INCIPIENT SUPERHEAT IN A CONVECTIVE SODIUM SYSTEM

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INCIPIENT SUPERHEAT IN A CONVECTIVE SODIUM SYSTEM

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Abstract

Experimental measurements are reported for incipient boiling superheats in a convective sodium system. The results show that definitive evaluation of the incipient wall superheat requires a knowledge of the location of inception and detection of any entrained noncondensable gas bubbles. It is shown that, when history and gas solubility effects are properly accounted for, a recirculant cavity model is representative of the data.

NOMENCLATURE

C : Concentration
D : Diameter
h : Heat transfer coefficient
K : Henry's Law constant
k : Thermal conductivity
P : Pressure
r : Radius
T : Temperature
 σ : Surface tension

Subscripts

g : Gas
h : Hydraulic
s : System
v : Vapor

Superscript

' : deactivation

INTRODUCTION

Several recent experimental investigations¹⁻¹² have been conducted to determine the amount of superheat a liquid metal can sustain before boiling is initiated. Data have been published in the literature²⁻⁵ which indicate a strong dependence upon the coolant velocity in the range of 0-2 m/sec, i.e., the incipient superheat decreases as the velocity increases. However, experimental results are also available which indicate comparatively high wall superheats for velocities in and above this range.⁶⁻¹² Two general criticisms of the data indicating a strong velocity dependence have been that neither the location of inception nor the entrained gas content were recorded during the experiments. The analysis presented in Ref. 14 illustrates the necessity of detecting the axial location of inception and the gas injection tests reported in Ref. 15 show that the injection of a noncondensable gas bubble into a superheated liquid metal will initiate bulk boiling.

The test section for this investigation was instrumented to detect both the axial location of boiling and the entrained gas content. Therefore, the relationship between coolant velocity and the incipient superheat can be definitively evaluated in the velocity range of interest.

EXPERIMENTAL APPARATUS

The facility used for this study is shown schematically in Fig. 1. The details of the test section and all the associated instrumentation are given in Fig. 2. An 0.584 cm OD sheathed-coil type of heater was used. The heater element was Nichrome V

Fig. 1 Basic Loop Schematic

wire rated for 38 kw at 440 V. Type 316 stainless steel was used for the sheath, and the downstream end of the heater was grounded to the sodium. A 0.178 cm OD wire, wrapped on a 30.5 cm pitch, maintained the annular coolant passage between the heater and the outer wall (0.953 cm ID x 1.27 cm OD).

In addition to the standard measurements of pressure, temperature, heater power, and flow rate, two other measurements were taken which proved to be valuable in analyzing the experimental data.

1) Electrodes were welded onto the outer tube through which a small (10 ampere) DC current could be supplied to the outer wall, wire wrap, heater sheath, and sodium coolant. Voltage taps on the outer wall enabled one to distinguish between nucleations within the superheated region and boiling initiation triggered by an entrained noncondensable gas bubble.

Fig. 2 Test Section

2) A converging-diverging nozzle in the test section bypass detected any average entrained gas volume fractions about 10^{-3} , which is the range of validity for such an instrument.¹⁶ This measurement complemented the voltage taps in that the voltage taps could detect a single bubble or chain of bubbles, and the nozzle could detect significant average concentrations.

For boiling inception within the superheated region, the superheat was evaluated as the highest heater wall temperature within that voltage tap increment minus the saturation temperature. When nucleation occurred downstream of the end of the heated length, the superheat was evaluated as the bulk coolant temperature in that increment minus the local saturation temperature.

EXPERIMENTAL PROCEDURES

As has been extensively discussed in the literature,¹⁻¹² incipient boiling data for liquid metals are dependent upon a large number of system parameters. Therefore, in order to report meaningful data on this phenomenon, it is important that the operating procedures are specified in detail.

1) The operating pressure was set by regulating the pressure in the gas plenum, and the entire loop was heated up to 427°C . This was accomplished in two different ways:

a) The loop was brought up to temperature by using only the trace and guard heaters. After the test section heater was energized, the first boiling run was taken within 15 minutes.

b) The test section heater was used in the heatup period in addition to the guard and trace heaters. Under these conditions, the downstream end of the heated region was at approximately 593°C for 2-3 hours. This was by far the highest temperature in the loop during this time.

2) The flow rate through the test section was set with the inlet valve. Boiling was achieved by increasing the heat flux in small increments until inception occurred.

3) Following inception, steady-state boiling was suppressed in one of two ways:

a) If the inception phenomenon caused a 20% flow reduction, a flow trip automatically cut off the heater power, and the temperatures throughout the test section quickly decayed to 427°C .

b) If (a) did not occur, the power was gradually decreased until boiling ceased; hence, the temperature at the end of the heated zone was slightly less than the corresponding saturation value.

4) After boiling was suppressed, the gas plenum pressure and/or the test section flow rate were set to new values and the next run was initiated.

5) For overnight operation, the system was cooled down to 315°C , and the gas plenum was then pressurized to 1.05 atm.

EXPERIMENTAL RESULTS

Figure 3 shows a typical heater wall temperature profiles in the region of boiling inception. The heater wall temperatures are calculated from the

Fig. 3 Coolant Temperature Profile

outer wall measurements using a Nusselt number (hD_p/k) of 6. The axial location of inception is noted, and it is clear that boiling does not necessarily begin at the point of maximum superheat. Therefore, to definitively evaluate the contribution of any proposed effect, it is essential to know the wall superheat at the point of inception.¹⁴

The convective incipient-superheat data for a system pressure of 0.143 atm are shown in Fig. 5. The upper graph is the superheat on the heater wall at the point of inception for all cases in which nucleation occurred within a superheated liquid region. In contrast, the lower graph displays the maximum superheat in the test section for all runs at this pressure regardless of the type of nucleation. The representation given in the lower illustration is equivalent to that used by several previous investigators.^{2,4,5} When the experimental results are interpreted on the basis of the maximum superheat and all nucleations are included, the

incipient superheat appears to decrease with increasing velocity. However, as shown in the figure, several runs were nucleations from entrained gas bubbles passing through the system. When the data are restricted to nucleations within the superheated zone and the point of nucleation is known, any dependence on system velocity is within the normal scatter of data. This is demonstrated by the upper illustration in Fig. 4 and the higher

Fig. 4 Incipient Superheats at 0-143 atm.

pressure results given in Fig. 5. As will be subsequently discussed, it is felt that the incipience phenomenon is controlled by parameters not delineated on Figs. 4 and 5.

Fig. 5 Incipient Superheats at 0-35 atm.

All the gas bubble nucleations at 4.5 ft/sec and below were caused by a single bubble or a single group of bubbles passing through a saturated or superheated region. For higher system velocities, the gas detection nozzle indicated a significant average gas volume fraction in the coolant, and for such cases, the coolant began boiling at zero bulk superheat.

Incipient-boiling phenomenon for a given fluid is a complex physical process, and it is not reasonable to expect that the controlling mechanism for one fluid also governs another fluid with greatly

Fig. 6 Surface Deactivation and Reactivation

different thermophysical properties.¹⁷ The inception criterion recommended by Hsu¹⁸ has been successfully applied to such data for many ordinary fluids although one must still be aware of the pressure-temperature history as illustrated by Fabric¹⁹. However, the high thermal conductivity of liquid metals dictates that the tangency criterion is not the dominant factor. This was experimentally demonstrated in Ref. 1 by showing that incipient-boiling events induced by heating or depressurization produced the same initial superheats. (The tangency criterion is meaningless for boiling due to depressurization.) Holtz²⁰ and Chen⁶ proposed that the pressure-temperature history determines the magnitude of incipient superheat in a liquid-metal system by dictating the size of the active surface cavities. Experimental data have been reported for sodium and potassium systems which demonstrate the effect of pressure-temperature history.^{1,3-10} It has been demonstrated experimentally^{1,11,12,19} that once boiling has been initiated, the surface can be reactivated (boiling hysteresis), and the effect of the previous history has been diminished or erased. Such behavior was also witnessed in this study and is shown in Fig. 6. Several successive runs were taken at 0.143 atm and 0.7 m/sec and rather low values of superheat were measured. The system was then exposed to a more severe deactivation condition. The next run at 0.143 atm required a considerably greater wall superheat for inception than the previous runs. However, the history was not reestablished, and the incipient superheat in the succeeding runs rapidly decayed back to a value corresponding to the runs which preceded the 0.7 atm history.

In Experimental Procedures, it was pointed out that the facility was brought up to temperature in two different manners. In particular, method (b) was used on two successive days and on these occasions, comparatively large superheats were measured for the first run of each day. In contrast, method (a) was employed on the remaining days and the first run of each day was characterized by low or negative values of incipient superheat (see Table I). This behavior is indicative of the presence of non-condensable gas in the surface cavities. The gas diffused into the cavities while the system circulated at 315°C and 1.05 atm gas plenum pressure

during off hours. When method (a) was used to heat up the loop, the test section was brought up to boiling in a comparatively short time, and thus, the gas may not have had time to go back into solution which would result in a high gas partial pressure in the surface cavities and a low incipient superheat. However, for method (b), the test section was maintained at a high temperature for a long period before the boiling runs were initiated. Under this condition, more gas could diffuse out of the cavities which would produce a lower gas partial pressure and a higher incipient superheat.

TABLE I

Heating Date	Method	P atm	V m/sec	T _w - T _{sat} °C	Type of Nucl.	Reentrant Cavity Model °C
5/11	a	0.21	0.32	0	W	10
5/12	b	0.21	0.69	61	W	53
5/13	b	0.35	0.72	59	W	56
5/14	a	0.14	0.67	-3	B	-12
5/14	a	0.21	0.66	1	W	10

W - wall nucleation

B - gas-bubble nucleation

To evaluate the gas behavior, it is assumed that the entire sodium inventory is in equilibrium with the gas plenum at 1.05 atm and 315°C (off-hour circulating conditions) as described by Henry's Law.

$$C = K(T)P_g \quad (1)$$

It is further assumed that during the operating hours there is no mass transfer communication with the gas plenum and also that no gas comes out of solution. As shown in Fig. 1, the argon-sodium interface is removed from the circulatory path and the necked-down portion between the gas disengagement tank and the expansion tank further impedes gas diffusion. Any noncondensable gas bubbles which circulated through the system probably were entrained at the argon-sodium interface in the heat exchanger. This surface is in equilibrium with the coolant as specified in Eq. 1. Hence, the gas concentration is assumed constant, or, at equilibrium,

$$P_{g2} = \frac{K(T_1)}{K(T_2)} P_{g1} \quad (2)$$

Using the expression given in Ref. 21 for Henry's Law constant describing the solubility of argon gas in sodium, the gas partial pressures at 427°C [method (a)] and 593°C [method (b)] are 0.061 atm and 0.0034 atm respectively. As described above, the heater was brought up to boiling in a comparatively short time which leaves little time for gas to diffuse into the coolant. If it is assumed that the gas is heated at constant volume from 427°C to 760°C and that no gas diffuses out of the cavity, the gas partial pressure is 0.090 atm for method (a). A similar analysis for method (b) yields a value of 0.0041 atm.

This simplified analysis demonstrates that it is reasonable to expect that heating methods (a) and (b) will produce significantly different cavity conditions in the surface cavities and thus, significantly different superheats.

ANALYSIS

As shown in the previous section, the effect of a given history is quickly erased if it is not re-established prior to each incipient-boiling test. The data in this study and generally for all other liquid-metal incipient-boiling experiments in convective systems^{1,2} have been accumulated by taking successive runs without reestablishing a given history between each run. A notable exception to this statement is the "K" series of Ref. 2 where a specific history was applied after every run and comparatively high incipient superheats were consistently obtained. This series of runs will be discussed later.

The various assumptions which can be employed in deriving the pressure-temperature-history model for liquid metals are discussed in detail by Holtz.¹ For the simple analysis considered herein, the reentrant cavity described by Bankoff²² affords a simple, convenient, and highly-illustrative model of the nucleation phenomenon. It is tacitly assumed in this analysis that reentrant cavities of the required physical dimensions are available.

For the given conditions, the maximum deactivation would be

$$r = \frac{2\sigma(T')}{P' - [P_v(T') + P_g(T')]} \quad (3)$$

Therefore, the incipient superheat under such conditions is expressed as

$$\{P_v(T_2) + P_g(T_2)\} - P_g = \frac{\sigma(T_2)}{\sigma(T')} (P' - [P_v(T') + P_g(T')]) \quad (4)$$

When a surface has existed at an elevated temperature (590°C or greater) for a couple of hours, the noncondensable gas partial pressure in the cavity can be neglected for gas concentrations typical of this study.

Assuming that a surface is reactivated after each run, this expression is applicable to data where successive runs are taken without reapplying the deactivation pressure; hence, $P' = P_g$. The deactivation is due to temperature variation. The prediction of Eq. 4 for various deactivation temperatures is shown in Fig. 7 along with the incipient measurements with similar deactivation conditions from this study, and the agreement is encouraging.

The above prediction is based upon the maximum deactivation conditions. In the preceding section, the role of gas diffusion into the surface cavities was outlined, and it was shown that the method of heating the loop determined the gas partial pressure in the cavities for the first run of each day. Evaluating the gas partial pressure as outlined above, Eq. 4 can be used to calculate the superheat under these conditions. Table I lists the predictions of the pressure-temperature-history model for the initial runs of each day. The reentrant cavity model gives a good description of the magnitude and trends of the data including the negative superheat observed on 5/14.

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Fig. 7 Reentrant Cavity Predictions

For the "K" runs reported in Ref. 2, the power was tripped following each run and a pressure history was applied prior to the next run. If gas partial pressure is assumed negligible and the history applied just prior to the run is used as the deactivation, a comparison can be affected between these experimental results and the prediction of Eq. 4.

Fig. 8 Reentrant Cavity Predictions

The resulting comparisons are given in Fig. 8 for two different histories, and the agreement is excellent.

CONCLUSIONS

- 1) Any effect of system velocity on the incipient wall superheat, for the conditions studied, is within the scatter of the data.
- 2) When previous history and noncondensable gases are properly accounted for, the reentrant cavity model provides a reliable estimate of the incipient wall superheat.