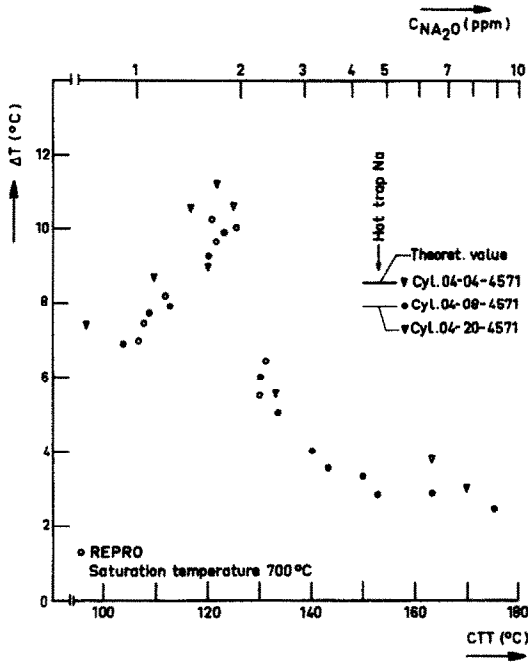


FIG. 8. Incipient boiling superheat of sodium for stainless steel test surfaces (cavity code: cylindrical-diameter-depth-material) [7].

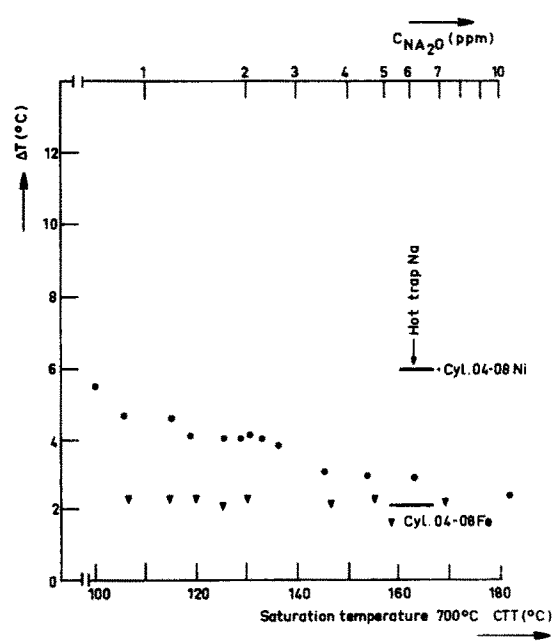


FIG. 9. Incipient boiling superheat of sodium for nickel and iron test surfaces [7].

effect of other parameters like forced convection, type of heating surface, operating conditions and pressure temperature history effect.

In both forced convection flow and pool conditions the trend is for the observed superheat to be greatest at the lowest oxide level and decreasing with increasing oxide level.

It has to be noted that especially on stainless steel surfaces the influence of the cleaning effect has to be taken into account.

A comparison of the absolute values of the superheat is not definitely possible, because of the different methods of determining the superheat.

Based on the experimental data an extrapolation formula can be deduced for the estimation of the wall superheat as a function of the oxide concentration.

$$\Delta T : -77 + \frac{163}{\log C} [^{\circ}\text{C}] \quad (1)$$

$C = \text{O}_2$ (ppm) concentration $\hat{=}$ C/C_0 ; $C_0 = 1$ ppm.

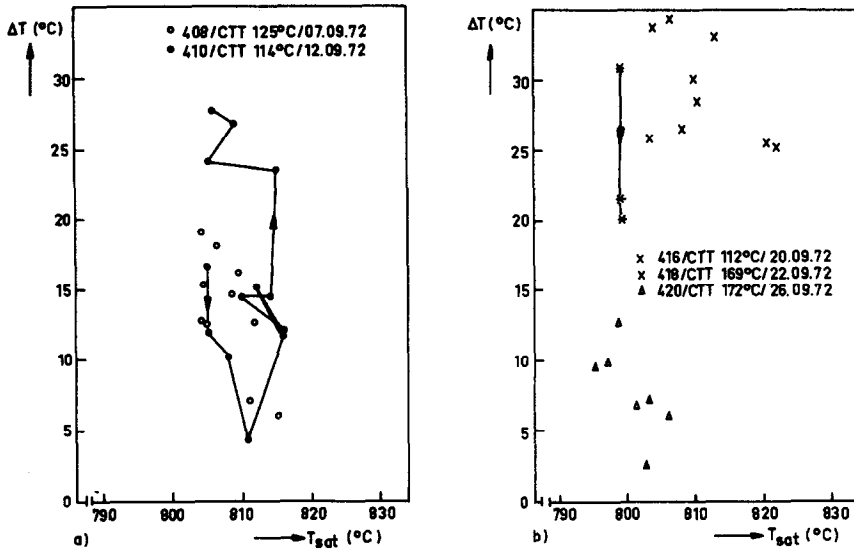


FIG. 10. Incipient boiling superheat ΔT vs saturation temperature T_{sat} of sodium, results of different test series with "hysteresis effect" [6].

This purely empirical correlation could be applied for "non-treated" stainless steel surfaces in the range of 5–60 ppm O_2 impurity (and coolant velocity of up to ~ 3 m/s).

SURFACE CONDITIONS

The surfaces employed in Na boiling experiments are of the following types:

(a) as received, (b) refinished with grit abrasive, (c) mechanically drilled tube, (d) drilled by electro erosion, (e) drilled holes in the surface.

The different surface preparation results in different surface roughness; (a) of different rms reading, (b) nature of the roughness and (c) definite cavities which are holes drilled in the surface.

Deane and Schultheiß studied, e.g. the superheat on cylindrical cavities of 0.06–0.4 mm dia and 0.2–2 mm depth. The agreement between superheat prediction and measurements is definite.

An example of systematic measurements in pool conditions is shown in Fig. 11.

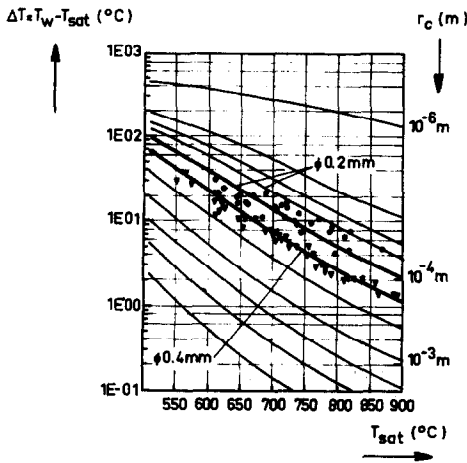


FIG. 11. Incipient boiling superheat of sodium at artificial cylindrical cavities of 0.4 mm and 0.2 mm dia [7].

Experiments were performed on cavities of 0.4 and 0.2 mm dia over a wide range of saturation pressure. The trend of the measured points follows the Laplace correlation. The scattering is in the limits of the experimental accuracy of the measurements. Less definite and pronounced are the results obtained on technical "as received" or "treated surfaces". The trend is for the observed superheat to be greatest for the electro-erosion treated surface and decreasing for mechanically treated surfaces in the following order: "refinished by abrasive" material, "as received" or "drilled" from rods.

Systematic studies have been done by Logan and Morovitz *et al.* on heater pins with 304 stainless steel sheath, the surface preparation of which was (a) as received, (b) refinished with 600 grit abrasive [8].

The heater pins "as received" were subjected to Na flow of 5.70 m/s and 654°C. Analysis done after 589 h of operation time revealed a complete change of the surface structure. The surface relief became similar to that of the "reference fuel cladding" of the LMFBR. Experiments performed by the same authors demonstrated that the same heater pin surface subjected to 170 superheat runs showed a severe pitting and change of the surface structure. A definite influence of the change of the surface relief on the amount of superheat is not reported because other parameters were varied and a direct connection between surface condition and superheat was not possible. Le Gonidec *et al.* [12], however, reported a lowering of superheat with intensification of roughness. Kottowski *et al.* retain [5] a connection between surface condition and superheat.

MATERIAL OF THE HEATING SURFACE

Materials reported being employed in superheat measurements in stagnant and forced convection flow are stainless steel AISI 307 and DIN 4571, Haynes 25, Ni, Fe, Mo.

A systematic analysis of the influence of the material on the superheat in forced convection flow and material surfaces is difficult because of the over shadowing effect of other factors. Dean, Rohsenow and Schultheiß performed small scale experiments on artificial cavities in nickel, molybdenum, iron and stainless steel heating surfaces. Dean and Rohsenow [9] did superheat measurements on a cylindrical cavity of 0.168 mm radius and 2.5 mm depth in a nickel, molybdenum and stainless steel test sample. They proposed an approximative correlation based on the experimental data:

$$\Delta T = -\frac{5}{9} \frac{T_{\text{sat}}^2}{B} \log_{10} \left[1 + \frac{\sigma}{P_{\text{sat}} \cdot r_c} \right] \quad [^\circ\text{C}] \quad (2)$$

where $B = 9396$, 75°R , an empirical constant of the fluid, $\sigma =$ surface tension obtained from [9], $T_{\text{sat}} = ^\circ\text{R}$, $P_{\text{sat}} =$ saturation pressure, and $r_c =$ radius of the cavity mouth.

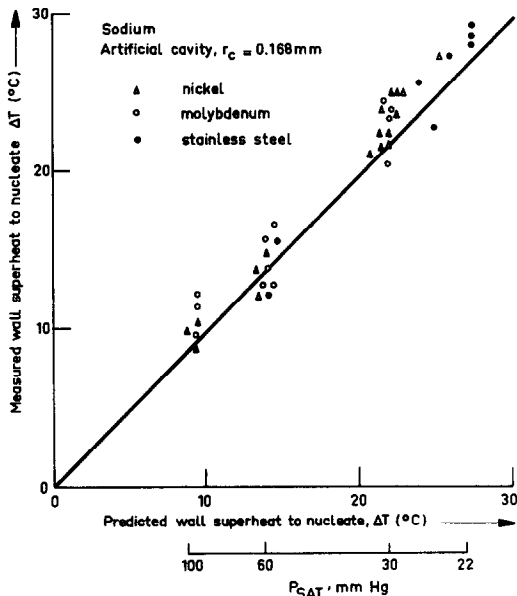


FIG. 12. Prediction of wall superheat for nucleation of boiling sodium from artificial cavities in nickel, molybdenum, and stainless steel [9].

Figure 12 shows an example of comparison of measured wall superheat with the prediction obtained from equation (2) as a function of the system pressure. Since in equation (2) no term appears taking into account the wetting contact angle, which could be representative for the surface material, the influence of the various materials seems negligible. The good agreement between measurements and calculation leads to the further conclusion that the wetting angle between Na and the employed materials is ~ 0 . The agreement between the predictions and experiments of Dean Rohsenow and Schultheiß data is excellent.

No further results on this subject are reported up to now.

OPERATION HISTORY

The real problem in connection with nuclear reactor safety is that of nucleation site deactivation during

pressurization and subcooling within the operation period of up to 3 years (expected life time of fuel rods):

Holtz and Singer proposed the so called pressure-temperature-history method to simulate in laboratory scale the deactivation of nucleation sites. The Holtz-Singer model was extended by Chen including the inert gas entrapped in wall cavities. The model is based on the fact that for a given fluid-surface combination there are three independent variables having an influence, namely: "deactivation pressure" (or variation of the system pressure), deactivation temperature (subcooling) and boiling pressure. The dependent variable in each case is the superheat required for incipient boiling.

The pressure-temperature history is believed by various authors to be a critical variable in determining the incipient wall superheat due to cavity deactivation during the pressurization and subcooling conditions. Systematic investigations especially devoted to this effect have been done by Holtz and Singer, Chen *et al.*, Kottowski *et al.*, Leonov and Prisyakov, Dean and Rohsenow. Accordingly, experiments were done to give measurements of " ΔT_{sup} " vs each of these parameters in term, while holding the other two parameters constant.

No concordant results are presented, though the same experimental procedures of deactivation have been applied. Chen *et al.* are reporting on experiments with potassium which show the superheat being affected by the degree of subcooling and pressure history the test section was submitted prior to boiling. The observations of Chen *et al.* are displayed in Figs. 13-16.

Figures 13 and 14 show the measured superheat plotted vs "deactivation pressure" (operation pressure in the test facility prior to boiling). The boiling runs were executed at an operation pressure of 1.06 bar. The temperature of the coolant during the deactivation process was held constant = 638°C for all runs shown

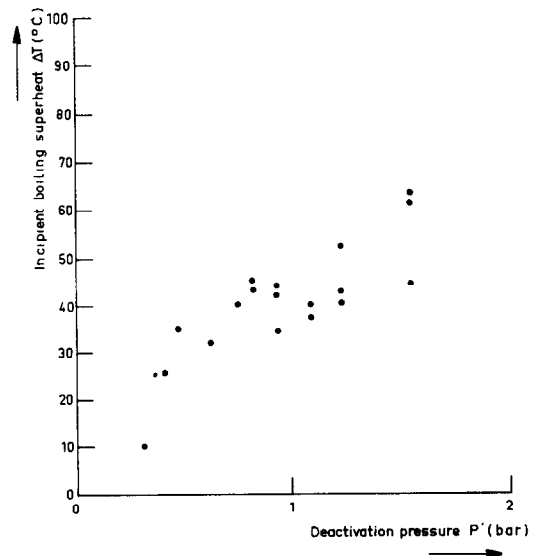


FIG. 13. Incipient-boiling superheats after deactivation at 638°C coolant temperature [14].

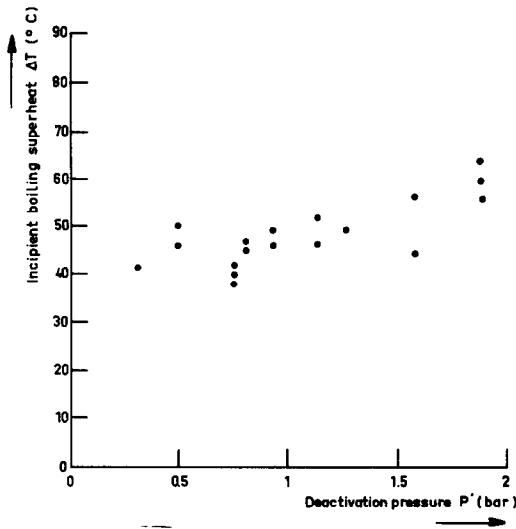


FIG. 14. Incipient-boiling superheats after deactivations at 94°C subcooling [14].

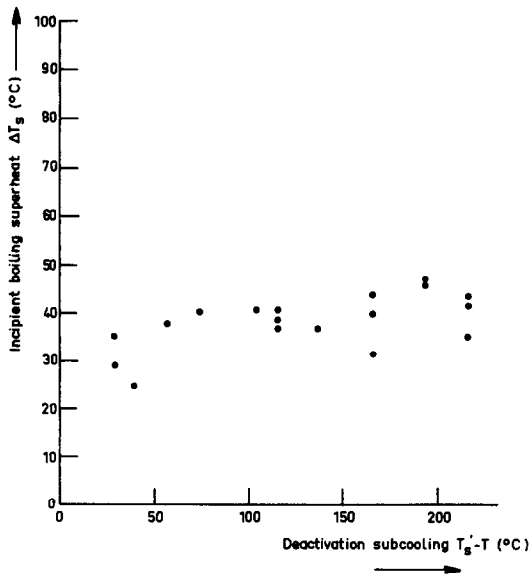


FIG. 15. Incipient-boiling superheats after deactivations at 0.8 bar [14].

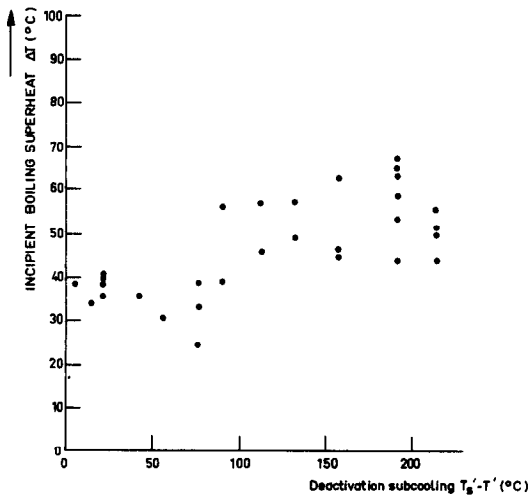


FIG. 16. Incipient-boiling superheats after deactivations at 1.667 bar [14].

in Fig. 13. Whereas during the runs shown in Fig. 14 the subcooling of the coolant was held constant = 94°C.

The possible influence of the subcooling on the superheat is shown in Figs. 15 and 16.

The boiling pressure for all test runs was 1.06 bar, whereas the operation pressure during the deactivation process was 0.8 bar (Fig. 15) and 1.667 bar (Fig. 16) respectively.

Based on these data the authors conclude that superheat is increasing with increase of the operation pressure in liquid flow conditions prior to boiling and that superheat is increasing with increasing subcooling in liquid flow conditions prior to boiling.

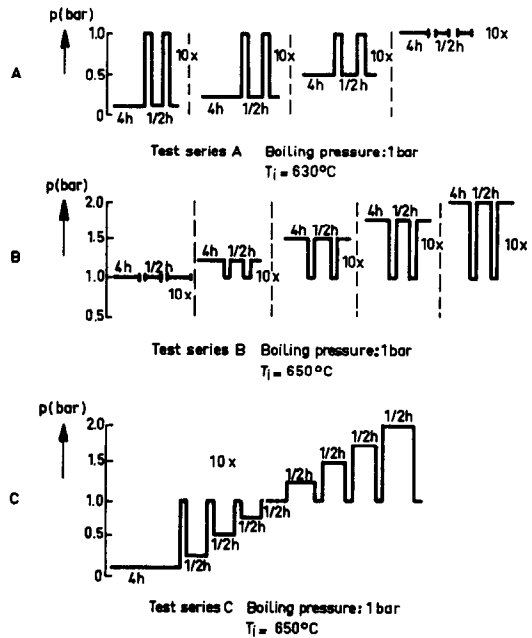


FIG. 17. Depressurization-pressurization history [5].

Analysing the experiments done by Kottowski *et al.*, who employed the same experimental procedure no definite conclusion on the influence of the depressurization and subcooling can be drawn. Four test series have been done: Test series O, ten repeating runs at 1 bar system pressure without depressurization but subcooling to test section inlet temperature of 630°C; (test series O represents start of boiling tests with a new test section); test series A, depressurization and subcooling runs starting with 0,1 bar depressurization and exposing the test section to the depressurization pattern history shown in Fig. 17(A).

The corresponding subcooling was ranging between 40–250°C; test series B, pressurization and subcooling runs starting with 10 runs at 1 bar system and boiling pressure, and a subcooling of 230°C and increasing the pressurization and as a consequence of it the subcooling (230–320°C) according to the pressurization pattern history shown in Fig. 17(B); test series C, ten repeating runs starting with depressurization and changing into pressurization according to the pressure history pattern shown in Fig. 17(C).

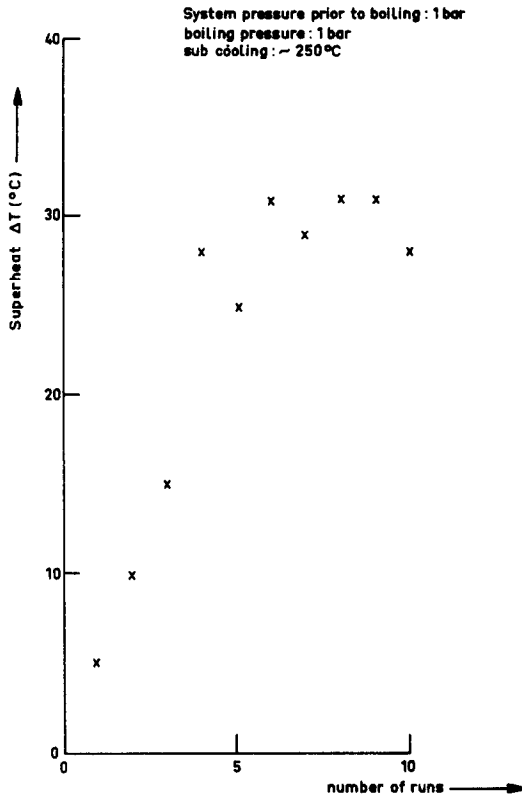


FIG. 18. History of superheat in a new test section [5].

An increase of superheat with increasing number of runs was only observed in test series O shown in Fig. 18. Test series A, B and C did not show a definite trend of superheat neither as a function of depressurization (pressurization) nor subcooling.

Figures 19–21 show the measured wall superheat, as a function of depressurization and pressurization.

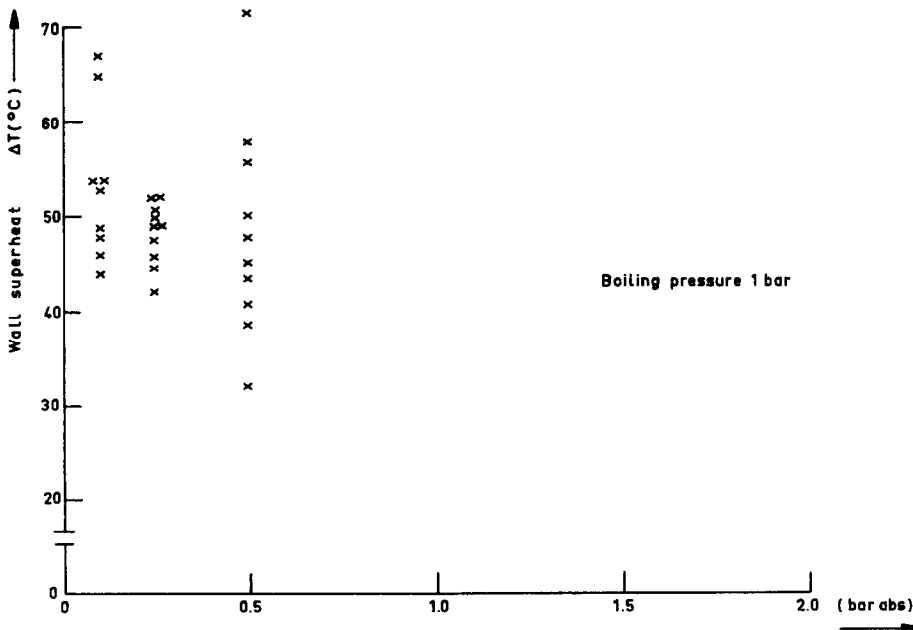


FIG. 19. Superheat vs depressurization test series A [5].

Between test series A and B the test loop was in operation continuously at 300°C and 1 bar system pressure for 1,900 h and between test series B and C for 1600 h. Test series C is shown in Fig. 21.

The variation of the absolute value of superheat between the various test series is due to different oxide levels. A better survey of the long term trend of the superheat as a function of pressure deactivation procedures is shown in Fig. 22. The points are average values of ten runs.

Experiments aiming at the investigation of effects on superheat due to operation time, pressurization or subcooling history prior to boiling were performed by Leonev and Prisnyakov [13]. The authors adopted the deactivation procedure described by Chen [14], but before subjecting the test section to this procedure the sodium was heated up to boiling to eliminate gas nuclei on the heating surface. Unfortunately no data on the boundary conditions are reported neither on pressure nor on subcooling except the so called “deactivation time” between pre-boiling and boiling run. The authors report that exposing the test section of about up to 1 h to the “deactivation” (time between preboiling and boiling) the superheat reached a threshold level which was not exceeded.

Figure 23 shows the measurements performed in a stainless steel tube of the surface quality “as received” vs the saturation temperature of operation. The data show the known trend of decrease of superheat with increase of the saturation temperature.

Leonev and Prisnyakov conclude an empirical correlation for the threshold superheat from their own and other experimental results reported in the literature

$$\Delta T = 485 - 0.71(T_s - 500)[^\circ\text{C}] \quad (3)$$

T_s = saturation temperature [°C].

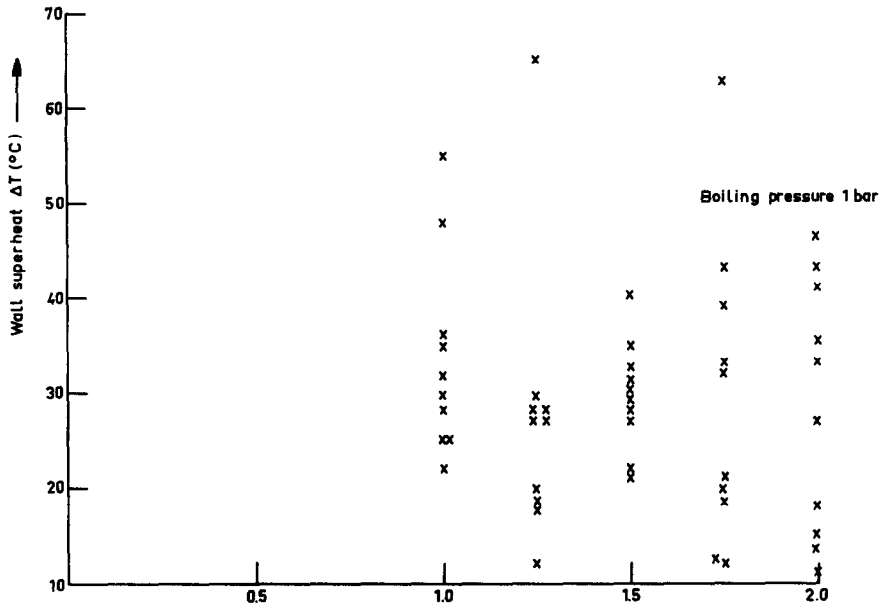


FIG. 20. Superheat vs pressurization; test series B [5].

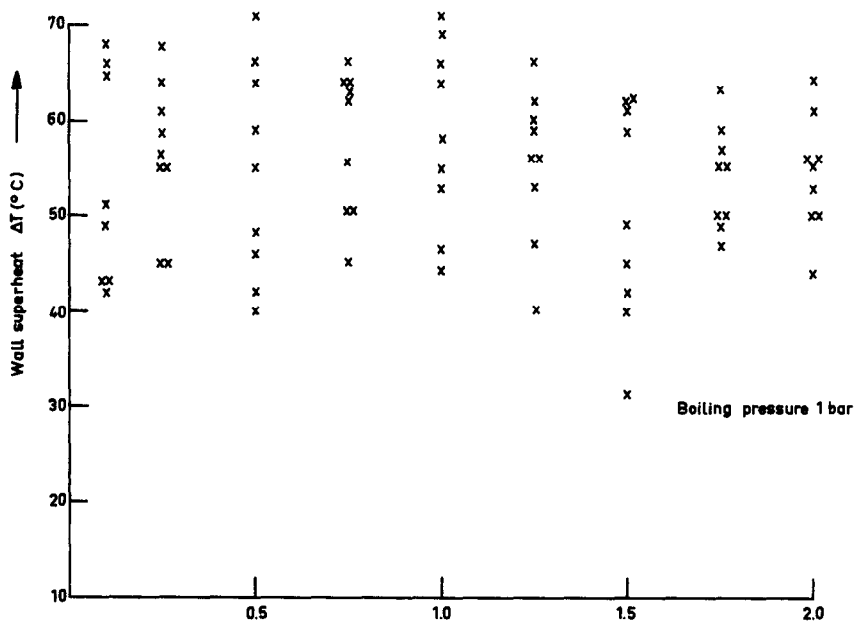


FIG. 21. Superheat vs depressurization and pressurization; test series C [5].

HEAT FLUX AND TEMPERATURE RAMP EFFECT

The effect of heat flux has received the most inconsistent and conflicting experimental evidence. For example, data have been presented indicating that incipient superheat may be decreased [16] increased or decreased [17], increased [18, 19] or unaffected [12] by an increase in the heat flux. Singer [20] made an analysis on the effect on heat flux and temperature ramp and he demonstrated that it is possible that variations in the heat flux are not responsible for the observed changes in the superheat. The mobility of

inert gas between active nucleation sites and the liquid can result in the observed behaviour. Since the solubility of inert gas in liquid alkali metals increases with increasing temperature, gas will be lost from nucleation sites during the heating prior to and during boiling and might be gained by the sites during the cooling between the tests.

The main requirement for tests studying this effect will be to maintain the gas partial pressure in the sites constant during the sequence of tests or this gas effect might mask other phenomena. This is a difficult experimental requirement since there is no way of

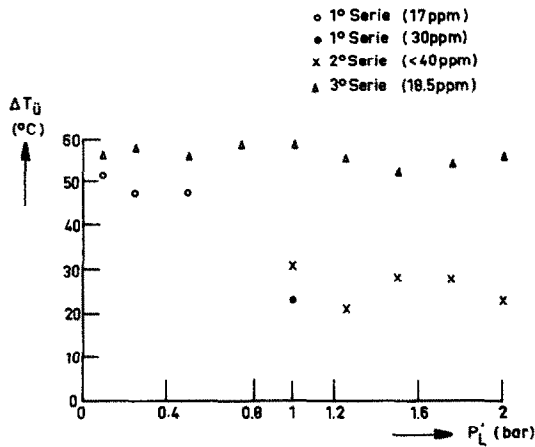


FIG. 22. Statistical mean value of wall superheat in forced convection flow [5].

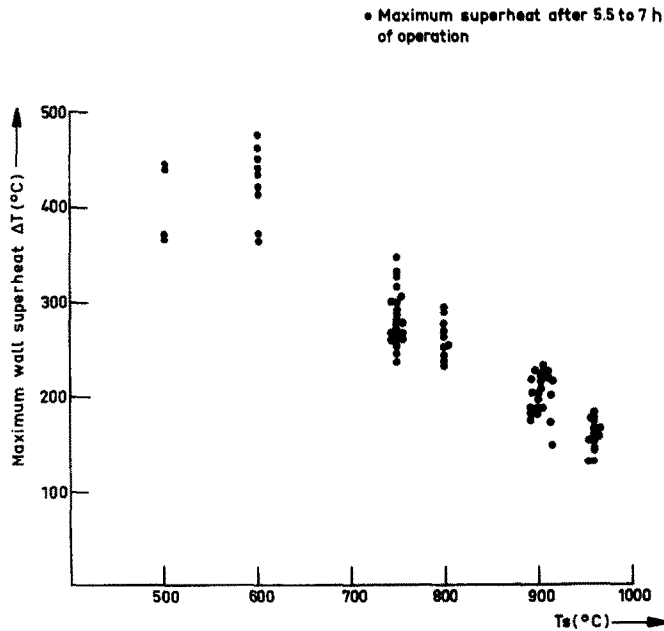


FIG. 23. Saturation temperature (deactivation exp. [13]).

direct measure of inert gas partial pressure in the microscopic cavity sites. Therefore, reported heat flux effects upon incipient superheat must be treated with considerable caution.

VELOCITY EFFECT

The effect of velocity has received inconsistent experimental evidence as well. Data have been presented indicating, for example, incipient wall superheat may be decreased or unaffected by an increase in velocity. The evaluation and comparison of the published data becomes often difficult or impossible due to insufficient instrumentation of the experiments. The weak point in nearly all experiments is the measurement of the location of the inception of boiling. Most of the authors are calculating the location by energy balance from measured inlet and outlet data.

Despite the various conditions, various heat flux, inlet subcooling and surface finishing the bulk superheat tends to lower values as velocity increases, both in magnitude and extent of variation (the use of the term bulk superheat is not definite. It is difficult to find out whether the local bulk superheat or bulk superheat at the outlet of the test section is referred to).

Chen *et al.* [44] report on bulk superheat measurements in potassium flow. The superheat varies from 10°C at about 1 m/s to about 50°C lowering the velocity to about 0.1 m/s (Fig. 24). Pinchera *et al.* [41] report (Fig. 25) on bulk superheat measurements in sodium flow varying the velocity from 1.8 m/s to 0.6 m/s which results in a change of superheat from 0 to 48°C. Extensive experiments on the importance of the velocity effect on the bulk superheat have been done by Logan *et al.* [8] (Fig. 26). Logan varied in his experiments not only the velocity but also the inlet subcool-

ing and heat flux. The trend already shown by Pinchera and Chen could be demonstrated. The decrease of superheat with increasing velocity occurs despite the fact that the heat flux required to initiate boiling increases with velocity. (This trend is contrary to that observed by Chen *et al.*)

As velocity and heat flux increase, the superheat characteristic is reported to change even to subcooled nucleation conditions (Fig. 26). Additional verification of the velocity bulk superheat relationship described above is to be found in the results of Kikuchi *et al.* [43] (Fig. 27).

The present experimental results show that for otherwise fixed conditions, for increasing velocity there is an effect on superheat. We think that this is an apparent effect and at least a consequence of mass flow rate in the particular flow channel, a trend which is in accord with the all liquid heat balance. It is not known

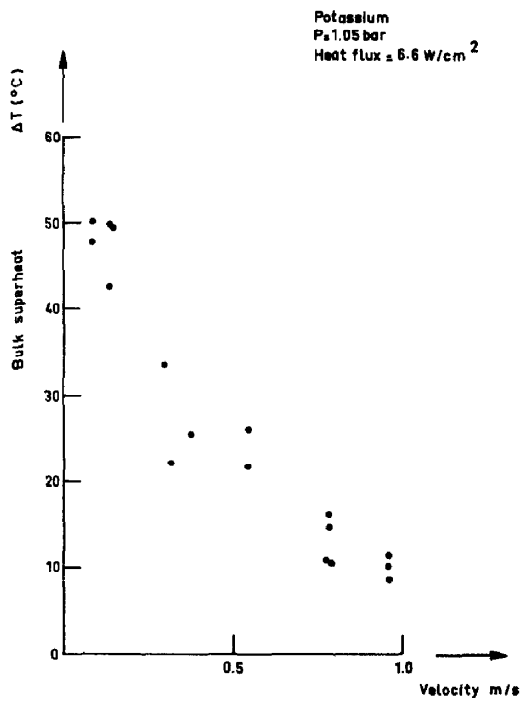


FIG. 24. Bulk superheat vs velocity [44].

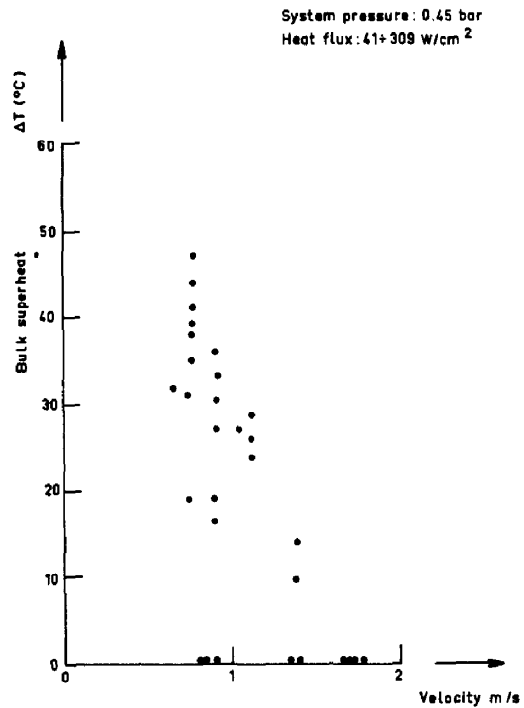


FIG. 25. Bulk superheat vs velocity [41].

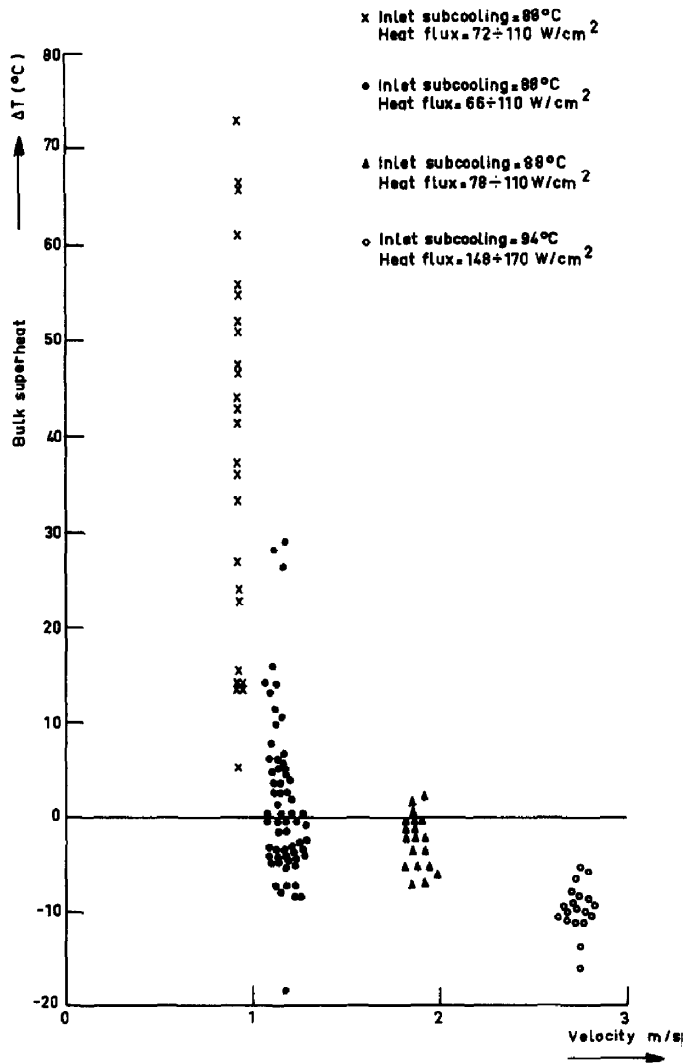


FIG. 26. Bulk superheat vs velocity [8].

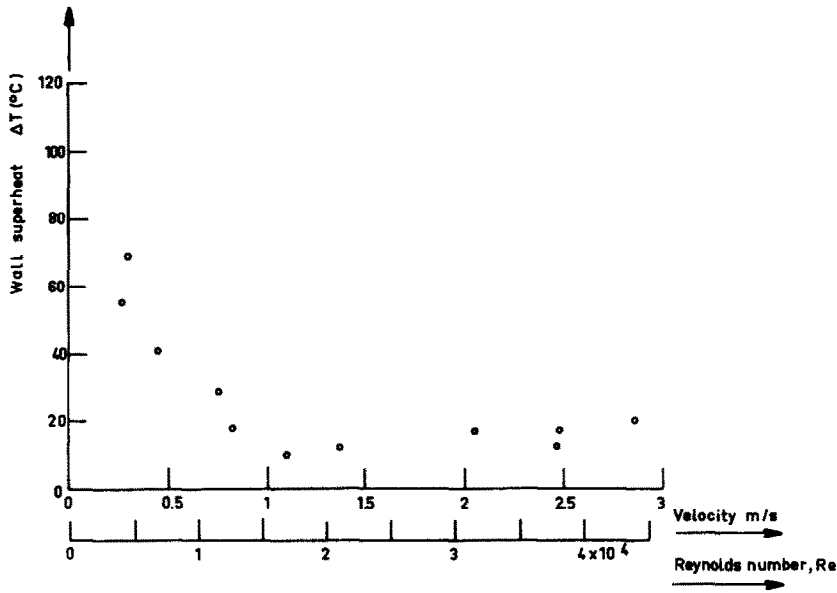


FIG. 27. Wall superheat vs velocity [43].

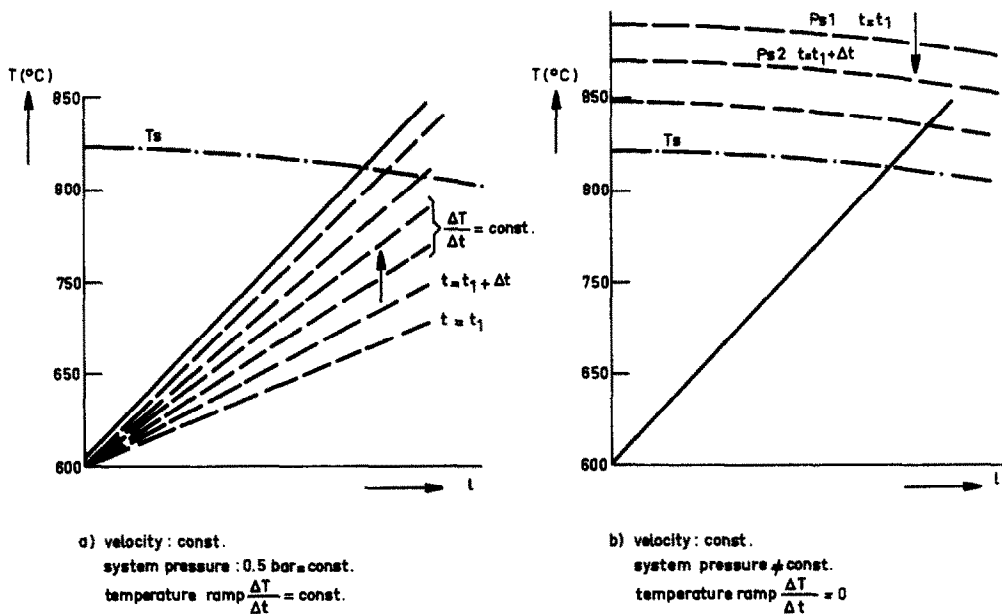


FIG. 28. Conditions of the $\Delta T_{sup} F(V)$ experiments [48].

whether velocity, of itself, should have a dominant effect on superheat. An attempt to a theoretical analysis has been made by Bankoff [45]. He proposes a random-walk model which takes into account the influence of the increase of turbulence with increasing velocity superimposing to the steady state condition pressure oscillations due to the increase of turbulence activating nucleation sites. But this model implies with the same probability also the deactivation of nucleation sites.

Taking into account the inadequate instrumentation in the previous experiments, investigations have been performed at Ispra emphasizing on sophisticated instrumentation to measure the

location of the inception of boiling in the test section. Great importance has been attached when executing the experiments to eliminate or at least maintain constant all factors but velocity. The conditions scrupulously controlled were: (a) the oxide level, (b) metallic impurity.

Not controlled because of no instrumentation available was the gas entrainment. Besides these experimental requirements, the following boundary conditions for the tests were met:

(a) Temperature transient conditions (Fig. 28a): (i) constant system pressure: 0.5 bar; (ii) constant temperature ramp $\Delta T/\Delta t$ (the power input was adopted to the mass flow) and (iii) constant inlet temperature.

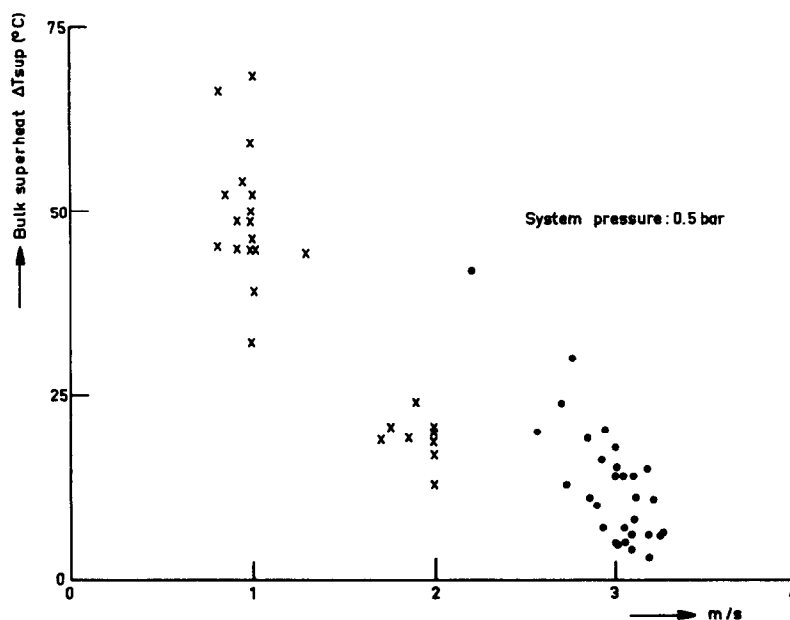


FIG. 29. Bulk superheat vs velocity [48].

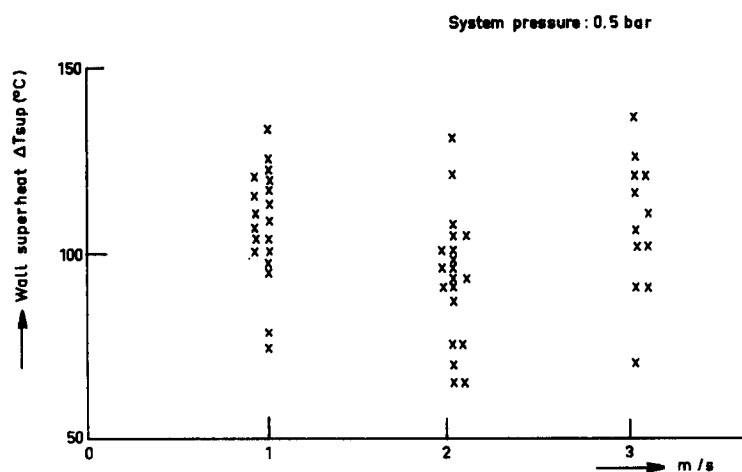


FIG. 30. Wall superheat vs velocity [48].

(b) Thermodynamic transient conditions (Fig. 28b): (i) constant temperature gradient along the test section; (ii) steady state thermo-hydraulic conditions and (iii) decrease of the system pressure at constant pressure-time ramp up to boiling.

The tests were evaluated for both, conditions with regard to local (measured) wall superheat and average coolant superheat at the end of the heated test section. Figure 29 shows the bulk superheat vs velocity for the so called "temperature transient test condition". The trend of superheat is definitely seen to decrease in amount and magnitude of scattering with increase of velocity.

The superheat becomes different when evaluating for the same tests the wall superheat at the measured location of boiling inception. The presentation in Fig. 30 does not show any measurable velocity effect neither in amount nor in magnitude of scattering of the superheat (compared to Fig. 29 less tests have been

evaluated). Comparing the "temperature transient tests" with the so called "thermodynamic transient tests" with regard to bulk- and wall superheat only a qualitative difference is seen. The decrease of bulk superheat with increasing velocity is less pronounced because boiling started almost only in the exit region of the test section (Fig. 31).

The measured local wall superheat does not indicate any velocity effect (Fig. 32). It is not excluded that other factors, like entrained gas mask the velocity effect. This effect can in all probability be assumed of minor importance for this experiment because of the relatively high values of superheat.

SUPERHEAT MEASUREMENTS IN BUNDLE GEOMETRY

Experimental data available in bundle geometry are not yet adequate. An analysis on parameters, the local

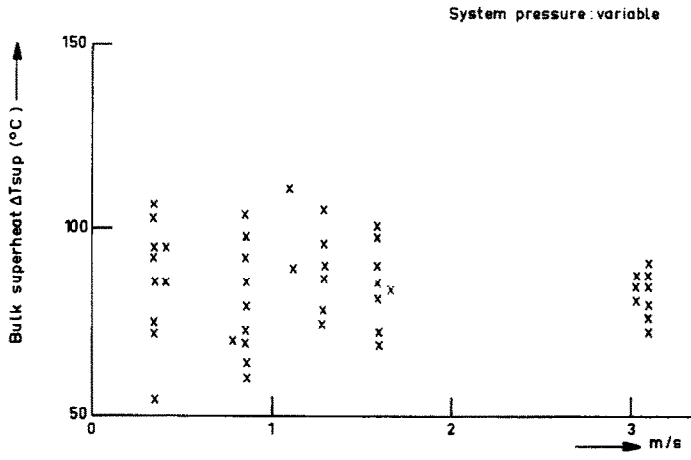


FIG. 31. Bulk superheat vs velocity [48].

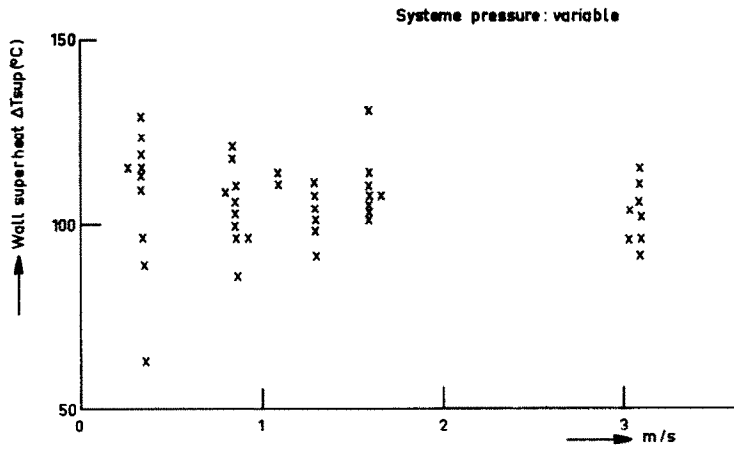


FIG. 32. Wall superheat vs velocity [48].

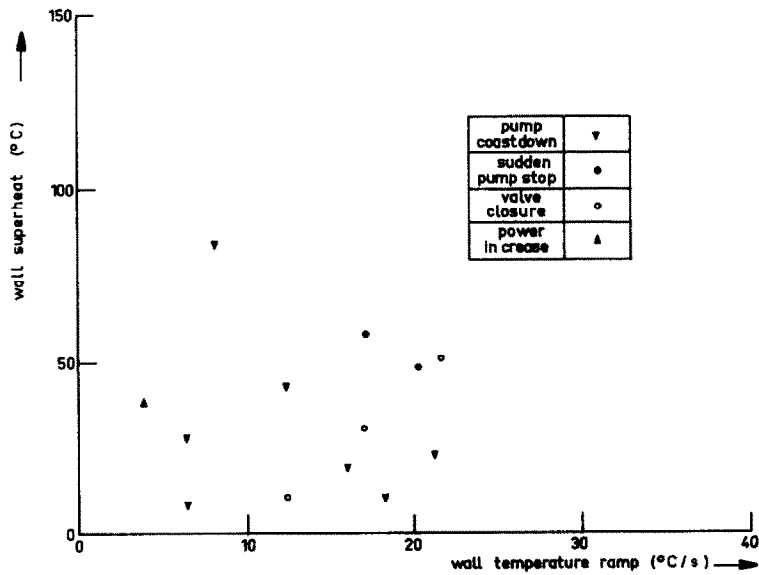


FIG. 33. Effect of wall temperature rise on wall superheat for sodium boiling tests in 7-pin bundle [55].

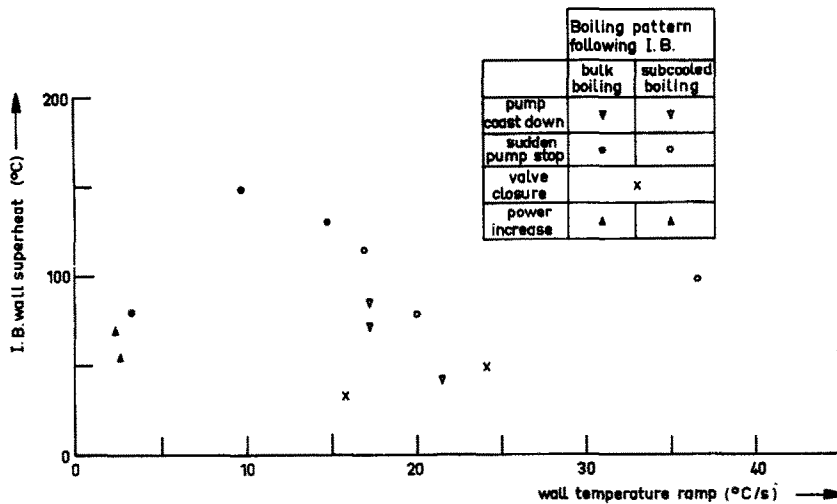


FIG. 34. Effect of wall temperature rise on wall superheat of loss-of-flow tests [55].

wall superheat, local bulk superheat or outlet bulk superheat might be influenced is still premature. The data available up to now can only give a qualitative indication on the amount of superheat which could arise, and which transient pattern in case of coolant superheat might appear. It is still unknown which influence has the geometry and the thermal and hydraulic conditions on boiling pattern in a bundle.

Boiling experiments reported by Menant *et al.* [53], Boswinkel [54], Kikuchi [55], exhibit "local wall superheat" of up to 150°C whereby contemporaneously zero outlet superheat has been measured. Menant *et al.* report that 98% of their boiling inception runs did not show any superheat, but 2% exceeded 100°C. Boswinkel reports on superheat of 0 to about 80°C in bundle experiments. Förster [56] observed in 3-pin experiments local wall superheat of 18–34°C, bulk superheat in the vicinity of boiling inception of 5–21°C and no bulk superheat at the test section outlet.

An extensive test program is started by Kikuchi *et al.* The superheat values measured in a 7-pin test section varying the conditions prior to boiling are shown in Figs. 33 and 34. The identification of the test conditions prior to boiling is noted in the diagrams. The representation of the data does not demonstrate any of the factors, being changed during the experiments, influencing notably the superheat.

SUMMARY

The published results of the various laboratories on the parameters having an influence on the superheat are not definite. The effect of some parameters has even received inconsistent and conflicting experimental evidence. The most consistent agreement in the trend is seen in the influence of the oxide impurity and gas entrainment. In both cases the superheat is decreasing with increasing gas entrainment and oxide level.

The most inconsistent and conflicting experimental evidence has received the effect of heat flux and of

temperature ramp. Data have been presented indicating that superheat may be decreased, increased or decreased, increased or unaffected. It is possible that variations in heat flux or temperature ramp were not responsible for the observed changes of superheat but the strong change of solubility of entrained gas with temperature variation. Uncertain is the effect of the velocity on the wall superheat. Data have been presented indicating that superheat is decreasing or unaffected with increasing velocity. Most of the experiments devoted to the investigation of the velocity effect suffered from inadequate instrumentation to locate the boiling inception so that at present from the data available definite conclusions are impossible to be drawn. In good agreement are the data of bulk superheat as far as the trend is concerned. The bulk superheat is decreasing definitely with increasing velocity.

An influence of the heating wall material on the superheat is uncertain. Experiments on materials compatible with sodium did not exhibit significant effects. A revise of the investigations on the effect of operation conditions indicates some inconsistency. Exposing the test section prior to boiling repeating depressurization and subcooling, the superheat is reported being increasing or unaffected.

Most of the experiments in which the influence of the operation time has been observed were short time tests. It is supposed that the effect of operation conditions was masked by the degassing of the heating surface during heating up or boiling. On the other hand, "so called" long duration tests show that operation time, depressurization, pressurization and subcooling did not influence a certain range of superheat which followed representative for the test conditions in question.

There is experimental evidence that for given test conditions a characteristic threshold superheat range is not exceeded. The threshold superheat level is presumably determined by the heating surface finishing, the oxide level and the gas loading of the sodium.

A general evaluation of the results of loop experiments shows an average value of superheat for technically clean sodium of $80 \pm 30^\circ\text{C}$ (O_2 -impurity of about 5–10 ppm) and for sodium with impurity of about 40 ppm of about $25 \pm 20^\circ\text{C}$. Laboratory scale experiments performed under extremely clean conditions exhibit values of up to 500°C . These peak values, however, have been measured at very low system pressure. A comparison of these experiments with the loop experiments seem objectionable. On the other hand, laboratory experiments performed at comparable system pressure yield only gradual differences (superheat range of 100– 150°C) [29].

How do we judge the actual knowledge on superheat as far as the reactor safety is concerned? The reactor safety analysis has to rely on conservative assumptions. Parameters decreasing or unaffected the superheat are improving the conservativity of the safety analysis. Leonov and Prisnyakov propose an empirical correlation for the most pessimistic operation conditions which can serve as a conservative approach.

We can sum up that the actual knowledge on superheat is not sufficient to provide reliable predictions as a function of operation conditions and operation time.

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EVALUATION DES MESURES DE SURCHAUFFE DU SODIUM VIS A VIS DE L'IMPORTANCE DES NOMBREUX PARAMETRES EXPERIMENTAUX ET PHYSIQUES

Résumés—Les résultats publiés par de nombreux laboratoires sur les paramètres ayant une influence sur la surchauffe ne sont pas définis. Il apparaît des inconsistances et des contradictions sur les effets de quelques paramètres. Le meilleur accord concerne l'influence de l'impureté due à l'oxydation et l'entraînement par le gaz. Dans les deux cas, la surchauffe décroît quand le niveau de l'entraînement gazeux et de l'oxydation augmente. Les plus grandes dispersions expérimentales et contradictions sont relatives à l'effet du flux de chaleur et de la rampe de température. Les résultats sur la surchauffe à coeur sont en bon accord. Cette surchauffe décroît quand la vitesse augmente. Une influence de la nature des parois chauffantes est incertaine. Des expériences sur les matériaux compatibles avec le sodium ne montrent pas d'effet significatif. La plupart des expériences dans lesquelles était étudiée l'influence du temps d'opération étaient conduites pendant des temps courts. On peut supposer que l'effet des conditions opératoires était masqué par le dégazage de la surface chauffée pendant la montée en température ou l'ébullition. Il est remarqué expérimentalement dans des conditions données, qu'un domaine caractéristique de début de surchauffe n'est pas dépassé. Le niveau du début de surchauffe est probablement déterminé par la finition de la surface, le niveau d'oxydation et la teneur en gaz du sodium. Une évaluation globale des résultats sur des boucles expérimentales donne une valeur moyenne de surchauffe égale à 80°C pour du sodium techniquement pur (impureté en O₂ de l'ordre de 5 à 10 ppm) et à 25°C ± 20°C pour du sodium à 40 ppm d'impureté environ.

DIE AUSWERTUNG VON MESSUNGEN DER ÜBERHITZUNG BEI BEGINNENDEM SIEDEN VON NARIUM IN BEZUG AUF DIE BEDEUTUNG VERSCHIEDENER EXPERIMENTELLER UND PHYSIKALISCHER PARAMETER

Zusammenfassung—Die von verschiedenen Laboratorien veröffentlichten Ergebnisse über die, die Überhitzung beeinflussenden Parameter sind nicht eindeutig. Über den Einfluß einiger dieser Parameter liegen unvereinbare und sich widersprechende experimentelle Befunde vor. Die beste Übereinstimmung liegt in bezug auf den Einfluß von Oxidverunreinigungen und Gaseinschlüssen vor; mit zunehmenden Gaseinschlüssen und Oxidverunreinigungen nimmt die Überhitzung ab. Am stärksten widersprechen sich die Versuchsergebnisse bezüglich des Einflusses von Wärmestrom und Temperaturanstieg. Hinsichtlich des Trends sind die Daten für die Flüssigkeitsüberhitzung in guter Übereinstimmung.

Mit zunehmender Geschwindigkeit nimmt die Flüssigkeitsüberhitzung eindeutig ab. Ein Einfluß des Heizflächenmaterials auf die Überhitzung ist ungewiß. Bei den mit Natrium verträglichen Materialien zeigten sich in den Versuchen keine besonderen Effekte. Die meisten Experimente, bei denen sich ein Einfluß der Betriebszeit ergab, waren Kurzzeitversuche. Es wird vermutet, daß der eigentliche Einfluß der Betriebszeit dabei durch die Entgasung der Heizfläche beim Aufheizen oder Sieden verdeckt war. Es gibt experimentelle Anzeichen dafür, daß die Überhitzung unter gegebenen Versuchsbedingungen eine charakteristische Schwelle nicht überschreitet. Diese Schwelle ist vermutlich durch die Oberflächenbeschaffenheit der Heizfläche, durch den Oxidgehalt und die Gasbeladung des Natriums festgelegt. Eine allgemeine Auswertung der verschiedenen Versuchsergebnisse ergibt eine mittlere Überhitzung von $80^{\circ}\text{C} \pm 30\text{K}$ für technisch reines Natrium (5 bis 10 ppm O_2 -Verunreinigung), bei einer Verunreinigung von etwa 40 ppm sinkt die Überhitzung auf ungefähr $25^{\circ}\text{C} \pm 20\text{K}$.

ОЦЕНКА РЕЗУЛЬТАТОВ ЭКСПЕРИМЕНТАЛЬНОГО ИССЛЕДОВАНИЯ ПЕРЕГРЕВА НАТРИЯ С УЧЕТОМ ВЛИЯНИЯ РАЗЛИЧНЫХ ЭКСПЕРИМЕНТАЛЬНЫХ И ФИЗИЧЕСКИХ ПАРАМЕТРОВ

Аннотация — В работах различных авторов по исследованию параметров, влияющих на возникновение перегрева натрия, имеются разноречивые, а иногда и прямо противоположные сведения. Наибольшее совпадение наблюдается в оценке влияния на перегрев натрия наличия в нем примесей окислов и газа. С увеличением их количества величина перегрева уменьшается. Наиболее противоречивые результаты получены при исследовании влияния на перегрев плотности теплового потока и линейного изменения температуры. Результаты по среднеобъемным значениям перегрева в основном совпадают. С увеличением скорости движения натрия среднеобъемные значения перегрева явно уменьшаются. Влияние состава материала поверхности на возникновение перегрева остаётся пока до конца невыясненным. Опыты с материалами, совместимыми с натрием, не подтвердили какого-либо заметного воздействия. Большинство экспериментов, в которых изучалось влияние времени контакта среды с материалом поверхности, не отличались длительностью. Предполагается, что картина влияния рабочих условий искажалась из-за удаления газа с поверхности в процессе нагрева или кипения. Результаты проведенных опытов свидетельствуют о том, что в данных экспериментальных условиях характерный пороговый диапазон перегрева превышен не был. Критическое значение перегрева скорее всего определяется классом обработки поверхности нагрева, степенью окисления натрия и степенью его насыщенности газом. Общая оценка результатов экспериментов показывает, что среднее значение величины перегрева составляет $80 \pm 30^{\circ}\text{C}$ для технически чистого натрия (O_2 не превышает 5–10 пррт) и $25 \pm 20^{\circ}\text{C}$ для натрия, имеющего 40 пррт примеси.