Boiling Burnout Heat Flux Measurements in a Non-Newtonian Suspension

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The flow and heat transfer behavior of non-Newtonian suspensions of thoria in water has been under study for several years at the Oak Ridge National Laboratory because of their potential application as the fertile nuclear material in breeder types of nuclear reactors. As part of this overall study a series of experiments was undertaken to determine the effect, if any, that the non-Newtonian nature of these slurries would have on the boiling burnout heat flux. A comparison was made between the experiment as carried out in water as a working fluid and as carried out in two representative thoria suspensions, the expectation being that any differences, especially those that would create problems in the design of breeder reactors, would become apparent during the experiments and that further work would then be done as necessary. The results of the study of boiling burnout of thoria slurries may also have application to other non-Newtonian slurries, for example in the food processing or plastics industry.

BACKGROUND

Mathematical analyses of possible mechanisms which may be responsible for the pool boiling burnout of Newtonian fluids have yielded several correlating expressions (*1*, *2*) for prediction of the saturation burnout heat flux and for the effect of subcooling. These expressions, when added to conventional nonboiling forced convection correlations, yield predicted burnout heat fluxes (*3*) which agree within satisfactory limits with nearly all of the applicable Newtonian data in the literature.

These correlations are restricted to Newtonian fluids, that is fluids whose viscosities are not functions of their hydrodynamic state. In order to predict the effect on the burnout heat flux of a non-Newtonian working fluid it is necessary to consider non-Newtonian flow behavior in relation to the mechanisms responsible for the burnout phenomenon.

DESCRIPTION OF THORIA SUSPENSIONS

The term non-Newtonian is too general to describe the nature of the slurries dealt with here. More specifically they are structured, shear-thinning, non-Newtonian fluids. The thoria particles, of the order of 1μ in diameter and of irregular shape, are suspended within the slurry and attract each other forming clumps of particles (flocs) or at higher concentrations a loose continuous structure. A consequence of the interparticle attractive force (van der Waals force) and of the resulting structure is the presence of a yield stress, which is the minimum shear stress necessary to maintain shearing of the fluid. When this shear stress is exceeded, flow will occur. The resulting shear rate is not proportional to the shear stress (the viscosity is not constant but decreases with increasing shear stress); hence the descriptive name shear thinning.

In the only previous investigation into the nucleate boiling behavior of a non-Newtonian fluid Thomas (*4*) reported four instances of burnout (one of physical burnout and three of transition to film boiling) of a platinum rod immersed in thoria slurries in saturated pool boiling. The heat flux at which burnout occurred averaged about half the value he obtained in water. Additionally the value of the wall superheat (ΔT_x) just prior to burnout averaged about 35°F. higher than that observed for water burnout. These effects he attributed to the build up of a loose, soft film of solids which he had observed during nucleate boiling. In order to verify and extend the utility of these results it is desirable to extend them to other slurry preparations and to a wider range of boiling conditions.

The slurries used for this series of experiments, designated S-I and S-II, were made from thoria powders by mixing with tap water or with deionized water. S-I was prepared from a thoria powder that had been calcined at 1,600°C. which resulted in particles with bulk densities of the order of 8 to 10 g./cc. The S-II slurry utilized a powder calcined at 650°C. containing porous particles with bulk densities of 4 to 6 g./cc. (*5*). Since the non-Newtonian behavior of a slurry is a function of the volume fraction of particles rather than the weight fraction, the concentration of S-I and S-II necessary to give the same non-Newtonian effect differ roughly by a factor of 2. Two concentration ranges of S-I were used, 1,650 to 2,000 g. thoria/liter and 800 to 1,000 g. thoria/liter. Data were taken with S-II in the range 850 to 1,000 g. thoria/liter, which because of the density difference between the two powders is comparable with S-I at its higher concentration.

The nature of the flow behavior of the thoria slurries can be displayed on shear diagrams (or plots of shear stress vs. shear rate in laminar flow). The slope of a line from the origin to the curve at a given shear stress is the viscosity for that shear stress, and the extrapolated shear stress intercept is the yield value.

A representative shear diagram for one of the suspensions used, obtained from capillary tube viscometry, is shown in Figure 1. Since the shear diagrams are functions of concentration and temperature, the curve shown cannot be used directly in estimating viscosity and yield stress for all of the experiments. However it is compared to a water shear diagram at the same temperature to enable the specific viscosity (ratio of isothermal slurry to water viscosity) at various shear stresses to be calculated.

ANTICIPATED EFFECT OF CONCENTRATION OF THORIA ON BURNOUT

The addition of thoria powder to water changes many of the physical properties in addition to viscosity, includ-

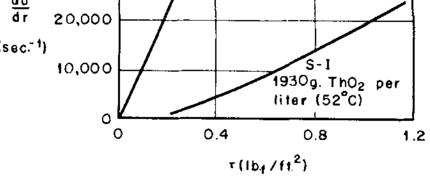

Fig. 1. Shear diagram of slurry compared with water.

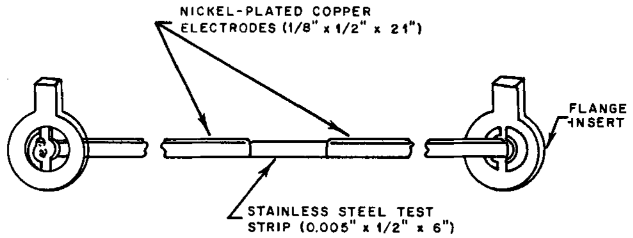

Fig. 2. Forced convection test strip and electrodes.

ing at least two that appear in pool boiling burnout correlations, density and heat capacity. Only the increase in suspension density is known to be significant however since the heat capacity per unit volume of a 2,000 g. thoria/liter suspension (which has a density 2.8 times that of water) is only 7% less than the water volumetric heat capacity. No measurements have been made of the vapor-liquid surface tension. However since calcined thoria is very insoluble, the surface tension along with the vapor density and the heat of vaporization were assumed to be independent of concentration of thoria. Thus the predicted effect of the addition of thoria, based on most burnout correlations (which do not include viscosity), would be an increase in the burnout heat flux both at saturation and with subcooling.

The effect of viscosity on the burnout heat flux is excluded from most burnout correlations due in part to the fact that the viscosity at the normal boiling point of nearly all Newtonian fluids is within 30% of 0.3 centipoise (*6*). Thus burnouts in fluids of sufficiently different viscosities have not been measured. When the fluid is shear thinning however, the viscosity at all temperatures will be large at low shear stresses. When the shear stress falls below the yield stress in fact, flow ceases (the viscosity becomes infinite).

The effect of a non-Newtonian suspension on the burnout heat flux is thought to depend on the relative magnitude of the shear stresses generated in the various processes involved in the removal of the heat from the boiling surface as compared to the slurry yield stress. As a hypothetical limit if the maximum shear stresses in the boiling process do not exceed the yield stress, the slurry would respond to the heated surface essentially as a solid and burnout would occur at very low fluxes. Since the yield stress increases with concentration, such a yield stress effect will occur for any shear-thinning suspension at sufficiently high concentrations.

Where the yield stress is lower than the maximum shear stress at the heated surface, regions may still exist elsewhere within the boiling fluid where local shear stresses will result in stagnation.

With forced convection the yield stress can cause an additional slight reduction in the nonboiling heat transfer coefficient in turbulent flow owing to the effectively larger viscosity.

An additional effect of forced convection is the generation of a shear stress at and near to the boiling surface. Depending on the relative magnitude of this shear stress as compared to those generated in the boiling process and as compared to the yield stress, stagnation regions which occur in pool boiling may not be present with forced convection. Thus forced convection of slurry may result in burnouts at fluxes higher than predicted from the additive method, which uses slurry pool boiling results.

EXPERIMENTAL

All the experiments used 0.005 in. thick type 304 stainless steel test strips cut to size from a single roll of stainless steel strip and brazed into position between copper electrodes. No pretreatment was used on the strips. The strips were resistance heated by one or more variable current d.c. arc welding machines whose outputs were connected in parallel. The voltage drop and the current flow through the test assembly were read from a potentiometer with appropriately sized precision shunts and dividing resistors. All burnout heat fluxes were for physical burnout of the test strip except in one pool boiling test in which stable film boiling occurred. Burnout was detected by the resulting open circuit as noted on a voltmeter installed in parallel with the potentiometer circuit. The procedure for the experiments was to gradually increase the power supplied to the test strip, waiting approximately 5 min. at each power level, until burnout occurred. The only exception to the procedure was for some of the low pressure forced convection experiments in which additional boiling heat transfer data were taken at well below burnout fluxes, so that the power was kept on the strip for longer periods.

Estimates of the strip average temperatures from the voltage and current readings at fluxes close to burnout were made for most of the pool boiling runs by reading the strip resistance at room temperature with a precision bridge and by using the resistivity vs. temperature curves for type 304 stainless steel (*7*). The strip wall temperature was then calculated from the mean temperature and the heat generation rate with an infinite slab model.

The accuracy of the experimental values of the burnout heat flux was limited by the measurement of the dimensions of the test strips. The strip thickness and width were assumed constant in calculating the heat flux, which introduced a minimum error of 3% in each of those dimensions. Since variation in heated length of the test strip could not be controlled as closely owing to the fillet of brazing metal at the electrodes, the measured length of each strip was included in the calculation of flux. This introduced a maximum measuring error of 1% for the length. Other estimated errors associated with the flux measurement were less than 1%.

The accuracy of the values of the wall temperature was lower since the resistivity of the strips varied only 6%/100°F. in the temperature range of interest. Because of a 1% random drifting of the amperage readings the uncertainty of the temperature measurement was of the order of ± 15°F. The bulk fluid temperature could be read to within 1°F. for low-pressure and 3°F. for high-pressure experiments.

FORCED CONVECTION EXPERIMENTS

For the forced convection experiments 6 × ½ × 0.005 in. test strips (Figure 2) were suspended axially within a 4 ft. long flanged test section fabricated of 1½ in. schedule 80 stainless steel pipe. Asbestos flange gaskets isolated the test strips from metal-to-metal contact with the test section barrel and loop proper. Measurements of the bypass resistance around the test strip with water in the test section showed resistances a factor of 200 greater than the strip resistance range of 0.0625 to 0.10 ohms.

The test section was mounted vertically in two existing experimental slurry loops, one capable of pressurization to 1,500 lb./sq. in. and one operating at atmospheric pressure. Flow

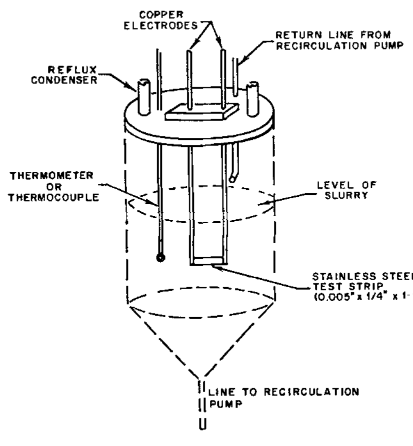

Fig. 3. Pool boiling experimental equipment.

TABLE 1. LOW PRESSURE FORCED CONVECTION BOILING BURNOUT IN WATER AND IN S-I SLURRY

Velocity (ft./sec.)	Pressure (lb./sq. in. abs.)	Subcooling (°F.)	Calculated nonboiling heat flux (water) (B.t.u./hr./sq. ft.) $\times 10^6$	Experimental burnout heat flux (B.t.u./hr./sq. ft.) $\times 10^6$	Concentration (g. ThO_2/liter)
2.0	17.1	95	0.1	1.0	0
2.75	16.6	94	0.1	0.91	0
11.7	25.1	125	0.5	1.82	0
2.0	17.9	116		0.73	950
3.1	19.2	101		0.98	1,035
6.8	22.9	100		1.2	1,140
3.1	24.5	121		0.72	1,700
3.25	29.6	124		0.61	2,030
8.2	28.3	120		0.67	1,930

Note: All burnouts occurred in upper (downstream) half of strips.

was upward in the low-pressure loop and downward in the high-pressure loop.

The low-pressure loop utilized a screw type of slurry pump driven by an electric motor through a variable speed drive. Flow rates were calculated from manometer readings of pressure drops across a calibrated venturi installed in the loop. The pressure at the test section was read with a pressure gauge. System temperature was obtained from a mercury thermometer located near the pump intake.

The high-pressure loop utilized a canned rotor centrifugal pump modified for slurry use. Flow rates were calculated from differential pressure cell readings of pressure drop across a calibrated venturi installed in the loop. Bulk system temperature and system pressure were obtained from a remote reading thermocouple and a remote reading pressure gauge installed in the loop.

POOL BOILING EXPERIMENTS

The pool boiling experiments utilized 1½ × ¼ × 0.005 in. test strips which were suspended horizontally on edge between vertical copper rod electrodes as shown in Figure 3. The electrode assembly was immersed in a conical bottom stainless steel beaker which had electrical heaters wrapped on the outside of the conical region. A small centrifugal pump permitted recirculation of the working fluid from a drain line at the bottom of the beaker to the top of the pool near the point of immersion of the electrodes. The superficial velocity of the fluid past the test strip was negligible. Two water-cooled glass reflux condensers were used to condense steam formed during the saturated pool boiling experiments. Pool temperature was read at the depth of the test strip but displaced 2 in. horizontally with either thermocouple and potentiometer or a mercury thermometer.

SUMMARY OF RESULTS

The first series of experiments utilized the low-pressure circulating loop. Three burnout tests were carried out with untreated tap water and three each with dilute and concentrated S-I slurry. The mean velocity was varied at each concentration with the subcooling held in the range 95° to 125°F. The experimental data are given in Table 1.

The second series of forced convection experiments were performed with the test section installed in the high-pressure circulating loop and with S-II slurry. These experiments were to determine the effect of pressure on the boiling burnout heat flux with mean velocity in the test section held constant at 15 ft./sec. and the subcooling ΔT maintained in the same range as in the low-pressure experiments.

Five high-pressure burnout experiments were conducted in the slurry, including one in which only an upper limit was established. The results appear in Table 2. Following these runs the loop was drained and filled with water. The resulting suspension was sufficiently dilute so that the flow properties were those of water. Three burnout experiments were carried out with successively more dilute fluids, as each run involved draining and refilling of the loop. The results are included in Table 2.

The atmospheric pool boiling burnout tests were conducted with the bulk fluid at temperatures ranging from the boiling point to 120°F. subcooling. Seven burnout tests were conducted with deionized water, including two tests with the bulk water at saturation temperature. Six burnouts were obtained in dilute S-I. For the high concentration of S-I eighteen burnout measurements were obtained including three at saturation temperature. The large number of tests were due to the erratic results noticed for subcooling less than 80°F. The results appear in Figure 4. Similar results were also obtained with S-II slurry.

Values of ΔT_x, the wall superheat, were obtained in the pool boiling experiments at fluxes close to burnout. The wall superheat in water was in the range 58° to 95°F., with the higher values associated with the highest burnout heat flux (greatest subcooling). The results for concen-

TABLE 2. HIGH PRESSURE FORCED CONVECTION BOILING BURNOUT IN WATER AND IN S-II SLURRY

Velocity (ft./sec.)	Pressure (lb./sq. in. abs.)	Subcooling (°F.)	Calculated nonboiling heat flux (water) (B.t.u./hr./sq. ft.) $\times 10^6$	Experimental burnout heat flux (B.t.u./hr./sq. ft.) $\times 10^6$	Concentration (g. ThO_2/liter)
15	230	131		2.6	977
15	340	122		2.5	910
15	530	127		2.3	965
15	1,025	169		<1.8	845
15	1,050	126		1.9	910
15	235	95	0.8	2.6	210
15	525	117	1.0	3.0	130
15	1,010	115	1.0	3.0	<100

Note: All burnouts occurred at upper (upstream) end of strips.

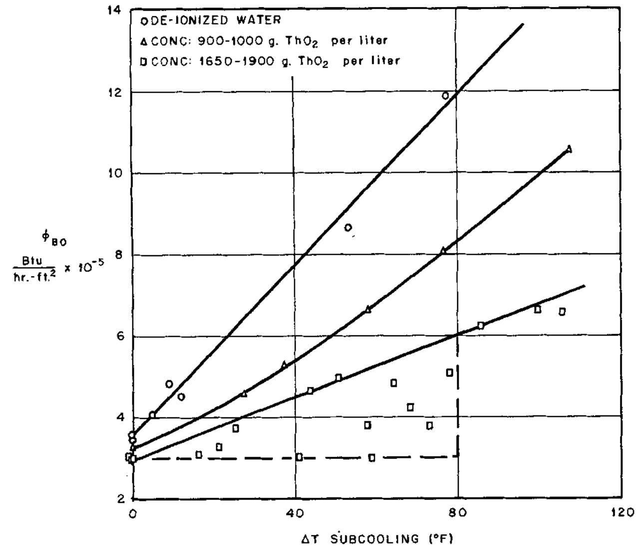

Fig. 4. Atmospheric pool boiling burnout test results in S-I slurry.

trated S-I slurry were in the range 27° to 71°F. with the scatter overshadowing any trends with flux. The fact that the superheat at burnout in slurry was not greater than in water is an indication that there was no build up of film on the strips of the type such as observed by Thomas (*4*), since this film manifested itself by an increased ΔT_x. Post burnout examination of the strips also did not show any film.

In addition to these results three burnouts occurred in concentrated S-I and one in S-II without the recirculating pump operating to maintain suspension homogeneity. This permitted the slurries to settle to higher concentrations than measured. Three of these tests were unintentional and were due to failure of the pump. The slurry settled in each of these instances for about 5 to 10 min. before burnout occurred. A fourth test, in which the pump was deliberately stopped for 30 min., resulted in stable film boiling. The results of these tests appear in Table 3.

DISCUSSION

A comparison of the slurry with the water results show that the presence of thoria either caused a decrease or did not affect the burnout heat flux in pool boiling and in forced convection. Thus it appears that in order to account for and to predict the burnout heat flux in non-Newtonian thoria suspensions the effects of the flow properties and in particular the yield stress, as discussed previously, must be considered. The data obtained in this series of experiments are insufficient to develop any correlations of the effects noted. However analysis of the results shows useful trends.

It should be noted that saturated pool boiling heat flux measurements in water show an inherent variability even under carefully controlled conditions (*8*). It is not possible to determine from the present data the effect of non-Newtonian properties on this variability, which is of the order of ± 10% of the saturated pool boiling burnout flux in water.

It is noted in Figure 4 that the percentage decrease in the burnout heat flux due to the slurry is proportional to the amount of subcooling of the bulk fluid. This suggests that the viscosity increase (due to the presence of a yield stress) is disturbing the flow of subcooled fluid to the heated surface. The wide scatter in the burnout heat flux for subcooled concentrated slurry (which never however falls below the saturated burnout heat flux) is a further indication of the disruption of this flow.

The low values of burnout heat flux, at times equal to the value with no subcooling, suggests that a stagnant pocket of saturated fluid envelopes the heated strip. Temperature fluctuations were observed in the bulk fluid under these conditions, further indicating the existence of these pockets of unsheared hot fluid.

The results (Table 3) obtained with no slurry recirculation are indicative of thickening of the slurry due to rapid settling.

The forced convection results (Tables 1 and 2) support the general observation that for the slurries considered here the burnout flux is decreased with increased slurry concentration.

TABLE 3. ATMOSPHERIC POOL BOILING BURNOUT RESULTS WITH RECIRCULATING PUMP NOT OPERATING

Slurry	Initial conc. (g. ThO_2/ liter)	Settling time (min.)	Burnout flux (B.t.u./hr./ sq. ft.)	Measured subcooling, °F.
S-I	1,850	Approx. 5	210,000	68
S-I	1,790	Approx. 5	143,000	46
S-I	1,770	30	91,000*	112
S-II	930	Approx. 5	227,000	90

* Stable film boiling.

CONCLUSIONS

Prediction and correlation of the boiling burnout heat flux in non-Newtonian suspensions cannot be accomplished with Newtonian correlations. The effect of the yield stress in increasing the low shear viscosity and in thus upsetting the flow patterns around the boiling surface must be taken into account.

The results of the present experiment indicate that a relatively mild non-Newtonian suspension will decrease the burnout heat flux below the value obtained in water. The decrease is proportional to the amount of subcooling, being small when the bulk fluid is at saturation temperature. The decrease in the burnout heat flux occurs with forced convection and at elevated temperatures.

NOTATION

ΔT_{sub} = subcooling ΔT, difference between saturation temperature and bulk fluid temperature, °F.
ΔT_x = superheat ΔT, difference between heated wall temperature and saturation temperature, °F.
$\frac{du}{dr}$ = local rate of shear
Φ_{Bo} = burnout heat flux, B.t.u./(hr.)(sq. ft.)
τ = local shear stress in fluid

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