Incipient Pool Boiling of Sodium

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This paper presents some recent experimental results and theoretical predictions for the incipient boiling of sodium, with primary emphasis on superheating. We will also discuss measured pressure pulses associated with the initiation of boiling. The measured effects of pressure, heat flux, and the system pressure-temperature history upon nucleation are shown. Future work will be involved with the effects of dissolved gas content, surface characteristics, oxide (or other impurities) content, and reactor environment.

INCIPIENT BOILING MODEL

A model has been developed (*1*) which predicts the incipient boiling superheats in liquid metals by examining the pressure-temperature history of the system, and by employing the bubble equilibrium equation.

This model examines the various possible conditions of wetting and nonwetting of surface cavities. Because the convex liquid interface will always force the vapor pressure to be lower than the system pressure, cavities which are totally wetted fill with liquid and cannot serve as nucleation sites, while cavities which are entirely nonwetted are incapable of reaching any degree of superheating. Hence, the only cavities which may produce liquid superheat are those which are wetted at the entrance and nonwetted in the lower portion.

When a liquid does wet a surface, the liquid-vapor interface at this surface is convex. A force balance on this surface yields

$$P_L - P_V = \frac{2\sigma}{R} \tag{1}$$

As the temperature of the liquid metal increases and the portion of the surface cavity in contact with the liquid metal is being cleaned (by solution of impurities in the liquid), a change from nonwetting to wetting will occur. Hence, the liquid-vapor interface will change from convex to concave and the force balance now yields

$$P_V - P_L = \frac{2\sigma}{R} \tag{2}$$

The portion of the cavity below the cleaned portion remains nonwetted; hence the liquid is unable to penetrate further into the cavity without an increase in system pressure.

The procedure used to obtain the liquid superheat is to calculate a *minimum* value of R from Equation (1) with knowledge of the pressure-temperature history. The maximum system pressure must be known as well as the temperature at which it occurred. This R is then used in Equation (2) to calculate $(P_V - P_L)$ from which the incipient boiling superheats are found.

The incipient boiling superheats for sodium have been computed from this model and have been compared with measured values of liquid superheat published in the literature (*1*); it was found that favorable agreement did exist.

EXPERIMENTAL APPARATUS

To obtain data in a carefully controllel fashion a pool boiler was constructed, so that the validity of the superheat model could be determined, and liquid metal boiling more thoroughly understood.

An isometric drawing of the sodium superheat apparatus is shown in Figure 1. This consisted of sodium contained inside a 2-in. diameter vertical pipe and pressurized with an argon gas blanket. Heating wires wrapped around the outside pipe wall supplied heat to the sodium over a 4 in. length; cooling coils were employed to remove heat. The inside surface of the test vessel was polished to an 8μ in. finish with extreme care taken to avoid any weld material in the vicinity of the heated area.

Chromel-alumel thermocouples were placed in the liquid sodium, the test vessel wall, and the gas blanket. All temperatures discussed in this report are those measured by two thermocouples which were immersed in the liquid sodium. These thermocouples were located essentially on the pipe center line, at the bottom and top of the heated section, as approximately shown in Figure 1. The pressure in the gas blanket was measured with both a manometer and a pressure gauge, and the transients caused by boiling were measured with a piezoelectric pressure transducer in contact with the liquid sodium. No attempt was made to measure the oxide content in the sodium.

The thermocouple signals were recorded on continuous-writing, strip-chart recorders, and the pressure transients on an oscillograph and oscilloscope. The initiation of boiling was detected by several means: the acoustic vibrations caused by sudden vapor growth were detected by using an accelerometer; vaporization of the superheated sodium resulted in a sudden

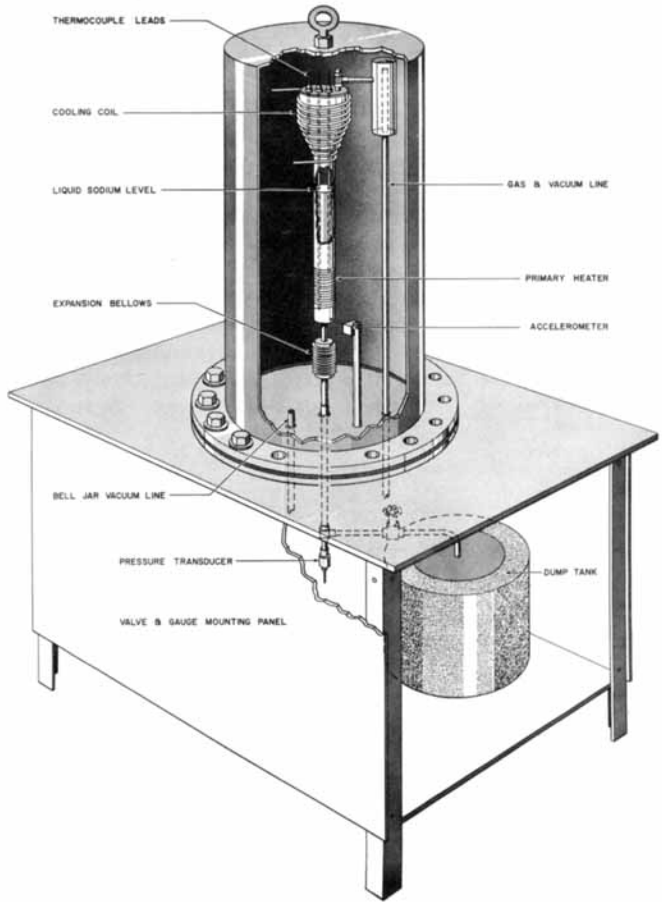

Fig. 1. Sodium superheat apparatus.

temperature drop in the liquid, which was measured by thermocouples immersed in the sodium; and vaporization invariably caused a pressure pulse which was recorded. The acoustic vibrations were found to be the most sensitive means to detect the instant of nucleation.

During a typical experiment, the following procedure was followed:

1. An initial steady state was achieved at some particular temperature (always at least 500°F. below the boiling point) with only the guard heaters used.
2. With all recorders operating, the primary heater was manually turned on, increasing the heat flux from essentially zero to a prescribed value in a single step and maintained at this value.
3. After the sodium nucleated, no changes were made to determine the steady state boiling conditions, or if the system was at an unstable condition (that is, repeated nucleations with significant periods of superheating), its fluctuating behavior was noted.
4. The system was then cooled, and the previous steps repeated.

The effects of system pressure, heat flux, and pressure-temperature history upon the incipient boiling superheats were investigated.

A single test vessel with a polished inside surface (average roughness of 8 μin.) was used for this work. Prior to being filled with sodium, the entire system was evacuated to 2×10^{-6} mm. Hg at 1,220°F. and liquid sodium at 600°F. was forced into the test vessel from the dump tank by using a slight pressure gradient. After the sodium level was adjusted to a prescribed height (measured by an X-ray flouroscope) and the system pressure was set to a fixed low value (with purified argon), a series of experiments was conducted varying only the heat flux. The pressure was then increased, and boiling initiated at various heat fluxes. This procedure was repeated up to pressures of 1.08 atm.

EXPERIMENTAL RESULTS

This paper reports the effects of the wall heat flux, system pressure, and pressure-temperature history upon the liquid superheat above the saturation necessary to initiate boiling in sodium.

Typical sodium temperature traces from a series of experiments in which only the heat flux was changed are shown in Figure 2. At the lowest heat fluxes, the boiling is quite unstable, with repeated periods of free convection superheating, sudden nucleation, and steady boiling. As the heat flux is increased, the boiling becomes quite stable; once the sodium nucleates, boiling continues indefinitely.

Figure 3 shows the effect of system pressure on the transient sodium temperatures. Quite unstable boiling is observed at low pressure, and becomes more stable as the pressure is increased. The pressure transients in the sodium are also illustrated in Figure 3. In all cases, considerable oscillation is noted, apparently due to alternate collapse and growth of vapor. The magnitudes of the pressure pulses show considerable scatter, varying from 10 to 180 lb./sq.in.abs. in duplicate runs. This behavior is quite

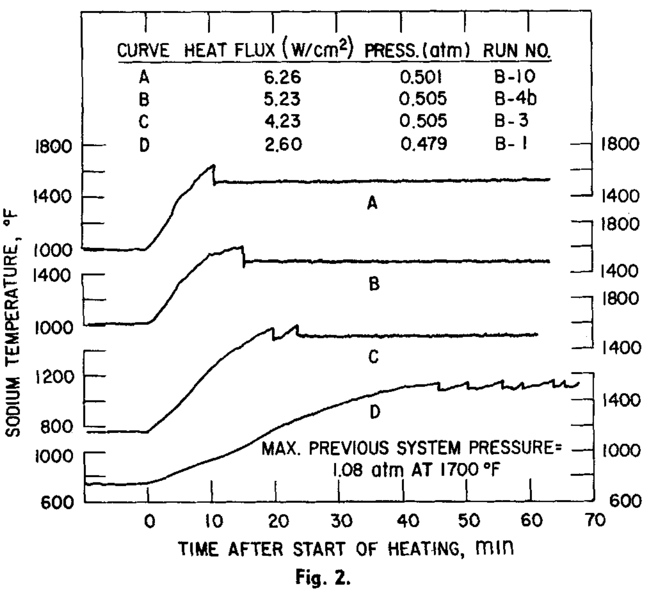

Fig. 2.

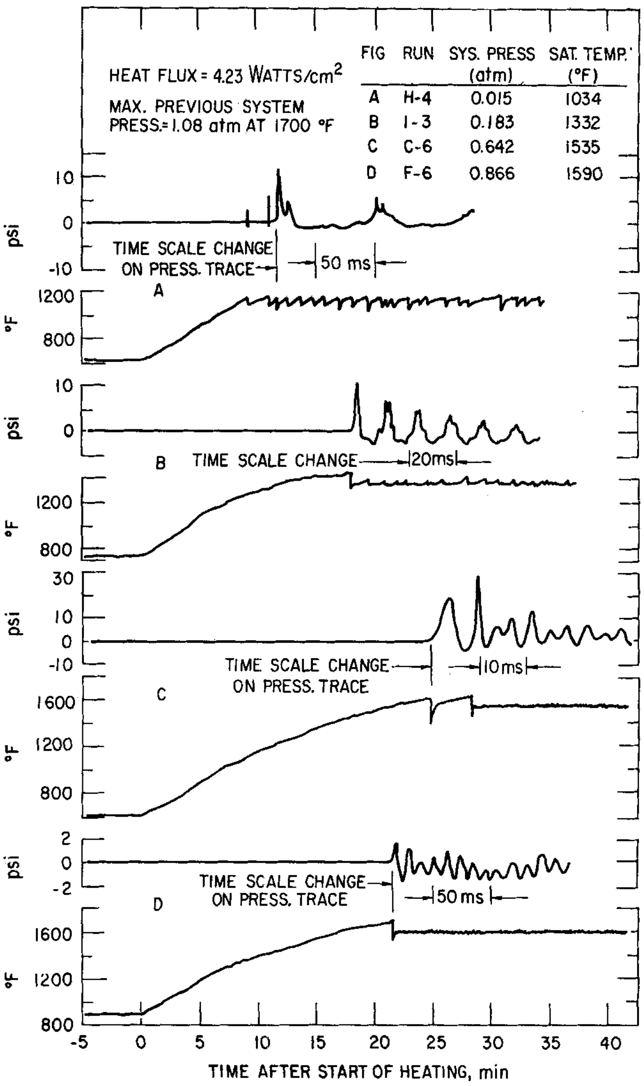

Fig. 3.

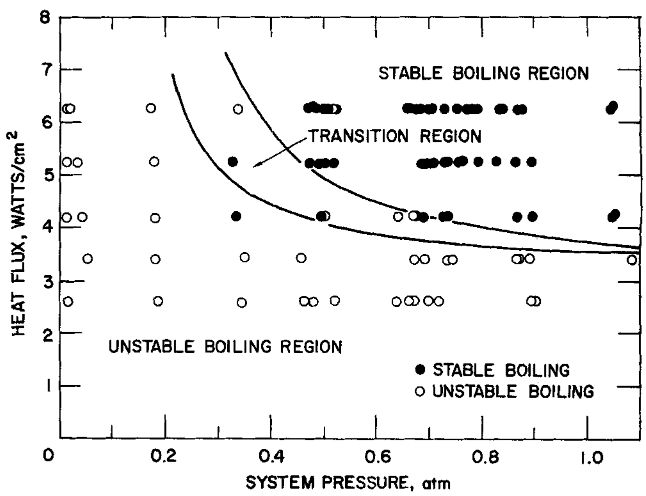

Fig. 4.

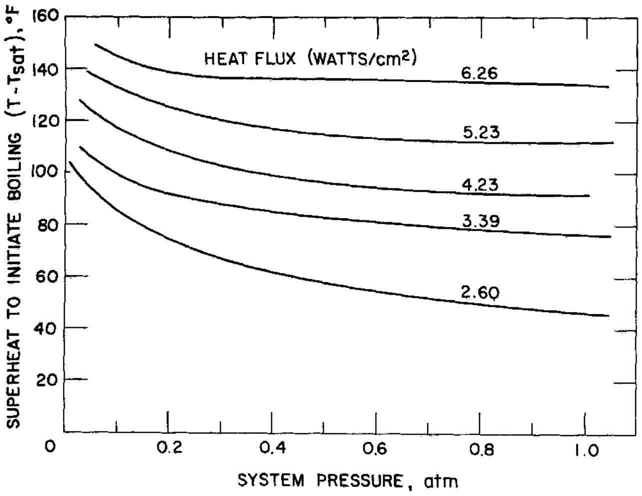

Fig. 5.

typical of that observed with water and other fluids as previously reported (*2, 3*).

From this discussion, it is apparent that sodium boiling is most unstable at low pressures and low heat fluxes (*4*), and becomes stable as these two quantities are increased. Figure 4 maps the region of stable and unstable boiling in the heat flux-pressure plane based on the present results.

The effect of pressure on the superheat to initiate boiling is summarized in Figure 5 for five different heat fluxes. As would be expected, the superheats decrease as the system pressure (or equivalently, the saturation temperature) is increased. It is observed, however, that the superheat increases markedly as the heat flux is increased. This effect was not accounted for in the present model, and the physical justification for this behavior is not quite clear. Since the reported temperatures were those measured directly in the sodium, such phenomena as wall scaling, etc., could not be responsible.

Other experiments have also indicated that the heat flux can strongly influence the incipient superheats. For example, the data of Petukhov et al. (*5*) indicate that the superheat can either be increased or decreased by changing the heat flux, the direction depending upon the system pressure. In addition, Pinchera et al. (*6*) have shown that the superheat decreases as the heat flux is increased, and Marto and Rohsenow's (*7*) data also indicate a heat flux effect.

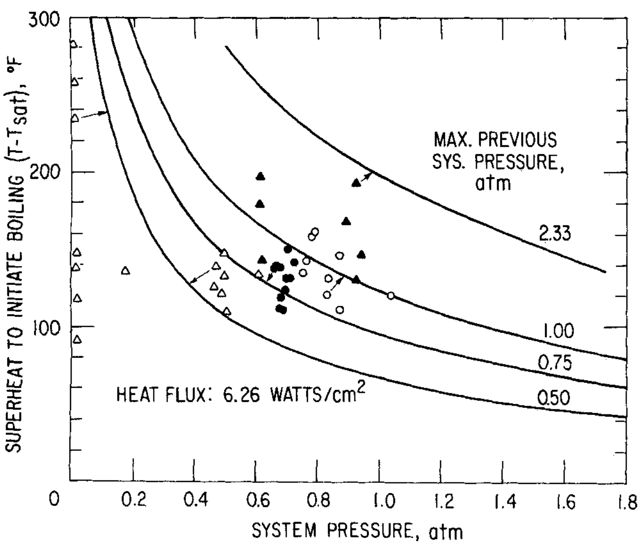

Fig. 6.

To illustrate the effect of pressure history on superheats, a series of experiments are summarized in Figure 6 in which the system was pressurized to a prescribed value by using purified argon and then the pressure was reduced to some low value before the heat flux was applied. The solid lines are those predicted by the theoretical model summarized here and more fully discussed elsewhere (*1*). As indicated, there is some agreement between theory and experiment; however, additional data is required before a general confirmation can be claimed. It is felt that the effect of pressure history may well account for some of the disagreement between data reported by various experimenters.

CONCLUSIONS

From the information obtained during this study, the following conclusions have been reached:

1. The pressure-temperature history definitely influences the degree of superheating required for incipient boiling in sodium. Some agreement exists between the incipient superheat model and the data obtained in this experiment.
2. The incipient boiling superheats are strongly dependent upon the heat flux, especially when the heat fluxes are small. The reason for this effect is not presently known.
3. At extremely low pressures and/or low heat fluxes unstable pool boiling occurs; however, stable pool boiling may be obtained by increasing either the system pressure or the heat flux.
4. The magnitudes of the pressure pulses at the initiation of and subsequent to boiling show considerable scatter and are unpredictable at this time.

ACKNOWLEDGMENT

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NOTATION

P_L = system pressure
P_V = vapor pressure
R = radius of curvature
T = temperature measured by thermocouple immersed in sodium
T_{Sat} = saturation temperature of sodium corresponding to system pressure
σ = surface tension

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