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ON SODIUM SUPERHEAT IN FLOWING SYSTEMS

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I. Introduction

Sodium superheat, i.e., the temperature differential above the nominal boiling temperature necessary to initiate boiling, is an important parameter in the design and safety analysis of sodium-cooled fast breeder reactors. Numerous experiments and analyses of this phenomenon have been motivated by this application over the past several years. However, most of the experimental work, and particularly that which tended to show large superheats, has been conducted in non-flowing systems (1, e.g.). Recent experiments in fact in flowing systems tend to show much smaller superheat requirements (2, e.g.). It is the purpose of this paper to investigate in preliminary fashion the possibility that large superheats are unlikely in flowing systems, such as would be encountered in real reactor loops, for several reasons. This result would follow of course if it can be shown that there will always be a sufficient quanity of sufficiently large gas nuclei ("microbubbles") to allow boiling to occur at moderate superheat.

II. Gas Nuclei Availability

The present author showed in a previous paper (3) that even though the solubility for inert gases such as argon and helium in sodium is quite small, that it is sufficient to fill an adequate gas nuclei population for nucleation at low superheat in an experiment involving a "vibratory horn", even at quite low sodium temperature, provided a mechanism exists for its normal dispersion in solution throughout the liquid. The sufficiency of the gas in solution in this regard becomes increasingly ample at higher temperatures, particularly above about 1000°F, since the solubility for an inert gas in sodium increases strongly with temperature.

In a completely static conventional heat transfer test, the required mechanism for gas concentration into the nuclei may not exist. However, there are various mechanisms which appear to be applicable to turbulent flowing systems. These involve primarily the pressure fluctuations which must exit in such systems.

Tests in static sodium in which the nucleating mechanism was pressure oscillation rather than temperature, i.e., the tests were made using an ultrasonic (vibratory) horn, were conducted in this laboratory to obtain some notion of the effect of frequency upon nucleation threshold (4). It was found in fact that this was quite insensitive to frequency below about 20 kHz, but became quite sensitive above that value. It was suggested at the time of the presentation of that paper, by M. S. Plesset (5), that perhaps results of this type were significantly influenced by "rectified gaseous diffusion" in the sodium under the influence of the high frequency pressure field. A later approximate analysis by the present author (3) showed that this might be the case for high temperatures, especially above 1000°F. Thus one can argue that in an oscillating pressure field, very large nucleation thresholds in sodium may not be possible, because of the induced diffusion of gas into a "microbubble" until it becomes large enough to cause observable nucleation under small "superheats", and this possibility will be investigated quantitatively later. If, in addition, the effect of a flowing sodium field is considered, the rate of input of inert gas into a microbubble, either moving with the stream or attached to a stationary object, is increased. In an engineering situation it is almost certain that the sodium flow will be turbulent. If the microbubble is stationary the sodium brought in contact with the bubble wall by the flow will always be nearly saturated with gas, so that the gas diffusion boundary layer will be very small compared to the case of a microbubble in a static field, even with large pressure oscillations as in ref. 4. If the microbubble is moving with the stream, its velocity is still probably somewhat different from that of the stream, i.e., positive or negative slip usually occurs depending upon whether the axial pressure gradient is negative or positive, so that there is still a substantial transport of gas to the microbubble boundary due to relative velocity between bubble and liquid as compared to the static case. Flow turbulence of course increases the rate of gas transport into the bubble (for either stationary or moving case) by reducing the diffusion boundary layer thickness and providing the pressure oscillations necessary for the rectified diffusion mechanism.

According to Maestrello (6), quoting Arndt and Daily (7), the upper bound for energy bearing eddies in a turbulent boundary layer is given by:

$$\frac{2\pi\delta f}{U} \lessapprox 1 \qquad (1)$$

where δ is the displacement thickness.

If one assumes a typical application which might occur in sodium-cooled reactors, a maximum velocity U = 30 ft/sec might be reasonable. In small passages such as exists through reactor cores, a minimum displacement thickness might be 1 mil. Substituting these values into eq. (1), we see that a maximum turbulence frequency of about 50 kHz is possible. Since the first-order relation to calculate the rate of gas diffusion into a bubble under conditions of pressure oscillations in the liquid is frequency independent (8, 3), the results of this writer's previous study on the importance of rectified diffusion for sodium in relation to an ultrasonic horn experiment are still pertinent to turbulence-induced pressure fluctuation. However, in the relationship for the rate of gaseous input to the microbubble, for a given ambient pressure, the magnitude of pressure oscillation comes in as the second power. It is hence necessary to estimate this pressure differential for the flowing sodium case.

According to the measurements of Daily, Lin and Broughton in a turbulent boundary layer (9, as quoted in ref. 7), the instantaneous reduction in pressure due to turbulence never exceeded 2 percent of the free stream dynamic pressure. Thus the "cavitation number" could only be affected by about 2 percent, which corresponds to a pressure oscillation of about 0.1 psi for sodium flowing at 30 ft/sec. Thus the pressure reduction itself is probably not a very significant effect for sodium boiling cases. This information can also be applied to determine whether the rectified diffusion mechanism could influence nucleation threshold in flowing sodium by comparing to the present writer's previous analysis of the vibratory horn case (3).

For the nucleation data in that case (3, 4) a pressure oscillation of the order of the ambient pressure occurred to cause nucleation (Table 6 of ref. 3). In the case of turbulent flow in a sodium-cooled reactor core, the turbulent pressure oscillation is the order of 1 percent or less of the ambient pressure. Since the pressure oscillation term appears squared in the relation for calculating bubble radius doubling time due to rectified diffusion, the doubling times for the turbulent sodium will be the order of 10^4 times those for the vibratory horn case. In the latter case, doubling times were the order of 10^2 sec, hence in the turbulent flow case the doubling time due to rectified diffusion would be the order of 10^6 sec. or 300 hours. Hence, it appears that this process could not be important in general unless much greater pressure fluctuations than those of turbulence are present. This is entirely possible, since pressure fluctuations, perhaps with frequency equal to that of the passage of a pump blade past a stationary object due to the normal operation of a centrifugal pump, can be of very substantial magnitude.

III. Conclusions

Several tentative conclusions are possible from this preliminary study.

1) Various apparently important influences exist which would cause nucleation to occur at lower superheats in flowing than in static systems. These concern increased diffusion rates of gas into microbubbles due to

relative velocity between bubble and liquid and to turbulence in the flowing systems. Quantitative evaluation of these effects has not been made, and would involve a very complex analysis.

2) Rectified diffusion, possibly important in our ultrasonic sodium nucleation tests provided the temperature is above the range of 1000°F, does not appear to be an important mechanism in the conventional reactor system if the only pressure fluctuation is that of the turbulence itself. However, this could be an important mechanism in promoting nucleation in such systems, if large pressure fluctuations such as might be provided by a centrifugal pump are present and the temperature is sufficient (probably greater than 1000°F).

IV. References

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