EFFECT OF ADDITIVES ON THE CRITICAL HEAT FLUX IN NUCLEATE BOILING

by

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Effect of Additives on the Critical Heat Flux in Nucleate Boiling

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Abstract

This investigation was undertaken to determine if the critical heat flux to water could be increased by the addition of small percentages of an additive. The mixtures used primarily contained small percentages of 1-Pentanol, which was chosen because of substantial increases noted in pool-boiling. A few runs were made using Lakeseal (detergent) as the additive in saturated pool-boiling. These additives provided little change in the properties of water except for a significant decrease in the surface tension.

Results of the saturated pool-boiling tests show a substantial increase in the CHF with 1-Pentanol, and a slight decrease with Lakeseal. The tests also showed a greater burnout heat flux for dc as compared to ac and a slight increase when the bigger wire (.020in.) is compared to the smaller wire (.010in.). There is also some indication that 1-Pentanol may be more effective with ac than it is with dc.

Results of subcooled pool-boiling tests on horizontal tubes (.065 in. o.d.) show that the effect of 1-Pentanol is dependent on the subcooling. In most of the range investigated, 1-Pentanol decreased the CHF. At high subcooling it increased the CHF, and extrapolation indicates the same would be true at very low subcooling. However, any increases were not as great as those obtained in the previous section.

The forced convection results using horizontal tubes (.047 & .246 in. i.d.) show a dependence on subcooling similar to that obtained in subcooled pool-boiling. At high subcooling, using 1-Pentanol was beneficial. As the subcooling was decreased, the CHF became lower than that for pure water. However, there was not an increase at very low subcooling, as mentioned in the previous paragraph. The increases produced in this phase were not as great as might have been expected from saturated pool-boiling results.

The 1-Pentanol seemed to adversely affect the gaskets and seals in the heat transfer system and collect at different locations, creating operational difficulties.

Thesis Supervisor: Arthur E. Bergles

Title: Associate Professor of Mechanical Engineering

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NOMENCLATURE

Symbols

A	surface area
CHF	critical heat flux
D	diameter
G	mass velocity
h	enthalpy
L	heated length
P	pressure
q	heat transfer rate
V	velocity
$(q/A)_{BO}$	heat flux at burnout
$(h_s - h_b)$	difference between outlet enthalpy and saturation enthalpy ("outlet" refers to forced convection)

Subscripts

b	property evaluated at mixed mean condition
BO	burnout condition
in	inlet condition
s	saturation condition
o	outlet condition

I. INTRODUCTION

Boiling heat transfer is still not well understood even though this phenomenon has been of scientific interest since as early as 1756 when Leidenfrost erroneously explained the sputtering of water droplets on a hot plate as a repulsion between the solid and the liquid. The first scientific study of boiling heat transfer was not made until 1934[20*] in Japan when Nukiyama experimented with the saturated pool-boiling of an electrically heated platinum wire. He was able to obtain both the nucleate and film boiling regions of the heat flux vs. temperature curve, but was unable to get any points in the range between which is transition boiling. The heat flux at which the platinum wire jumped from nucleate boiling to film boiling was 260,000 Btu/hr ft^2 which may have been the first of many recorded burnout points.

Heat transfer with boiling yields heat transfer coefficients which are substantially higher than those obtained with nonboiling forced convection at moderate velocities. Boiling is the only practical method to remove the high heat transfer rates characteristic of such devices as nuclear reactors and plasmarc torches. It was these and other devices which accelerated the study of boiling heat transfer.

Rohsenow and Clark[33] determined experimentally that only a small percentage (c. 2%) of the heat transferred in boiling can be attributed to the heat of vaporization of the liquid. They then postulated that the major portion must be due to the turbulence

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* Numbers refer to bibliographical references.

caused by the formation and departure of the bubbles from the surface. The number of bubbles per second per unit area increases monotonically as the heat flux is increased. The critical heat flux, or burnout occurs when these bubbles coalesce to form an insulating vapor layer. After this point, the system will not again reach equilibrium with the same heat transfer rate as that at burnout until the surface is upwards of 2000 $^{\circ}$F. This may result in a melting of the surface and a break-down of the system.

According to Krieth[9], the entire range of heat flux from incipient boiling to the critical heat flux may only encompass a range of 60 F$^{\circ}$. Therefore, as long as less heat than that required for burnout is being transferred, the system will adjust itself to carry the load with little change in surface temperature. Thus any scheme which increases the critical heat flux, increases the heat that can be safely transferred by the same amount.

Various augmentative schemes to increase the critical heat flux have been proposed; they include: vibration, swirl flow, and using small percentages of an additive. The latter has certain advantages which makes it particularly desirable. Small percentages will allow retention of the desirable properties of the principal fluid, will probably not be costly, no expensive equipment is involved, and few adjustments would be necessary in existing systems.

Investigations of this scheme have been made with both forced and natural convection. The earliest investigation of the effect of additives on the critical heat flux of water appears to be that of Bonilla and Perry in 1939[34]. They worked with ethanol-water mixtures and obtained a maximum critical heat flux at 5 mol-percent ethanol. However, this maximum was only 8 percent greater than the burnout heat flux of pure water.

Van Stralen and associates [5,6,11,12] have run extensive saturated pool-boiling tests using binary liquids, mainly water-alcohol mixtures. They report that for every alcohol-water system tried, a critical heat flux higher than that for pure water was obtained. The maximum increase was obtained with 1.8 percent by weight 1-Pentanol which yielded a burnout heat flux 3.4 times that of pure water. However, in all cases the burnout flux was a function of concentration (see Fig. 5). They obtained similar effects at pressures other than atmospheric and with different types and diameters of wire. Runs were made with mixtures of two organic liquids, and results were obtained similar to those for the water mixtures.

The observation was made in all mixtures investigated that the smallest diameter bubbles occurred at the maximum critical heat flux. They also imply that smaller bubbles lead to higher frequencies of formation. Considering the report by Rohsenow and Clark[33], it would seem logical that these smaller bubbles would allow a greater heat flux before coalesence. The alcohols used by Van Stralen and co-workers greatly decreased the surface tension, which could partially account for the smaller bubbles. However, they feel that the smaller bubbles are due to the difference in the liquid-vapor equilibrium concentration for a binary mixture. This will allow bubbles to form with a boiling point elevated with respect to the bulk liquid. This elevation depends on equilibrium constants and concentration. If at a certain concentration, the elevation equals the superheat necessary for boiling, the bubble's growth will be determined by mass diffusion only. This bubble will be smaller than that of a pure liquid because the latter rises through the superheated liquid and grows to a greater size due to heat transfer.

Some of the additives investigated were not completely miscible with water. 1-Pentanol has a maximum miscibility of 2.36 wt. percent at 20 °C and decreases with increasing temperatures[30]. It would seem that when the miscibility limit is reached, the burnout heat flux shouldn't be affected by an increase in 1-pentanol. However, Van Stralen and associates report that immiscibility has no effect on the continuity of the burnout vs. concentration curve.

Carne[38] investigated the effect of geometry on the CHF of many of the organic liquids used in the previous study. He reports that both the wall thickness and diameter affect the CHF. When solid heater elements were used, as the diameter increased, the CHF varied but eventually reached an asymptotic value. However, for pure water the CHF is subasymptotic for small diameters, while the organic liquids approached the asymptote from above. When wall thickness was varied, asymptotic values were also obtained, but how they were approached depended on the outside diameter. With this knowledge, he ran burnout tests on the binary mixtures used by Van Stralen, et al. using tubes large enough so that asymptotic values would be obtained. For many of the systems he obtained no peak, but just a decreasing CHF with decreasing H_2O concentration. For some systems he did obtain a peak at about the same composition reported by Van Stralen, however they were much smaller. For instance, a peak was obtained with 1-pentanol which was only 30% higher than the CHF for pure water. Therefore, because Van Stralen, et al. used wires in the range of diameters where the critical heat fluxes of the alcohols were superasymptotic and that of the water was subasymptotic, he feels that their results were due to a flux depression at high water concentration and not an increase of flux with composition.

The Van Stralen data are in agreement with Huber and Hoehne[4] who investigated the pool-boiling on horizontal tubes of Benzene-Diphenyl mixtures and obtained large increases in burnout for small additions of Benezene to Diphenyl (100 percent increase for 6.3 wt. percent Benzene). They also noticed that for the pure liquid the bubbles were larger than for the mixture. They report a correlation by R. Pelham between the maximum burnout and the maximum concentration difference between the liquid and its equilibrium vapor of the more volatile component.

A report by Averin and Kruzhilin[31] on saturated pool-boiling of isoamyl alcohol-water mixtures on horizontal tubes at atmospheric pressure shows agreement with the Carne report. They investigated the effect of surface tension on the CHF. The highest percentage of alcohol investigated was 2.5 wt. percent. This decreased the surface tension 50 percent but did not appreciably affect the other properties. This percentage yielded an 18 percent decrease in CHF whereas Van Stralen, et al. always obtained an increase for the alcohols until the peak was reached.

Other researchers have tried to determine if surface tension is the important factor in increasing burnout. On the negative side of the issue is Westwater[36]. He reports that a 1 percent solution of Hyamine in methanol caused a 40 percent increase in burnout for pool-boiling but does not affect the surface tension or bubble contact angle. He speculates that the increase with additives might be due to the large organic molecules acting as sites for nucleation.

An experiment made by Jontz and Myers[27] lends weight to Westwater's speculation. Their experiment consisted of two phases. First they determined the effect of an addition of Aerosol-22 on the dynamic surface tension of water. This was done by comparing the size of bubbles blown by their apparatus in pure water, and in the solution, this closely approximated the boiling condition for surface tension measurements. They found it had no effect on the dynamic surface tension. However, when they boiled pure water and a water solution of 7.5 parts per ten thousand of Aerosol-22, the former had 30 active sites while the latter had 200 active sites for the same heat flux. This they felt could be explained by Westwater's hypothesis. They also ran the test for a Tergitol-water solution which did decrease the surface tension (from 72-38.5 dynes/cm) and obtained similar results.

Both Westwater and Jontz and Myers report an increase in the heat transfer coefficient when additives were used. This would seem logical because an increase in nucleation sites would mean an increase in turbulence and, therefore, a greater heat flux. However, it would also seem that if increasing the number of bubbles present at a given heat flux is the only effect, this would create a greater tendency for coalesence and a lower CHF.

Leppert, et al.[2] investigated forced convection subcooled boiling outside electrically heated tubes. Aqueous solutions of propanol and methanol were used with maximum concentrations of 1.5 wt. percent and 2.65 wt. percent, respectively. He reported much smaller bubble size for the binary mixture, but obtained little effect on the burnout heat flux.

Bergles[1] investigated forced convection surface boiling in tubes. He used 1.8 percent by weight 1-Pentanol which had yielded the highest increase for Van Stralen, et al. He generally found a decrease in the CHF, but the decrease was dependent on subcooling. He felt that the smaller bubbles yielded a smaller percentage of nonequilibrium vapor in the tube which in turn meant that the liquid phase of the flow would have a lower velocity than the liquid phase of pure water for the same flow rate. This lower velocity would then reduce the critical heat flux.

Ellion[32] experimented with a 1 percent solution of Aerosol in water. This decreased the surface tension from 72 to 34 dynes/cm, yet did not greatly effect the other properties. The tests dealt with pool-boiling on a metal strip. He found that at high subcooling, the burnout was 50 percent that of pure water. But as the subcooling decreased, the effect decreased, and at saturation conditions, the CHF was the same as for pure water.

In review it can be said that the pool-boiling results with volatile additives look promising, but the forced convection data is less encouraging.

The main purpose of the present investigation is to determine the effect of using a volatile additive such as Van Stralen, et al. used with tubes larger than those used by Bergles. It is felt that larger tubes might diminish the void fraction effect mentioned by Bergles and lead the way for the phenomenon encountered by Van Stralen, et al. to assume enough significance to actually increase the CHF. This investigation had two other objectives. The experiments of Van Stralen, et al. were to be duplicated and clarified by an extension into subcooled pool-boiling. The second was prompted by a report by Szetela[37]. He obtained a lower CHF with ac than with dc in pool-boiling and attributed this to the fact that with ac the peak heat flux is greater than the average heat flux. It was felt that the additives would create smoother boiling and lessen the variation of surface temperature when ac is used. This would mean that the CHF for ac heating would increase relative to dc heating.

II. APPARATUS

A) Subcooled Pool and Forced Convection

All of the tests except those concerned with saturated pool-boiling were made on the equipment shown in Fig. 1 (referred to as "the loop"). It is the Heat Transfer Lab low-pressure system and had been previously designed and constructed by Bergles and Rohsenow for the investigation of boiling heat transfer phenomenon[35]. The system consists of a filler tank, pump, accumulator, filters, demineralizer, preheaters, heat exchanger, test section, bypass loop, power supply, degassing tank, and necessary gages, instruments, and piping.

The stainless-steel filler tank was used, as its name implies, to fill the loop. However, it also served as a reserve to replace any fluid lost during normal operation or when a burnout occurred. When a test was in progress, the tank was open to the atmosphere.

A Fairbanks Morse two-stage regenerative pump was used to provide circulation. It is driven by a 3 hp Allis Chalmers induction motor and provides 3.6 gpm at a discharge pressure of 260 psi. To prevent contamination of the system, the pump seals were made of asbestos and teflon.

The Greer accumulator was installed to damp out pressure fluctuations coming from the pump. It has a capacity of 2.5 gal. and is pressurized with nitrogen.

Filtering of the loop is accomplished through the use of Fulflo filters. One was installed in the city water line to keep impurities from the heat exchanger; the other, installed at the pump entrance, served to entrain any impurities that might have entered the loop due to construction of the system and test sections. The Barnstead demineralizers were installed with the alcohol-water mixtures in mind. They were chosen because of their lack of crevices where the alcohol would concentrate. Two double chambers (four chambers in all) were installed which could accommodate 5 to 50 gph with a maximum pressure of 50 psi. The cartridges used were of the mixed resin type. The small amount of alcohol used should affect neither the filter nor the demineralizer.

The preheaters allowed regulation of the subcooling. They are essentially Chromalax immersion heaters in large tubes through which the liquid passed on its way to the test section. The preheater used at the beginning of the investigation was capable of developing 5 kw. However, this proved insufficient for the large flow rates and an 18 kw heater was added. Variacs and switches are used to regulate the power to the preheaters.

The counterflow heat exchanger was designed to dissipate 50 kw. It consists of a series of concentric tubes--the inner ones containing the system water, while city water flowed through the annuli. Except at high power input, the preheater inlet temperature was independent of the power supplied to the test section.

The bypass loop, which is in parallel with the test section loop, has as its main function the adjustment of the pressure in the test section. It consists of brass piping and a Jamesbury ball valve which regulates the system pressure drop.

Power is supplied by two dc 12-volt, 36-kw Chandeysson externally excited generators driven by 440 volt, 3-phase, 660 R.P.M. synchronous motors. The outputs are connected in series, and by adding or subtracting the output of one generator to that of the other, a range of 0-24 volts is possible. Regulation of the voltage is accomplished by means of a set of coarse and fine potentiometers.

The stainless steel degassing tank has a capacity of 4.7 gal and contains heaters with a total output of 12 kw. When alcohol-water mixtures were being investigated, the degassing tank was not used because this would result in a loss of alcohol. Instead, the liquid in the loop would be circulated for a few hours before starting the runs and the entrained air vented to the atmosphere. When pure water was used, the filler tank was not in the system, and the degassing tank was used as a reserve as well as to degas the system.

When higher degrees of subcooling than that obtained with the heat exchanger were desired, a precooler was used. This was put right before the test section and was effective in the pool-boiling tests and for the low velocities of the smaller tubes. It consisted of a copper cooling coil immersed in a watered mixture containing Halite rock salt and ice. A stirrer from an oxygen bomb calorimeter was used to improve the cooling.

All pipes and fittings were made of either stainless-steel or copper-brass alloys except where flexibility was important; in these places Imperial rayon-rubber hose was used. Fittings other than ordinary pipe fittings were either of three types: Imperial, Conax, or Swagelock.

The electrical power to the test section was the quantity used in calculating the heat flux. Voltage was read directly on a Weston multirange dc voltmeter, while a shunt was used to determine the current, the potential across which was recorded on a Minneapolis-Honeywell Brown recorder. By means of a selector switch, voltages from 0-26 millivolts could be recorded which corresponded to a maximum of 1560 amps. When this was exceeded, a Wilson Maulen millivolt meter with ranges of 0-30 and 0-60 was used.

A check on the power was made with a heat balance on the fluid flow through the test section. The flow rate was read from a Fischer-Porter flowrator. By changing the tube and float, a range of flows from 10 lbm/hr to the maximum output of the pump (2500 + lbm/hr) could be accommodated. Inlet and outlet temperatures were determined using thermocouples made from Leeds and Northrup 30-gage duplex, copper constantan wire. These were connected to a 12-position Leeds and Northrup selector switch which in turn is connected to an ice-bath and the millivolt recorder.

Helicoid test gages with an accuracy of .25 percent of full scale were used for all pressure measurements except upstream of the needle valve, in which case a Supergage was used. To avoid compressible volume effects due to the gages, the test section pressure tap holes were made as small as practical. For later forced convection tests, a valve was installed before the upstream pressure hose and was closed when burnout was approached. This had little effect on the results.

Two different types of test sections were used with the previously described apparatus. The type used for forced convection burnout is shown in Fig. 2, and those used for subcooled pool-boiling is shown in Fig. 3.

The former were stainless-steel tubes of varying geometry which were soldered to a brass cap on one end and a brass ring near the other end. These served as connections to the bus bars and the power supply. The distance between the ring and the end of the tube served as a calming length having an L/D ranging from 9-20, depending on the tube diameter. The 20-turn needle valve directly upstream served to isolate the test section from any compressible volume effects of the loop. The exterior of the tube was insulated with fiberglas to prevent loss of heat to the air. Two sizes of tubes were investigated: 0.047-in. i.d. with 0.065-in. o.d. and 0.246-in. i.d. with

0.314-in. o.d.

Figure 3 presents the apparatus used for subcooled pool-boiling. It had been constructed for a previous study, and only slight modifications were necessary. The diagram shows besides the test section, the container in which the pool-boiling took place. It is a fabricated brass box having walls 3/16-inch thick to accommodate high pressures. A glass window had been installed to permit viewing of the test section. With a very low flow, it was possible to get a large range of subcooling by making use of the preheater. The velocity was so low that its effect on the burnout flux was assumed negligible. The liquid entered at the top, but exited at both the top and bottom. The purpose of the upper exit was to prevent stratification of the mixture. The bottom exit provided better mixing and created a flow that was opposed by natural convection. The test section itself is a stainless-steel tube (0.047-in. i.d. and 0.065-in. o.d.) soldered to rectangular brass connectors. These in turn are attached to the bus bars which came in through the top of the container.

B) Saturated Pool-Boiling

The apparatus used for this phase of the investigation is shown in Fig. 4. It is merely a Pyrex glass beaker with a copper sheet on top of it to retard evaporation. Copper leads going through the plate bring power to the wire attached to these leads. The spring mechanism shown kept the test section wire in tension. With 1-Pentanol-water mixtures, the equilibrium vapor composition is different than that of the liquid, and, therefore, the composition of the liquid in the beaker would not remain constant as boiling proceeded. Thus, the quantitative effect of composition on CHF could not be obtained with this apparatus. However, it could show qualitatively the effect of 1-pentanol on the burnout heat flux. Using the subcooled pool-boiling apparatus, it was possible to get close to saturation and avoid the problem of a varying composition. However, the saturated pool-boiling apparatus was used for the first tests as it was easier and more convenient to use than the rig for subcooled pool-boiling. Also, the first interest was in only qualitatively reproducing the results of Van Stralen, et al. for saturation conditions, which the above-described apparatus could do.

The test sections were lengths of Chromel 30-A and 24-A wire. Tests were run with both ac and dc. The former came directly from a 115-volt line and was regulated by a variac. A transformer was added when higher current was needed to burn out the larger wire. Direct-current power came from the motor generators.

Before taking data, the relationship between the mixture composition and surface tension was experimentally determined (Fig. 6). This result was then used for determining the percentage of 1-pentanol in any mixture. A Cenco-du Nuoy interfacial tensiometer was used for these measurements.

III OPERATING PROCEDURE

In all cases, before each run the test section used would be thoroughly cleaned with acetone. When saturated pool-boiling data were taken, the liquid would first be heated to its saturation temperature (atm. pressure). The test section power would then be increased while recording data at established voltage intervals (usually 1/2 v). This would be continued until the wire ruptured or went into stable film boiling indicated by a glowing of the wire which would be considered the CHF. While increasing the power, the potential was continually observed so the burnout voltage would be known. The rest of the variables were then calculated from data taken during the approach to burnout.

When alcohol-water mixtures were used, the problem of changing alcohol content was present, as previously mentioned. The mixture would start at, say, 4 percent by volume of 1-Pentanol and might end up as low as 1 percent. It should be realized that if the wire did not rupture, a run might have contained many burnouts. It was felt that if enough points were taken, any effect such as that indicated by the data of Van Stralen, et al. would show itself in some of the burnout points, as was the case.

The procedure for subcooled pool-boiling was the same as above with the addition that the amount of subcooling was set at the beginning of the run by adjusting the preheater. With forced convection data, the flow rate inlet temperature, and exit pressure was set at the beginning of the run, and the heat flux was slowly increased to burnout. Care was taken to obtain a large pressure drop across the needle valve preceding the test section so as to insure system stability. Burnout for these tests was defined by tube rupture.

IV OPERATIONAL NOTES

There were certain problems involved in the use of 1-Pentanol that seem worth mentioning. The main problem was that the alcohol seemed to aggrivate any leaks in the system. After operating with the alcohol for a while, the pump seals seem to have deteriorated. Some rubber gaskets also seem to have been affected. Pipe joint compound tended to dissolve in the mixture especially in fittings where the alcohol collected. The alcohol either leaked out faster than the water or collected in substantial amounts in the fittings. The stainless filler tank was filled with 2.6% by wt. of 1-Pentanol while the test section always contained 2.2%. Since degassing in the normal manner was not possible, heat transfer results would be difficult to obtain. Perhaps most annoying to the operator, the 1-Pentanol has an irritating if not slightly toxic odor

One problem not connected with alcohol was due to the brass tee located downstream of the needle valve. Tests run by R. Daleas indicated that air might have been caught in the tee and have caused premature burnouts in two of the runs (Fig. 11, pure water at 65psia and Fig. 9, 1-Pentanol at 20 ft./sec.) due to a compressible volume effect. Subsequent runs made with the tee removed did not bear this out however, it would seem good practice to either make certain that no air is trapped or to put the thermocouple upstream of the needle valve thus eliminating the need for a tee.

V RESULTS

A) Saturated Pool-Boiling

A total of 52 burnout points were taken with the saturated pool-boiling apparatus. The results are summarized in Table I. For the wires used, considerable increases were obtained in the critical heat flux for small additions of alcohol. This increase is supported by the observation that the wires did not rupture with pure water, but frequently did when alcohol was added. This is in agreement with Van Stralen and co-workers; their increases were greater than those reported here, but they had considerable scatter.

The increases obtained with ac were greater than those obtained with dc. This may mean that additives are more effective with the former; however, the experimental procedure leaves some doubt as to whether this can be considered a definite conclusion. There was an increase of about 35% in the burnout flux with pure water when dc was used as opposed to ac. This corroborates the qualitative results of Szetela[37], but he estimated a ratio of 2:1 for dc vs. ac from his data. This discrepancy may be due to the difference in thermal properties of the metals used. He used Nichrome wire (0.010 in.) while Chromel A was used in this investigation.

For pure water, there was a slight increase in the critical heat flux when the larger diameter was used. This is in agreement with other authors (5,38).

The runs made with Lakeseal were done with the express purpose of determining the effect of surface tension on the critical heat flux.

Lakeseal decreased the surface tension of water from 72 to 28 dynes/cm at 78°F, while it presumably affected the other properties very little. 1-Pentanol also lowered the surface tension of water; but when used with the saturated pool-boiling apparatus, the concentration and thus the surface tension would continually change. With Lakeseal, the surface tension had the same value after the run as it did before the run. A slight decrease in the CHF was obtained and this agrees with Ellion[32] and roughly agrees with Averin and Kruzhilin[31] who obtained a variation of the critical heat flux with the 1/4 power of the surface tension.

There are certain problems that arise when dealing with surface tension that are best discussed now. It is, of course, a surface phenomenon which, in the case of alcohol-water mixtures, results in an excess of alcohol at the surface. When a new surface is formed, a migration and orientation of alcohol molecules is necessary. This requires a finite amount of time and therefore a new surface will have a surface tension which is a function of time. In order for the equilibrium surface tension to be important in boiling, it must be reached in time to significantly affect the bubble while it is still near the heat transfer surface. Bond and Puls[16] investigated this phenomenon in alcohol-water mixtures. They report that for a 1.6 wt.% solution of amyl alcohol in water, the half-way mark was reached in 5×10^{-4} sec., and it had gone 96% of the way towards its equilibrium surface tension in 5×10^{-3} sec. Halfway times for the water mixtures of the other alcohols investigated ranged from 2×10^{-4} to 1.1×10^{-2} sec. A typical bubble formation frequency in saturated pool-boiling might be 0.01[22] sec., which means that for 1-Pentanol (n-amyl alcohol), the equilibrium surface tension might exist for a significant time while the bubble is on the surface. However, this is not so in forced convection as will be discussed later. Consideration of this and the result that Lakeseal did not increase the CHF, would favor Van Stralen's explanation for the increases he obtained rather than a surface tension explanation.

B) Subcooled Pool-Boiling

The results of the subcooled pool-boiling experiments are shown in Fig. 7. The saturation temperature of the alcohol-water mixture was considered to be 5F° below that of water. This number was chosen for several reasons. When running forced convection tests at 15psig, the mixture seemed to reach saturation at 245°F which is 5 less than that of pure water. When working with saturated pool-boiling at atmospheric pressure, the mixture would boil at about 206°F. At first this seemed unusual because the azeotropic mixture (46 wt.% of 1-Pentanol) has a boiling point of 205°F; however, data shown in Table II for isoamyl alcohol-water mixtures shows this type of behavior (small percentages having a strong effect on the boiling point with an extreme leveling at higher percentages) is not unusual, therefore, a decrease of 5F° seemed reasonable.

Figure 7 shows that the degree of subcooling affects the behavior of additives. One might expect the water-1-Pentanol curve to be a straight line, however this was not the case, though it may straighten out at higher subcooling. The pure water curve appears to cross the mixture curve at both high and low subcooling. This means that 1-Pentanol produces desirable results only in certain ranges of subcooling. The intersection of the curves at low subcooling allows for rather interesting speculation. Carne[38] with a different size tube than used here obtained about a 30% increase in CHF in saturated pool-boiling with the same percentage of 1-Pentanol as used in this report. It is possible that his increase as well as the large increase obtained by Van Stralen et al. are limited to a small range of subcooling close to saturation conditions. This would fit in with the latter's explanation, because as the subcooling increases, the small elevation in temperature due to composition difference between the vapor and the liquid would become insignificant. It would also seem that because subcooling affects the additive effect, the speculation mentioned by Westwater dealing with large molecules acting as sites for nucleation would be invalidated.

Extrapolation of the 1-Pentanol curve to saturation conditions does not yield the same increase as that obtained with the wires in saturated pool-boiling. This indicates a geometry affect on the behavior of additives which is in agreement with Carne[38].

The explanation of the behavior of 1-Pentanol is further complicated by other observations. Between 95 and 180°F the 1-Pentanol mixture investigated appears to be an emulsion made manifest by the solution becoming very hazy in this range. This observation was made in all three portions of this investigation and was completely reproducible. It was observed through the Pyrex beaker, the glass window in the subcooled pool-boiling apparatus, and the flowrator used for forced convection when the loop temperature was sufficiently high. It is suggested this may affect the burnout results and partially explain why the subcooled boiling curve is not linear.

C) Forced Convection

The results of the forced convection experiments are shown in Fig's. 8,9, and 11. These are the least encouraging, though they are the most important from a practical standpoint. Fig. 8 presents the results for the largest tubes used. The addition of 1-Pentanol proved beneficial only at high subcooling and even under these conditions the increases were not substantial. At low subcooling the decrease is significant, especially with a velocity of 20 ft/sec. An important result obtained with these tubes, but not with the smaller ones, is that the addition of 1-Pentanol has increased the amount of scatter in the burnout data especially for the higher velocity. This scatter wipes out the small advantage at high subcooling that the mixture has over pure water.

The data for the smallest tubes are shown in Fig. 9. These resulted in essentially the same type of curves as did the large tubes, but without the scatter. Again there is a crossover, with the alcohol being advantageous only at higher subcooling. This is in agreement with the result of Bergles, Fig. 10, who used an intermediate sized tube. The experiments summarized by Fig. 11 were run to determine if increasing the pressure had any effect on the 1-Pentanol mixture or its comparison to water. Data for both the 1-Pentanol mixture and pure water at 30 and 65psia are presented. The pressure had little effect on the mixture or pure water. Crossovers are again obtained, except that at the higher pressure, the 1-Pentanol did not decrease the CHF at low subcooling as it did at lower pressures. This would lead to the speculation that 1-Pentanol might be advantageous at pressures higher than those reported here. Higher pressures were not tried because of limitations of the system.

The forced convection results are not very encouraging; however, this might have been expected since the subcooled pool-boiling results were not too favorable.

If the results at high subcooling are interpreted as a merging of the two curves instead of a cross-over, a possible explanation using the void fraction effect mentioned by Bergles can be given. Gunther[25] reports that bubble lifetimes in forced convection are in the order of magnitude of 6×10^{-4} sec. Accepting the data of Bond and Puls[16], this lifetime is not long enough for the surface tension of the 1-Pentanol solution to reach its equilibrium value. However, it would be logical to assume that during its lifetime, a vapor bubble in a 1-Pentanol solution would have a lower surface tension than that in a pure water solution. This would encourage smaller bubbles in the 1-Pentanol solution which would mean a lower void fraction and a lower burnout. Gunther also reports that increasing the velocity and increasing the subcooling decreases the bubble lifetime. Therefore, as the subcooling is increased, the difference between the average surface tension of the 1-Pentanol bubble and that of the water bubble may decrease. The point where they merge (or crossover) would be where the velocity and subcooling are the dominant parameters in determining the bubble characteristics and the surface tension difference is only of minor importance. However, whether there is a crossover or a merging of the curves will have to be determined by further experiments.

VI SUMMARY

Any investigation into the effect of additives on burnout should not be limited to saturated pool-boiling because this may not be representative of the general behavior. If surface tension is used in any correlation or explanation of burnout, consideration of its time dependence should be made.

Geometry and type of power affect the burnout heat flux and the behavior of additives in saturated pool-boiling. Direct-current yielded a higher CHF than alternating-current. Additions of 1-Pentanol showed substantial increases with both types of power, but it seemed to be more effective with ac than it was with dc. However, additions of Lakeseal did not increase the CHF, which means the increase obtained with the alcohol was not solely a surface tension effect.

Greater increases in the CHF with additions of 1-Pentanol were obtained with the wires in saturated pool-boiling than would be indicated by extrapolation of the curve obtained from subcooled pool-boiling on the tubes. This would indicate a geometry effect on the behavior of additives.

The bigger wires used in saturated pool-boiling burned out at a slightly higher heat flux than did the smaller wires.

Subcooling is an important variable in both pool-boiling and forced convection. While varying this, additives produced both increases and decreases in the CHF. With subcooled pool-boiling, the increase occurred at high subcooling and probably would have occurred at low subcooling. With forced convection, the increases obtained were at high subcooling. The decreases obtained were substantial, while the increases were not. It is not certain if the latter were crossovers of the 1-Pentanol-water and pure water curves or just an indication that they would merge at a higher subcooling than investigated here.

There is some indication that 1-Pentanol may be advantageous in forced convection with higher pressures than those investigated here.

Operational difficulties were caused because the 1-Pentanol would collect in cavities and attack some of the seals and gaskets in the system. Inert seals should be used in further investigations.

The most promise for 1-Pentanol as an additive seems to be at high pressures and high subcooling. It is recommended that these areas be further investigated.

Results

Chromel 30A wire (0.010 in.)

ac

Pure water - avg. ≃ 2.68, range ≃ 2.55-2.75 $(q/A) X 10^{-5} \text{Btu/hr Ft}^2$

1-Pentanol mixture - maximum ≃ 5.72, avg. ≃ 4.22

Lakeseal mixture - avg. ≃ 2.54, range ≃ 2.03-2.99

dc

Pure water - avg. ≃ 3.51, range ≃ 3.17-3.74

1-Pentanol mixture - maximum ≃ 5.95, avg. ≃ 3.97

Chromel 24A (0.020 in.)

ac

Pure water - avg. ≃ 2.79, range ≃ 2.12-3.26

1-Pentanol mixture - maximum ≃ 5.80, avg. ≃ 5.66

dc

Pure water - avg. ≃ 4.12, range ≃ 4.06-4.205

1-Pentanol mixture - maximum ≃ 5.60, avg. ≃ 5.16

Comparisons

Ratio of CHF for 24A vs. 30A

ac - 1.04
dc - 1.17

Ratio of CHF for dc vs. ac

30A - 1.31
24A - 1.475

Maximum CHF ratios for 1-Pentanol mixtures vs. pure water.

30A wire

ac 2.15
dc 1.69

24A wire

ac 2.08
dc 1.36

TABLE II

BOILING POINT OF WATER-ISOAMYL ALCOHOL MIXTURES[14]

(760 mm)

Wt. % of alcohol	Boiling point °C
0.0	100.0
3.0	95.5
50.0	94.50
60.0	94.50
89.50	101.00
95.00	114.50
97.00	118.00
100.0	129.50

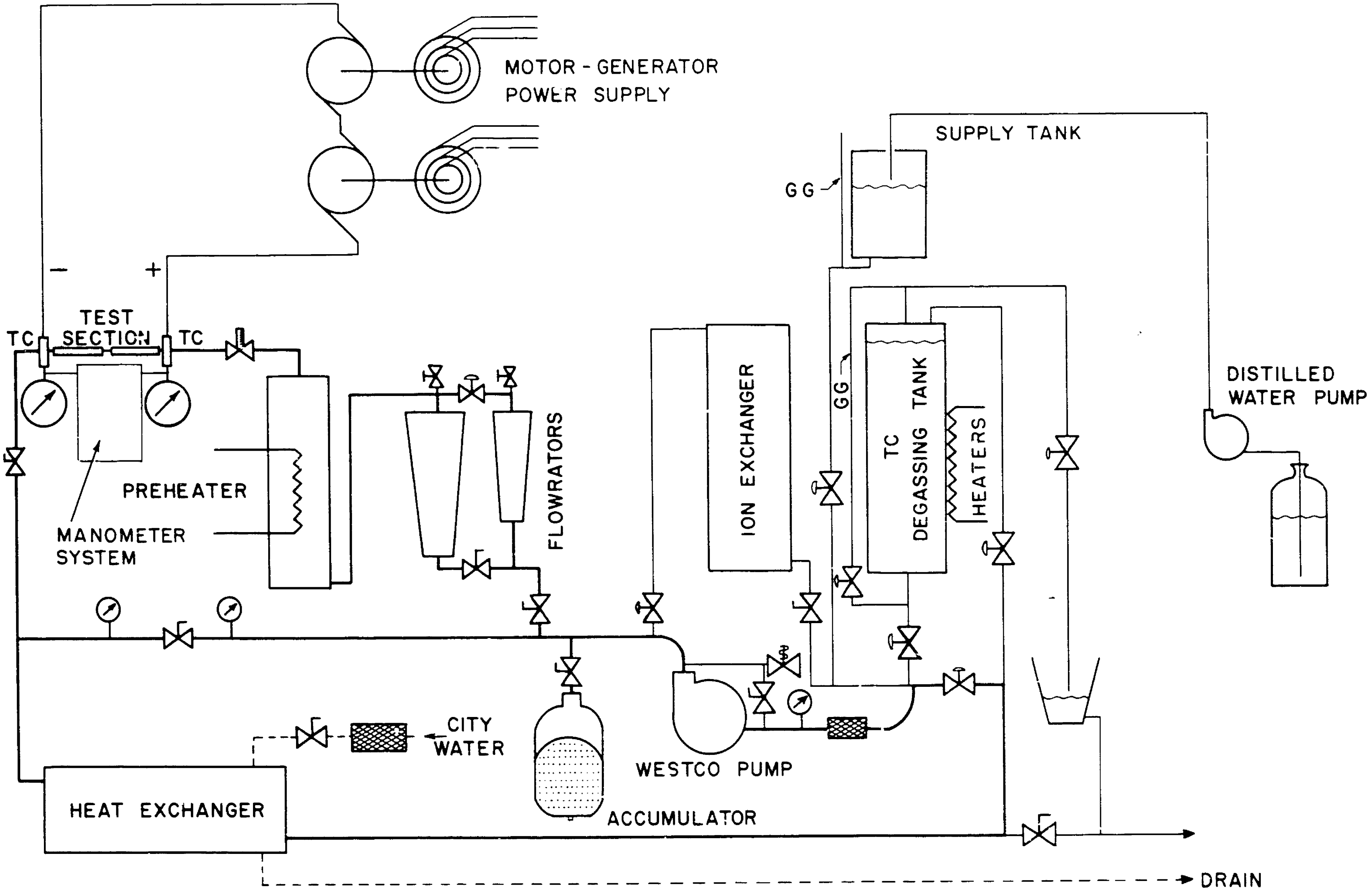

FIG. 1 SCHEMATIC LAYOUT OF EXPERIMENTAL FACILITY

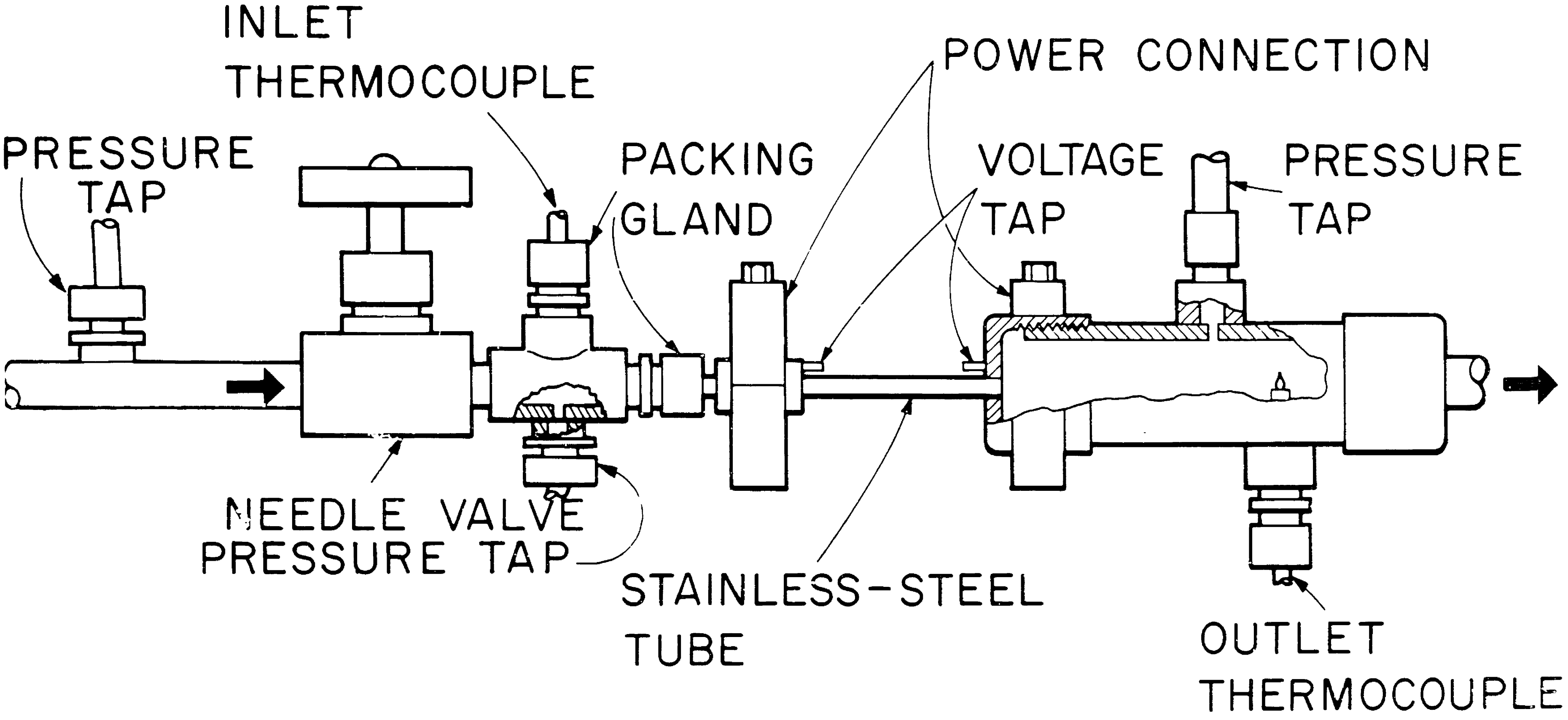

FIG. 2 FORCED CONVECTION TEST SECTION ASSEMBLY

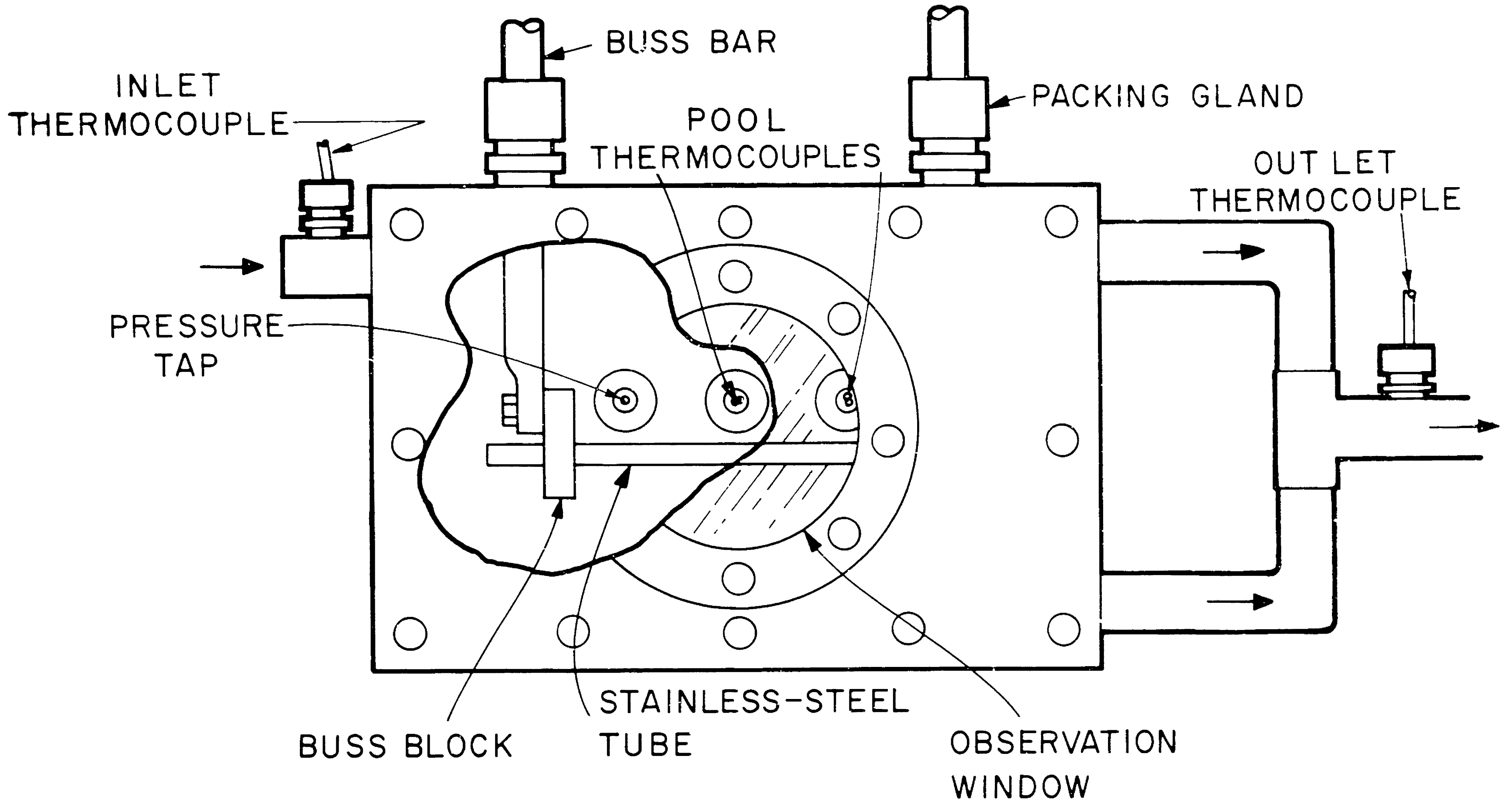

FIG. 3 SUBCOOLED POOL-BOILING ASSEMBLY

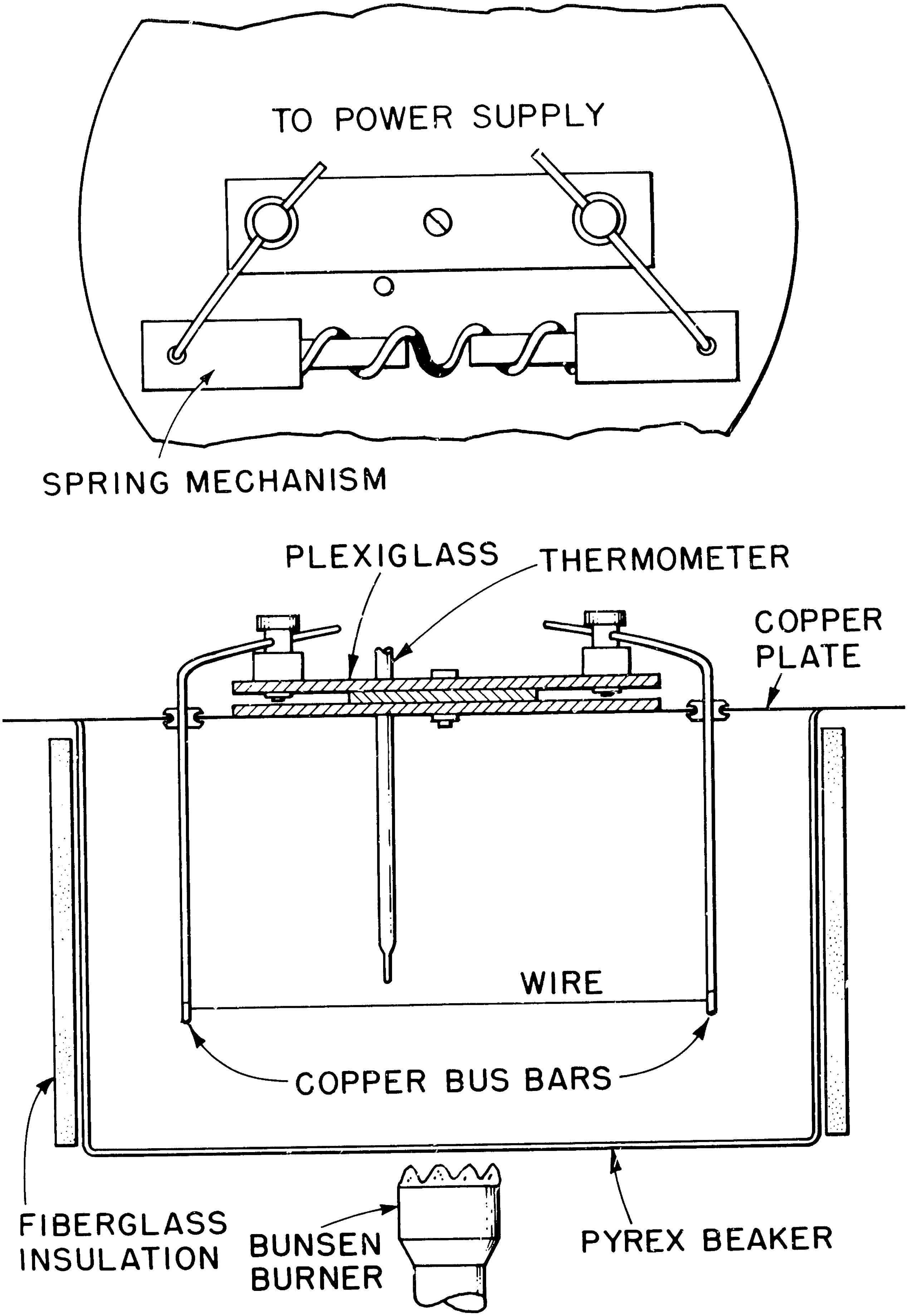

FIG. 4 SATURATED POOL-BOILING ASSEMBLY

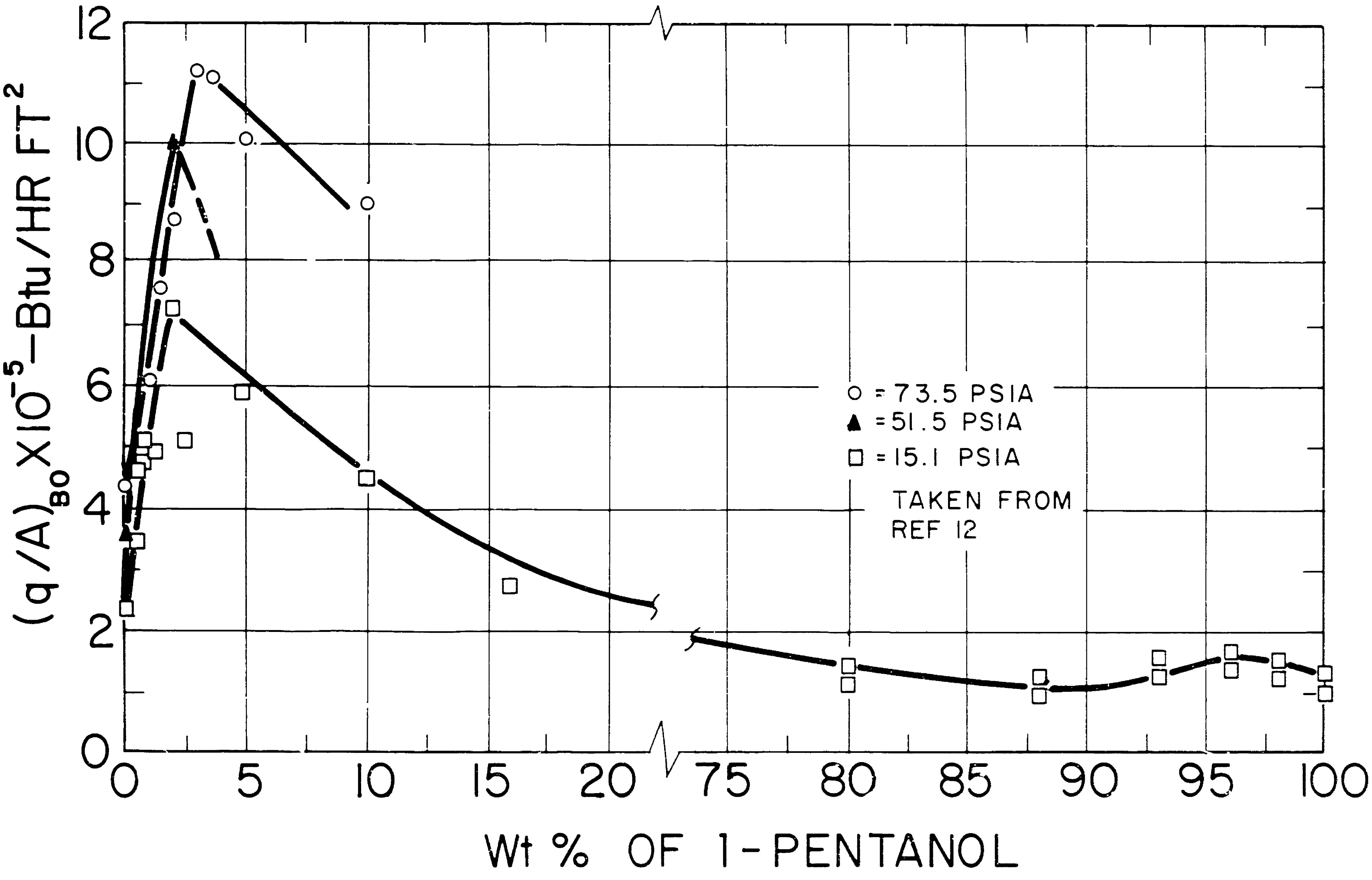

FIG. 5 VARIATION OF THE CRITICAL HEAT FLUX WITH 1-PENTANOL-WATER COMPOSITION AT VARIOUS PRESSURES

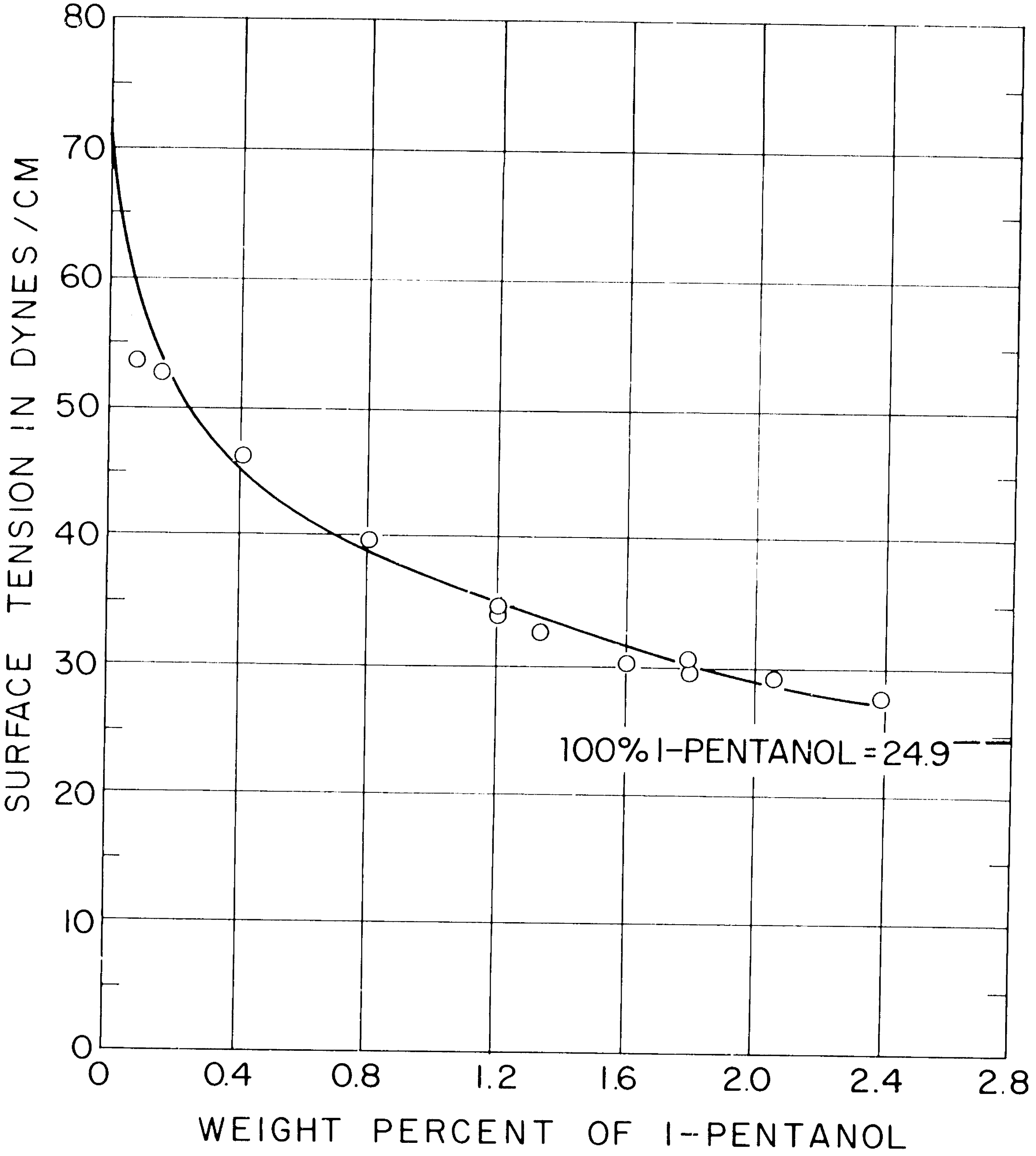

FIG. 6 EFFECT OF COMPOSITION ON SURFACE TENSION OF 1-PENTANOL-WATER SOLUTIONS

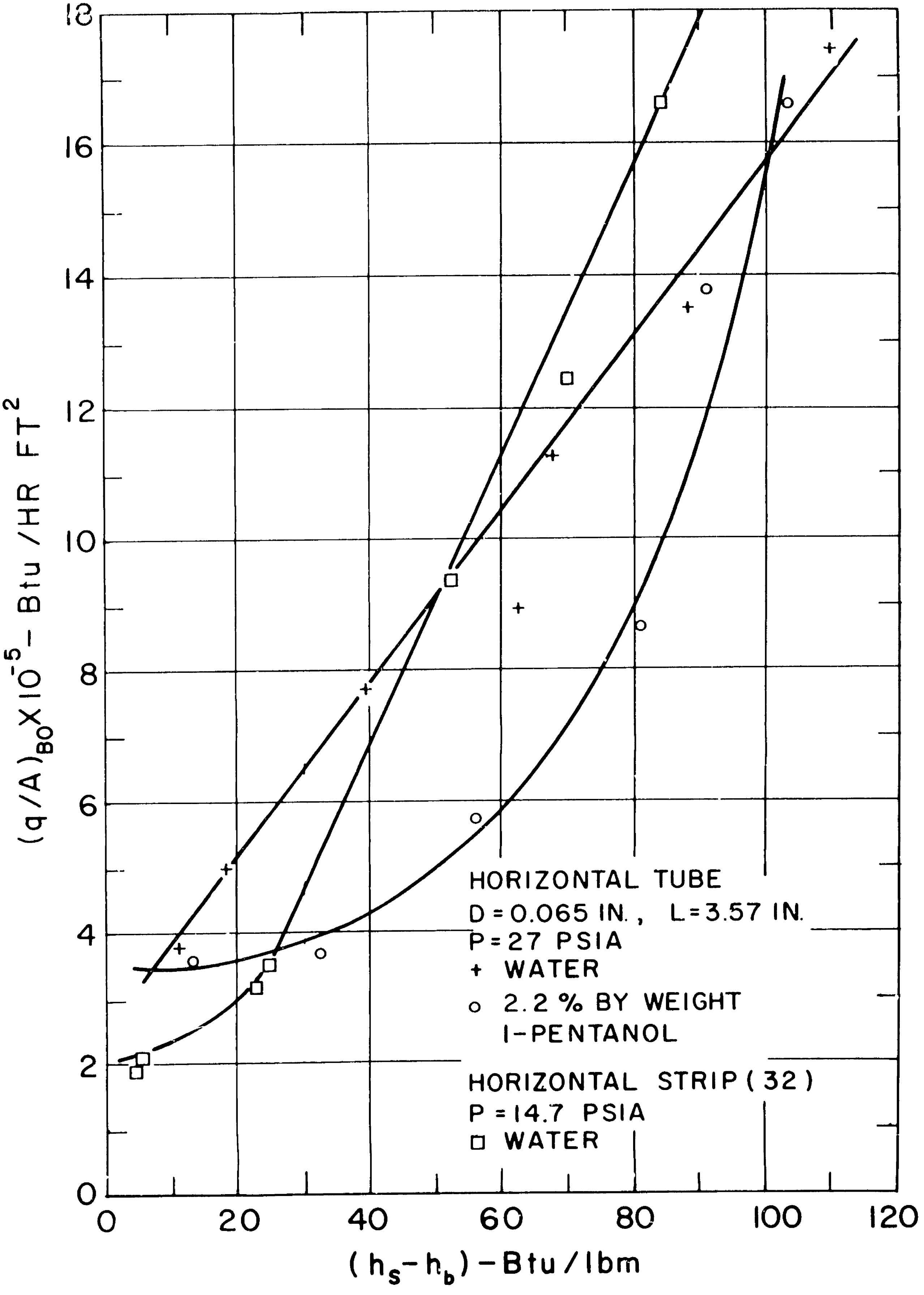

FIG. 7 INFLUENCE OF ADDITION OF 1-PENTANOL ON THE BURN-OUT HEAT FLUX IN SUBCOOLED POOL-BOILING

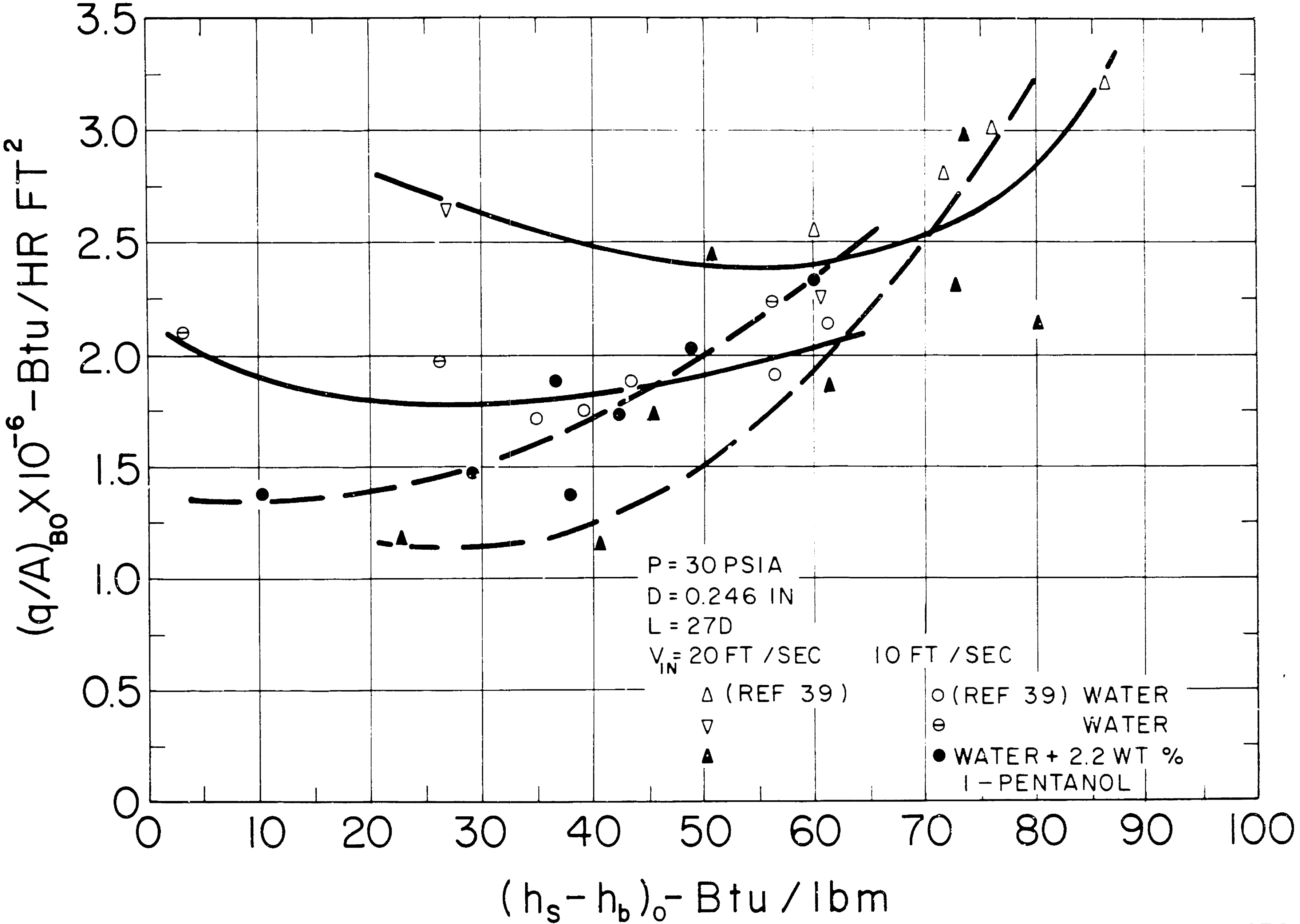

FIG. 8 INFLUENCE OF ADDITION OF 1-PENTANOL ON THE BURNOUT HEAT FLUX IN FORCED CONVECTION

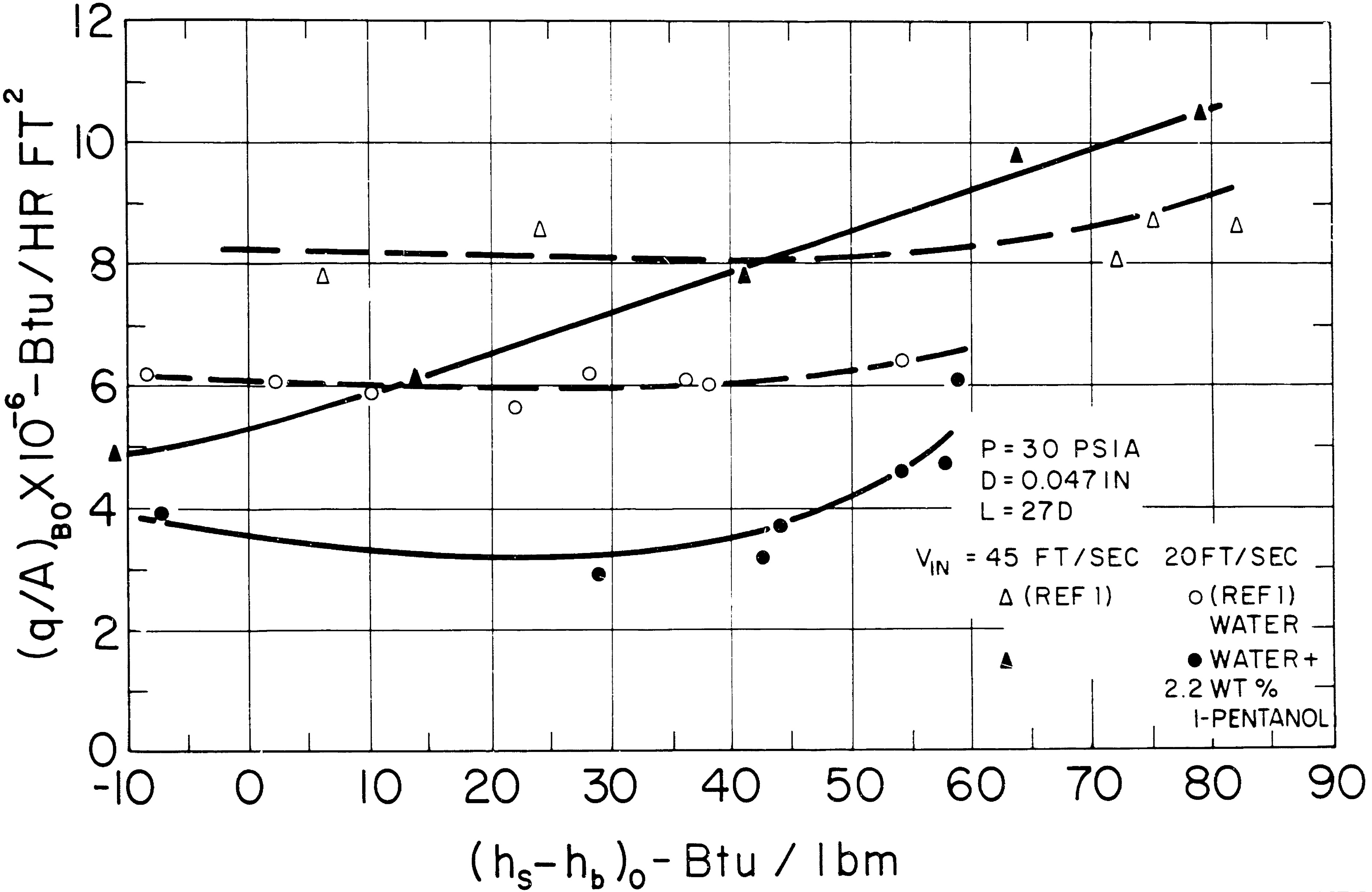

FIG. 9 INFLUENCE OF ADDITION OF 1-PENTANOL ON THE BURNOUT HEAT FLUX IN FORCED CONVECTIO

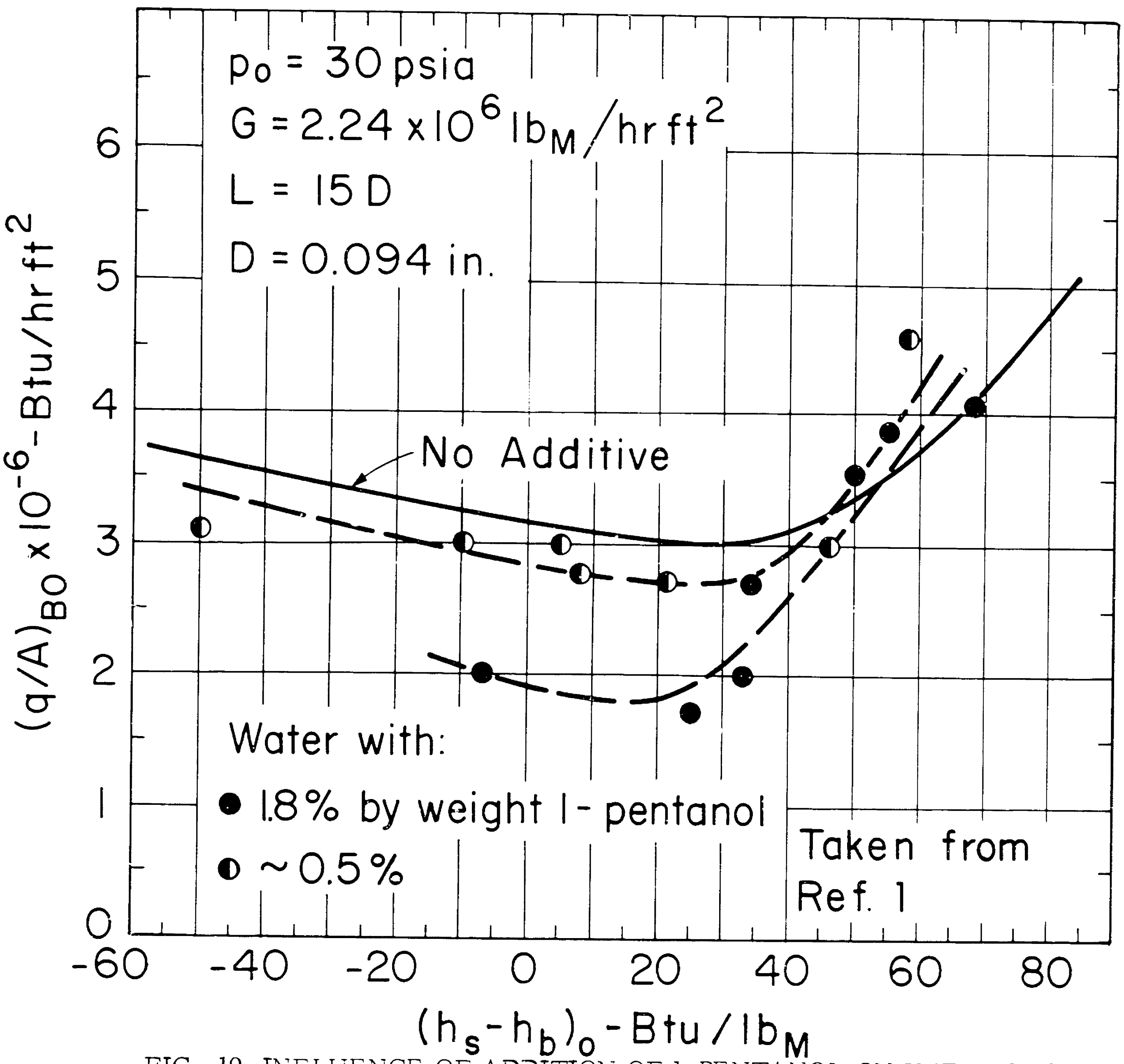

FIG. 10 INFLUENCE OF ADDITION OF 1-PENTANOL ON THE BURNOUT HEAT FLUX IN FORCED CONVECTION

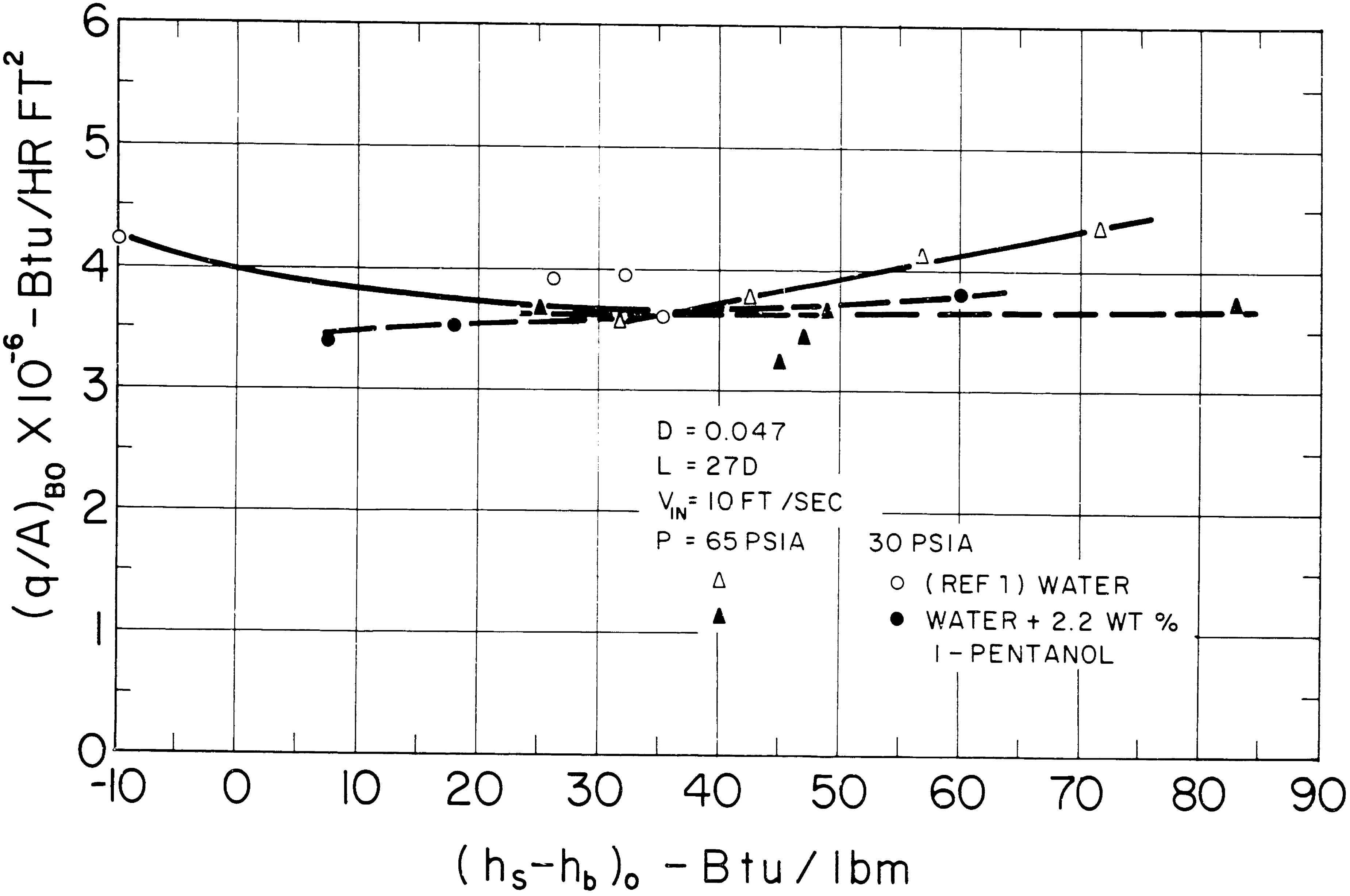

FIG. 11 INFLUENCE OF PRESSURE ON THE EFFECT OF ADDITIVES IN FORCED CONVECTION

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