

Correlation of Pool Boiling Curves for the Homologous Group: Freons

J. W. Westwater,¹ J. C. Zinn,² and K. J. Brodbeck³

Nomenclature

C_L	=	specific heat of liquid
g	=	gravitational acceleration
h_{fg}	=	latent heat of evaporation
k_L	=	thermal conductivity of liquid
P_C	=	thermodynamic critical pressure
q, q_{\max}, q_{\min}	=	heat flux, maximum flux, minimum flux
T_{BP}, T_C	=	atmospheric boiling temperature, thermodynamic critical temperature
$\Delta T, \Delta T_{\max}, \Delta T_{\min}$	=	temperature difference between solid surface and boiling liquid at heat flux q, q_{\max}, q_{\min}
ρ_L, ρ_V	=	density of liquid, vapor
σ	=	surface tension

Introduction

A knowledge of the complete boiling curve q versus ΔT for a liquid, including the regimes of nucleate boiling, transition boiling, and film boiling, and the peak and minimum crisis points is needed for the design and operation of various types of heat transfer equipment. No general method exists for predicting the complete curve. Most difficult is the prediction of the nucleate boiling curve, the transition curve, and the temperature that separates the two. If the curve for every liquid at every pressure must be determined experimentally, we are faced with a formidable task. This paper shows that some simplification is possible for members of a homologous group.

Experimental

A homologous group consists of a series of compounds that are closely related chemically. For the present study, a series of six freons manufactured by the DuPont Co. was selected. The pool-boiling curve for each was determined in our laboratories at atmospheric pressure on pure copper having a mirror polish. The solid copper pieces were large enough to be representative of commercial heat transfer surfaces. They are not representative of small wires. For R-113 (CClF₂-CCl₂F) a horizontal, steam-heated tube of 7.94 mm o.d. in a large liquid pool was used (Broussard and Westwater, 1985). For this freon only, the tests were at steady state. For R-116 (CF₃-CF₃) a face-up, horizontal plate of 6.35 cm thickness

and 5 cm diameter, connected to a vessel of the same diameter, was quenched from room temperature (Zinn, 1984). The temperature versus time data were received at high speed in a digital computer and were reduced to the boiling curve by means of an inverse-conduction mathematical technique (Westwater et al., 1986; Peyayopanukul and Westwater, 1978). This method does not assume uniform temperature throughout the solid as does the older lumped-parameter technique. For R-22 (CHClF₂), R-12 (CCl₂F₂), R-114 (CClF₂-CClF₂), and R-11 (CCl₃F), a solid sphere of 5 cm diameter was heated in an oven and then quenched in a liquid pool in a vessel of 9.53 cm diameter (Brodbeck, 1987). The high-speed temperature versus time data were reduced to boiling curves by use of a two-dimensional, inverse-conduction mathematical technique (Irving and Westwater, 1986; Westwater et al., 1986). This method allows the temperature to vary with azimuthal angle and radial distance at any instant.

Four other liquids not part of the freon family were considered also. Three were tested in our laboratories at atmospheric pressure on mirror-smooth copper. Ethane (C₂H₆) was used with the quenching technique on a 5 cm diameter plate, 6.35 cm thick (Zinn, 1984). Helium was used (Zinn, 1984) with the quenching technique on a 6.35 mm diameter sphere in a 0.35 liter Dewar vessel. For this small sphere only, the simple lumped-parameter data reduction method was justified and was used. Nitrogen was used with the quenching technique on a 5 cm diameter sphere (Irving and Westwater, 1986) and also on horizontal plates, including effectively infinite diameter and effectively infinite thickness (Peyayopanukul and Westwater, 1978; Lin and Westwater, 1982; Zinn, 1984; Egan and Westwater, 1985). The boiling curves for nitrogen in Figs. 1 and 2, and the nitrogen heat transfer data in Table 1, are for the 5 cm sphere. Data for nitrogen in Fig. 3 include the effectively infinite flat plate, as well as the sphere, for comparison purposes.

The tenth liquid, water, was not tested in our laboratories. The boiling curve shown is that of Braunlich reported by McAdams (1954). The minimum in film boiling was not obtained. The minimum tabulated in this paper is from Nishio (1987).

Table 1 shows physical properties plus the measured crisis points during boiling for the six freons and four comparison liquids, all boiling at atmospheric pressure. The physical properties for the freons are from the manufacturer (DuPont Co., 1969). In cases where the surface tension was not given at the atmospheric boiling point, the value was estimated herein by linear interpolation, assuming the value to be zero at the thermodynamic critical temperature. The physical properties in Table 1 cover a great range: For example the surface tension varies from 0.12 to 58.9 dynes/cm, and the latent heat of evaporation varies from 21 to 2253 kJ/kg.

Results

The ten boiling curves are shown in Fig. 1. The apparent symbols on the freon curves are used to separate the lines; they are not discrete data points. Continuous smooth lines result from the quenching technique coupled to computer data acquisition and automatic graphing. For every case, from three to five replicate runs were made. The average curve for each liquid is shown herein, and the amount of data scatter is illustrated for R-113 and nitrogen only by the vertical bars in Fig. 1.

The curves for the freons are similar in that the nucleate boiling branches of the curves (positive slope region on the left) have nearly the same slope. The transition boiling branches of the curves (negative slope) also have nearly a common slope. The four nonfreons are different. The similarity of

¹Department of Chemical Engineering, University of Illinois, Urbana, IL 61801; Mem. ASME.

²Monsanto Co., St. Louis, MO 63167.

³Clorox Corp., Pleasanton, CA 94566.

Contributed by the Heat Transfer Division for publication in the JOURNAL OF HEAT TRANSFER. Manuscript received by the Heat Transfer Division December 10, 1987. Keywords: Boiling, Modeling and Scaling.

Table 1 Physical properties and heat transfer data for ten liquids boiling at atmospheric pressure

	R-116	R-22	R-12	R-114	R-11	R-113	Helium	Nitrogen	Ethane	Water
T_c , K	293	369	385	419	471	487	5.2	151	306	647
P_c , atm	29	49	41	32	44	34	2.3	33	49	218
T_{BP} , K	195	232	243	277	297	321	4.22	77	185	373
k_L , W/m \cdot K $\times 10^{-3}$	80	138	98	65	86	60	27	156	187	678
C_L , J/kg \cdot K	967	1054	887	962	870	933	4561	1987	2435	4210
ρ_L , kg/m 3	1587	1194	1311	1456	1476	1565	125	810	543	958
ρ_v , kg/m 3	9.00	4.73	6.33	7.83	5.88	7.33	16.69	4.61	2.06	0.598
h_{fg} , kJ/kg	117	233	165	136	180	147	21	199	489	2253
σ , N/cm $\times 10^{-5}$	16.8	15.4	14.7	14.1	17.8	15.2	0.12	8.85	16.31	58.9
q_{max} , kW/m 2	186	237	197	205	106	190	6.5	142	338	1200
q_{min} , kW/m 2	18	4.0	3.7	3.8	3.4	23	1.4	5.4	22	25
ΔT_{max} , K	26	26	25	22	28	35	14.5	9.3	26	22
ΔT_{min} , K	40	66	63	58	66	88	16	22	48	105

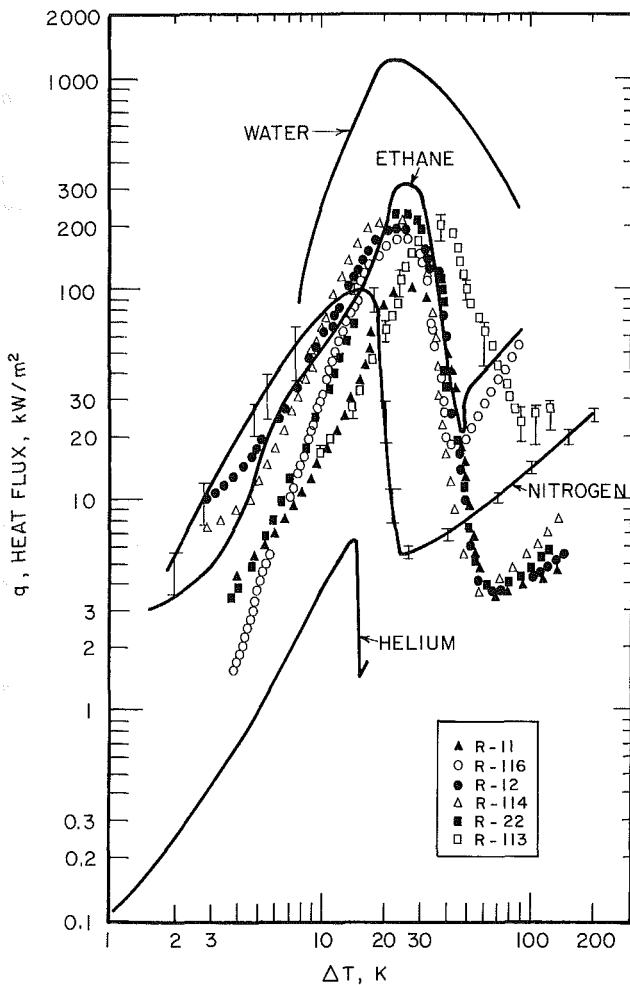


Fig. 1 Pool boiling curves for ten liquids at atmospheric pressure on mirror-smooth copper; vertical bars illustrate the data scatter for R-113 (three runs) and nitrogen (five runs)

the freons is not surprising, because the physical properties of the freons are similar even though their atmospheric boiling points range from 195 to 321 K. The surface tensions of the freons vary from 14.1 to 17.8 dyne/cm, and the latent heat is from 117 to 233 kJ/kg.

The freon boiling curves may be normalized. Each heat flux is divided by the maximum heat flux for that liquid, and the corresponding ΔT is divided by the ΔT at the maximum heat flux. This was done in Fig. 2. The peak flux crisis has coordinates of unity on both axes. The six curves coincide to a significant degree for the ascending left branch (nucleate boiling) and the descending right branch (transition boiling), but not for film boiling.

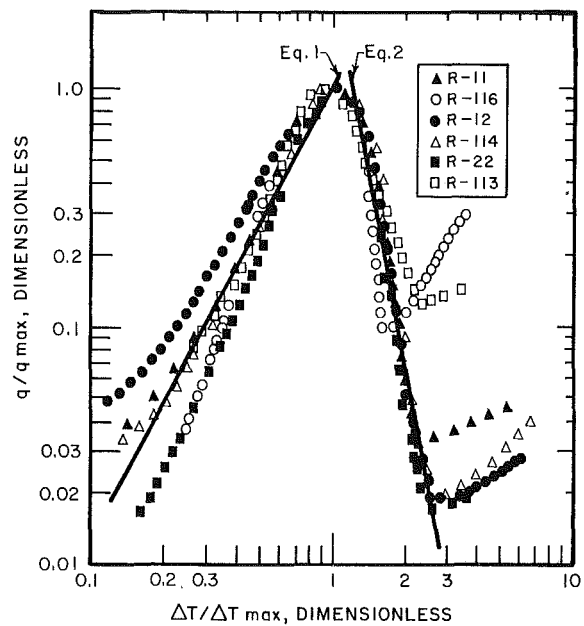


Fig. 2 Normalized pool boiling curves for freons at atmospheric pressure on mirror-smooth copper

For the nucleate boiling regime, a fit for all the freons is equation (1). It is graphed in Fig. 2.

$$q/q_{max} = (\Delta T/\Delta T_{max})^{1.89} \quad (1)$$

(nucleate boiling freons on smooth copper)

The equation is good from about $0.3 < (\Delta T/\Delta T_{max}) < 1.0$. At an abscissa value of 0.3, the mean deviation for the ordinate is 22 percent. The deviation decreases to zero as the normalized ΔT approaches unity. As the normalized ΔT decreases below 0.3 the equation is poor. At low ΔT , free convection becomes dominant, and the exponent on ΔT should be 1.25 to 1.33.

The peak heat flux in Fig. 2 is not a sharp spike. Rather q_{max} is more or less constant for $\Delta T/\Delta T_{max}$ from 1.0 to about 1.2. If electric heat is used, physical burnout does occur at the crisis, and a sharp endpoint is observed. With steam heat, or if the quenching technique is used, a gradual roundoff occurs. The shape of the curve at the peak is dependent also on the thermal mass of the heater. A "large" thermal mass was used herein for the freons.

For the transition boiling regime, a fit for all the freons is equation (2). It is graphed in Fig. 2.

$$q/q_{max} = 2.60(\Delta T/\Delta T_{max})^{-5.31} \quad (2)$$

(transition boiling freons on smooth copper)

The equation is excellent for abscissa values from 1.2 to the onset of film boiling. For example at an abscissa value of 2, four freons are still in the transition boiling regime, and the

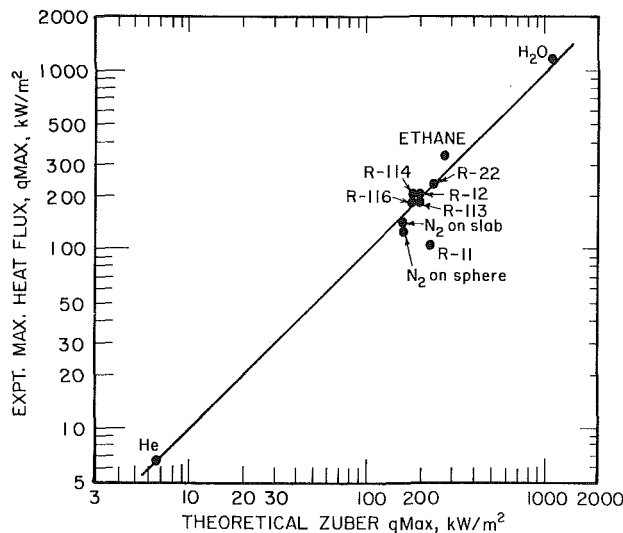


Fig. 3 Comparison of the Zuber prediction of the maximum pool-boiling heat flux with the measured values for ten liquids at atmospheric pressure on mirror-smooth copper

mean deviation of the ordinate from the normalized curve is only 6 percent. The usable range of equation (2) is: $1.2 \Delta T_{\max} < \Delta T < \Delta T_{\min}$. At high ΔT values, film boiling occurs, and the exponent on ΔT is usually about 0.75.

Film boiling curves are seen as ascending lines on the far right side of Fig. 2. They are not coincident when this style of normalized graphing is used. Fortunately, prior equations exist that give good values for q versus ΔT in film boiling (Bromley, 1950; Breen and Westwater, 1962; Sakurai et al., 1984).

Figure 2 does not show normalized curves for the four non-freons. Water, helium, and nitrogen give poor fits to the "universal" curves for freons. Ethane comes closer, but we do not recommend that it be considered as equivalent.

Use of the Homologous Group Correlation

If one intends to use a different member of the homologous series, that is a freon which has not been tested, how may one proceed? If the intended use is on smooth copper, the general correlation of Fig. 2 should apply. It is necessary to locate a specific point on the graph. The obvious choice is the peak heat flux and its driving force, that is, q_{\max} and ΔT_{\max} . The value of the peak flux poses no problem, because it may be predicted from the theoretical equation (3) by Zuber (1958)

$$q_{\max} = (\pi/24) h_{fg} \rho_v^{0.5} [g\sigma(\rho_L - \rho_v)]^{0.25} \quad (3)$$

or from some recent modifications of the same, for example Lienhard and Dhir (1973).

The line in Fig. 3 shows that equation (3) gives good agreement with the observed peak heat flux for nine of the ten liquids. Only freon-11 has unsatisfactory agreement. The mean of the absolute values of the deviation between the observed values and the theoretical values in Fig. 3 is 9.0 percent excluding freon-11, or 18.8 percent including freon-11. According to Zuber, equation (3) has an inherent uncertainty of ± 12 percent. We conclude that the Zuber equation is reasonable for an estimate of q_{\max} .

Prediction of the critical driving force ΔT_{\max} is unreliable at present. For decades it has been known that ΔT_{\max} is a strong function of the surface texture. In addition, it depends on the metal used (Lin and Westwater, 1982). At present its value is best determined experimentally.

There exists a real need for an improved method for predicting ΔT_{\max} . This requires the prediction of the number of nucleation sites for bubble formation not only as a function of

the ΔT but also as a function of the metal used and its surface preparation (machining, polishing, fouling, corrosion).

Once the peak point is fixed for the new freon, the normalized boiling curves for nucleate boiling and transition boiling in Fig. 2 are assumed to apply. Equation (1) holds from about $0.3 \Delta T_{\max}$ to ΔT_{\max} ; q_{\max} persists from ΔT_{\max} to about $1.2 \Delta T_{\max}$; and equation (2) applies from $1.2 \Delta T_{\max}$ to ΔT_{\min} or from q_{\max} down to q_{\min} . The minimum flux may be predicted by one of various relationships, such as those of Zuber (1958), Berenson (1961), or Lienhard and Dhir (1980). The corresponding ΔT_{\min} may also be predicted, but with less reliability, from published relationships such as those of Berenson (1961), Lienhard and Wong (1964), or Nishio (1987). For film boiling one of the various prior equations should be used.

An alternate way of predicting the boiling curve for a new freon is to work backward from the film boiling crisis that occurs at q_{\min} , ΔT_{\min} . One would select published equations such as mentioned above to predict q_{\min} , ΔT_{\min} , and q_{\max} . The ratio of q_{\min}/q_{\max} will lie on the normalized transition-boiling line in Fig. 2. The abscissa value read from the graph is the ratio $\Delta T_{\min}/\Delta T_{\max}$. From that, ΔT_{\max} is found, and we can proceed to calculate the peak flux crisis point and the rest of the complete boiling curve. The reliability of this procedure remains to be tested.

Conclusions

It is interesting to speculate further. For every homologous group, for example the simple alcohols, the straight chain hydrocarbons, or the aromatics (benzene, toluene, xylenes), we expect that a general normalized boiling curve exists. The relationship will not be identical with Fig. 2, unless the physical properties fall within the range of the freon properties in Table 1. The surface texture of the heater will be an important variable, because it affects nucleate boiling and the value of ΔT_{\max} . The choice of metal can become a significant parameter, particularly if the solid has a poor conductivity.

We conclude that it is not necessary for anyone to produce a reference book with thousands of experimental boiling curves, one for each known liquid. Instead, the profession can manage with appropriate curves for homologous groups. This paper demonstrates that conclusion for freons.

Acknowledgments

Financial assistance was provided by the National Science Foundation. Graduate fellowships were furnished by E. I. DuPont Co. and General Electric Co.

References

- Berenson, P. J., 1961, "Film Boiling Heat Transfer From a Horizontal Surface," *ASME JOURNAL OF HEAT TRANSFER*, Vol. 83, pp. 351-362.
- Breen, B. P., and Westwater, J. W., 1962, "Effect of Diameter of Horizontal Tubes on Film Boiling Heat Transfer," *Chem. Eng. Progress*, Vol. 58, No. 7, pp. 67-72.
- Brodbeck, K. J., 1987, "Effects of Thermophysical Properties on the Boiling Curves of Five Freons," M.S. Thesis, Chemical Engineering Department, University of Illinois, Urbana, IL.
- Bromley, L. A., 1950, "Heat Transfer in Stable Film Boiling," *Chem. Eng. Progress*, Vol. 46, pp. 221-227.
- Broussard, R. A., and Westwater, J. W., 1985, "Diameter and Velocity Effects for Cross-Flow Boiling," *AIAA Journal*, Vol. 23, No. 10, pp. 1615-1620.
- DuPont Co., 1969, *Freon Product Information B-2*, E. I. duPont de Nemours and Co., Wilmington, Del., 10 pages; also see Bulletin T-113B, *Properties of Freon-113*, no date, Bulletin T-11-B, *Thermodynamic Properties of Freon-11*, 1938, and Bulletin D-27A, *Surface Tension of Freon-12 and Freon-22*, 1960.
- Egan, J. P., and Westwater, J. W., 1985, "Effect of Horizontal Plate Diameter on Boiling Heat Transfer From Copper to Nitrogen," *J. Thermal Engineering*, Vol. 4, No. 1, pp. 1-12.
- Irving, M. E., and Westwater, J. W., 1986, "Limitations for Obtaining Boiling Curves by the Quenching Method With Spheres," *Proceedings, 8th Interna-*

tional Heat Transfer Conference, C. L. Tien et al., eds., Hemisphere, Washington, DC, Vol. 4, pp. 2061-2066.

Lienhard, J. H., and Dhir, V. K., 1973, "Hydrodynamic Prediction of Peak Pool Boiling Heat Fluxes From Finite Bodies," ASME JOURNAL OF HEAT TRANSFER, Vol. 95, pp. 152-158.

Lienhard, J. H., and Dhir, V. K., 1980, "On the Prediction of the Minimum Pool Boiling Heat Flux," ASME JOURNAL OF HEAT TRANSFER, Vol. 102, pp. 457-460.

Lienhard, J. H., and Wong, P. T. Y., 1964, "The Dominant Unstable Wavelength and Minimum Heat Flux During Film Boiling on a Horizontal Cylinder," ASME JOURNAL OF HEAT TRANSFER, Vol. 86, pp. 220-226.

Lin, D. Y. T., and Westwater, J. W., 1982, "Effect of Metal Thermal Properties on Boiling Curves Obtained by the Quenching Method," Proceedings, 7th International Heat Transfer Conference, V. Grigull et al., eds., Hemisphere, Washington, DC, Vol. 4, pp. 155-160.

McAdams, W. H., 1954, Heat Transmission, 3rd ed., McGraw-Hill, New York, p. 380.

Nishio, S., 1987, "Prediction Technique for Minimum Heat Flux (MHF) Point Condition of Saturated Pool Boiling," Int. J. Heat Mass Transfer, Vol. 30, pp. 2045-2057.

Peyayopanukul, W., and Westwater, J. W., 1978, "Evaluation of the Unsteady State Quenching Method for Determining Boiling Curves," Int. J. Heat Mass Transfer, Vol. 21, pp. 1437-1445.

Sakurai, A., Shiotsu, M., and Hata, K., 1984, "Film Boiling Heat Transfer on Horizontal Cylinder (II)," Proc. 21st National Heat Transfer Symp. Japan, pp. 466-468.

Westwater, J. W., Hwalek, J. J., and Irving, M. E., 1986, "Suggested Standard Method for Obtaining Boiling Curves by Quenching," I and EC Fundamentals, Vol. 25, No. 4, pp. 685-692.

Zinn, J. C., 1984, "Determining Boiling Curves of Different Liquids by the Quenching Method," M.S. Thesis, Chemical Engineering Department, University of Illinois, Urbana, IL.

Zuber, N., 1958, "On the Stability of Boiling Heat Transfer," Trans. ASME, Vol. 80, pp. 711-720.

ϵ = void fraction

λ = thermal conductivity

μ = viscosity

ρ = density

σ = surface tension

Subscripts

l = liquid

m = equivalent

p = bead particles

v = vapor

Introduction

A number of experimental studies of boiling heat transfer in liquid-saturated porous media have been motivated by such diverse technological problems as high-flux heat transfer porous surface, geothermal energy extraction, and heat-transport characteristics in heat pipes (e.g., Costello and Redeker, 1963; Cornwell et al., 1976; Sugawara et al., 1978; Nakayama et al., 1980; Sommerton et al., 1981; Bergles and Chyu, 1982; Itoh et al., 1982; Bau and Torrance, 1982). Most of the previous studies of boiling heat transfer in liquid-saturated porous layers have been carried out for the purpose of finding methods to augment nucleate pool boiling.

Recently, Fukusako et al. (1986) conducted an experimental study of the boiling heat transfer characteristics of a liquid-saturated porous bed. They focused their attention in particular on the effect of diameter of the beads on boiling behavior in both transition boiling and film boiling regions, and found that for small bead diameters, the heat flux q rose both continuously and monotonically with temperature difference ΔT_s from nucleate boiling to film boiling without going through a peak heat flux.

From the literature survey, it is apparent that very little is known about the boiling heat transfer behavior in a saturated porous bed with liquid injection to the heating surface, which appears to provide the fundamental data for the geothermal energy-extraction technology.

The objective of this technical note is to report the results of an experimental study of the effect of saturated-water injection on boiling heat transfer in a water-saturated porous bed.

Water-Injection Effect on Boiling Heat Transfer in a Water-Saturated Porous Bed

S. Fukusako¹ and N. Hotta²

Nomenclature

A = area of heating surface

C = specific heat

d_p = diameter of beads

g = gravitational acceleration

H = height of water-saturated porous bed

L = latent heat of evaporation

M = water-injection rate

m = mass flux of water injection = M/A

Nu = Nusselt number = $qd_p / (\Delta T_s \lambda_{ml})$

Pr = Prandtl number

q = heat flux

Re_m = modified Reynolds number = $d_p m / (\mu_l \epsilon)$

T_s = temperature of saturated water

T_w = temperature of heating surface

ΔT_s = temperature difference between heating surface and saturated water = $T_w - T_s$

Experimental Apparatus and Procedure

The schematic diagram of the experimental setup is shown in Fig. 1. The apparatus consists of an inner Pyrex tube 60 mm in diameter and 80 mm in height and an outer Pyrex tube 220 mm in diameter and 150 mm in height. The inner tube was filled with a water-saturated porous bed, while the other annulus was used as both an insulating thermal guard and a saturation-water storage. In order to maintain the saturation temperature within the inner tube, four guard heaters were inserted in the annulus.

The inner tube and the outer annulus were filled to the same height with saturated water and a constant water level was held above the heating surface. To prevent fluidization of the porous bed, a screen plate (12 or 18 mesh, depending on bead diameter) was attached to the top of the inner tube. All of the data reported here were obtained at atmospheric pressure. As is shown in Fig. 1, a water make-up tank, condensate collection equipment, and a reservoir tank for maintaining system pressure and water level were used. Water injection was accomplished using three stainless tubes 3 mm in diameter, which were arranged in a triangular array (distance between tubes is 25 mm) at a distance of about 2 mm from the heating

¹Professor, Department of Mechanical Engineering, Hokkaido University, Sapporo 060, Japan.

²Graduate Student, Department of Mechanical Engineering, Hokkaido University, Sapporo 060, Japan.

Contributed by the Heat Transfer Division for publication in the JOURNAL OF HEAT TRANSFER. Manuscript received by the Heat Transfer Division October 27, 1986. Keywords: Boiling, Porous Media.