Determination of the bulk-saturated liquid condition for maximum heat fluxes at boiling crises

K. SRINIVASAN and M. V. KRISHNA MURTHY

Refrigeration and Airconditioning Laboratory, Department of Mechanical Engineering,
Indian Institute of Technology, Madras—600 036, India

Abstract—In this paper is presented a method of predicting the thermodynamic state of the bulk-saturated liquid at which peak nucleate boiling and minimum film boiling heat fluxes attain a maximum in pool boiling. The data in the form of saturated pressure and temperature in both absolute and reduced quantities are listed for several cryogenic liquids, hydrocarbons and halocarbon refrigerants. It is observed that the bulk liquid condition for a maximum in critical heat flux in nucleate boiling corresponds to intermolecular separation at maximum attractive potential, which in turn can be determined from saturated liquid density data. The predictions are fairly well corroborated by experimental data available in literature.

1. INTRODUCTION

IN THE design of heat transfer equipment one often encounters the problem of transferring large heat fluxes across small temperature differences. Boiling heat transfer offers a lot of promise in this direction. A study of boiling liquids has other practical applications such as refrigerant evaporators, nuclear reactors, and several other cooling systems wherein cryogenic liquids, hydrocarbons, halocarbons and water are used. It is well known that nucleate boiling heat transfer can be augmented by raising the pressure of the bulk liquid. It is also established [1] that peak nucleate boiling heat flux (PNBHF) increases with saturation pressure up to a certain value and thereafter decreases reaching a value of zero at the thermodynamic critical point. It is also observed [1] that the value of saturation pressure at which PNBHF is a maximum is approximately $0.3p_c$, where p_c is the critical pressure. In the case of cryogenic liquids data on nucleate pool boiling of nitrogen [2–5], oxygen [3], argon [2,4], methane [6] and neon [7] have reaffirmed the above observation. For this class of liquids the bulk saturation condition of $0.3p_c$ corresponds to a saturation temperature of $0.82T_c$ where T_c is the critical temperature.

Several theoretical and empirical studies have been reported in the past to correlate the PNBHF as a function of fluid properties. It has also been appreciated that to do so one must account for characteristics of the boiling surface such as roughness, geometry and orientation. A review of previous work on predictions for PNBHF has been presented by Cobb and Park [2]. The predictions have been, however, successful in showing that the PNBHF goes through a maximum at a particular saturation pressure. No empirical correlations are available to determine the

value of this saturation pressure although a majority of experimental investigations indicate that it is approximately equal to $0.3p_c$.

Based on certain observations made on the behaviour of saturated liquid properties, we attempt to correlate the thermodynamic state of the bulk liquid at which $(\text{PNBHF})_{\text{max}}$ occurs. The saturation pressure and the corresponding temperature (both in absolute and reduced quantities) at which $(\text{PNBHF})_{\text{max}}$ can be expected to occur are listed for several cryogenic liquids (Ne, Ar, Kr, N_2, O_2), hydrocarbons (methane, ethane, propane, *n*-butane, ethylene), halocarbons (Refrigerants 11, 12, 12B1, 13, 13B1, 14, 21, 22, 23, 113, 114, 115, 216), water and carbon dioxide. The method can be extended to other liquids as well.

2. THEORETICAL

In our earlier work [9] it has been shown that for all liquids the product of saturation temperature and the corresponding saturated liquid density goes through a maximum at a characteristic temperature, T^*, which is a property of a liquid. The value of T^* is approximately equal to $0.82T_c$ irrespective of the nature of the liquid, e.g. monatomic, polyatomic, polar or non-polar. This temperature is also found to be a point of inflexion on the liquid viscosity–temperature curve and the saturation curve on $\ln p$ vs T^{-1} co-ordinates. T^* is analogous to ε/k where ε is the depth of the potential well in the intermolecular pair potential energy function and k is the Boltzmann constant. Thus, when the bulk liquid is at this saturated temperature, intermolecular forces of attraction, which resist evaporation will be the strongest. The PNBHF corresponds to a state at which maximum thermal energy can be added without formation of vapour film around the heater surface. To cause evap-

Table 1. Predicted saturation temperatures and pressures at which maximum in peak nucleate boiling heat flux occurs

Liquid	T^* (K)	$T_r^* = T^*/T_c$	p^* (bar)	$p_r^* = p^*/p_c$
Neon	36.5	0.821	8.43	0.316
Argon	123.0	0.816	14.27	0.293
Krypton	170.0	0.812	15.37	0.280
Nitrogen	103.0	0.816	9.53	0.280
Oxygen	126.0	0.815	14.25	0.283
Methane	156.0	0.819	13.51	0.294
Ethane	250.0	0.819	13.01	0.267
Propane	303.2	0.819	10.77	0.253
n-Butane	349.8	0.823	9.45	0.248
Ethylene	232.0	0.822	14.03	0.278
CO_2	246.0	0.809	15.70	0.213
R-11	383.2	0.813	10.19	0.231
R-12	312.2	0.811	9.38	0.227
R-12B1	347.2	0.813	9.66	0.224
R-13	246.2	0.815	9.30	0.240
R-13B1	277.2	0.815	9.44	0.238
R-14	185.0	0.813	8.74	0.233
R-21	367.2	0.813	11.71	0.226
R-22	299.2	0.810	10.72	0.215
R-23	241.2	0.806	9.43	0.195
R-113	396.2	0.813	7.29	0.214
R-114	340.7	0.813	6.99	0.214
R-115	287.6	0.814	6.82	0.215
R-216	370.2	0.817	5.71	0.207
Water	525.2	0.811	41.12	0.186

oration, thermal energy added must be higher than the attractive potential corresponding to average intermolecular separation at a given state of a liquid. The average molecular separation is governed by molar volume which in turn is a function of temperature. Thus, the heat flux necessary to cause evap-

oration without transformation to the unstable film boiling region will be the largest when the bulk liquid is at a saturation temperature of T^*, i.e. a saturation pressure of p^*. Further, since evaporation is governed more by properties of a liquid than by the characteristics of the heating surface, it can be expected that the value of pressure at which a maximum in PNBHF occurs will be independent of the heating surface characteristics. Table 1 shows predicted bulk liquid conditions at which $(PNBHF)_{max}$ can be expected to occur for several liquids.

The second boiling crisis, i.e. the minimum film boiling heat flux (MFBHF) can also be expected to go through a maximum at the same bulk saturation pressure of p^* since PNBHF and MFBHF are related directly through fluid properties.

3. COMPARISON WITH EXPERIMENTAL DATA AND DISCUSSION

Figure 1 shows PNBHF data for several liquids. The geometry and roughness factors are different in different investigations. Consequently, no significance can be attached to relative magnitudes of PNBHF. To normalize several different sources of data the reduced pressures are plotted against a non-dimensional PNBHF (Fig. 2). The non-dimensionalization is done merely by dividing PNBHF for a liquid at any pressure by the maximum PNBHF reported for that set of data. The purpose is to show that the pressure dependence of PNBHF is identical for all heater surface characteristics. In addition to liquids listed in the inset of Fig. 2, propane, n-butane and R-11 have also been analysed. These data are not shown because the experimental points
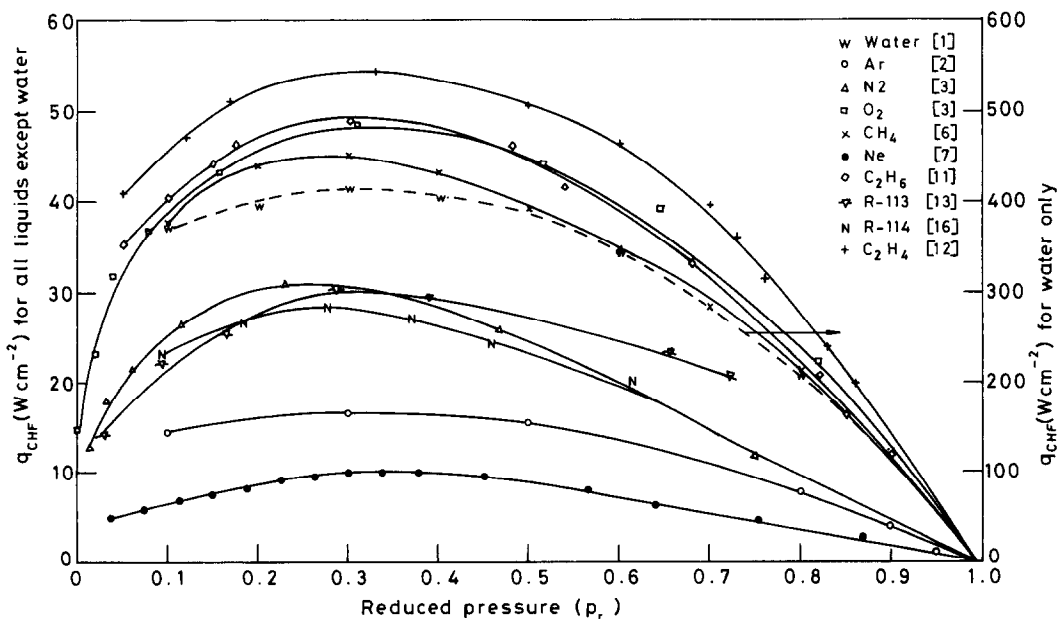

FIG. 1. Experimental peak nucleate boiling heat flux data for several liquids.
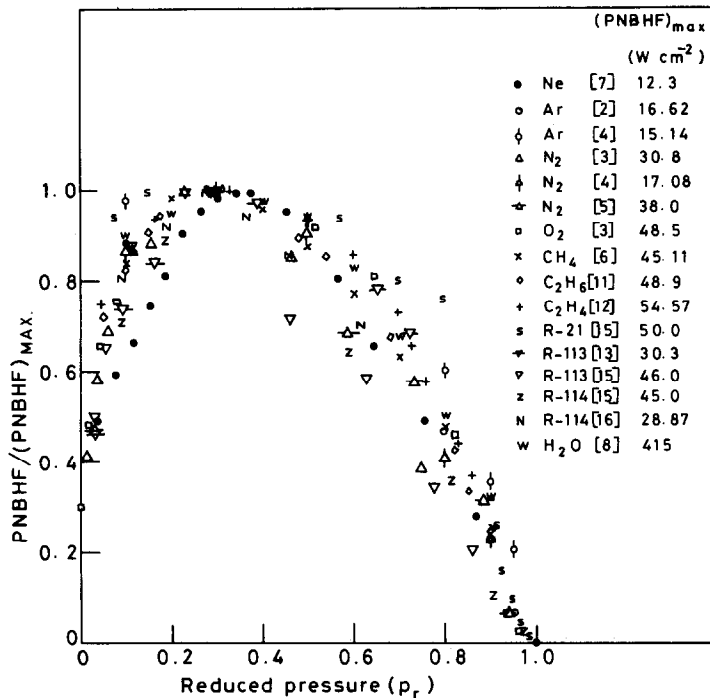
FIG. 2. Non-dimensional peak nucleate boiling heat flux plotted against reduced pressure for several liquids.

could not be distinguished from the others already plotted.

Table 2 shows a comparison of predicted and experimental values of saturation pressure at which the maximum in PNBHF occurs for liquids for which experimental data are available. It may be seen that the agreement is generally good, considering the fact that experimental data were available only at selected pressures in the region of interest. Perhaps if experimental data were available at close pressure intervals in the region of p^* it may be possible to confirm our predictions. In the case of ethane there appears to be

Table 2. Experimental and predicted values of saturation pressure for maximum peak nucleate boiling heat flux

| Liquid | Predicted values | | Experimental value | Pressures in the range of interest at which data are available | Ref. |
	Absolute (bar)	Reduced			
Neon	8.43	0.316	10 bar	4, 8, 10 bar	[7]
Argon	14.27	0.293	$0.3p_c$	0.1, 0.3, $0.5p_c$	[2,4]
Nitrogen	9.53	0.280	7.72 atm	3.86, 7.72, 15.73 atm	[3]
			$0.3p_c$	0.1, 0.3, $0.5p_c$	[4]
			10 bar	1, 10, 20 bar	[5]
Oxygen	14.25	0.283	15.5 atm	7.93, 15.5, 25.65 atm	[3]
Methane	13.51	0.294	$0.3p_c$	0.2, 0.3, $0.4p_c$	[6]
Ethane	13.01	0.267	$0.3p_c$	0.175, 0.3, $0.48p_c$	[11]
			$0.46p_c$	0.2, 0.37, 0.46, $0.6p_c$	[12]
Ethylene	14.03	0.278	$0.32p_c$	0.17, 0.32, $0.5p_c$	[12]
Propane	10.77	0.253	$0.3p_c$	0.28, 0.3, $0.4p_c$	[11]
n-Butane	9.45	0.248	$0.3p_c$	0.2, 0.3, $0.4p_c$	[11]
R-11	10.19	0.231	14 kg cm^{-2}	8, 14, 20 kg cm^{-2}	[17]
R-21	11.71	0.226	between 8 and 15 kg cm^{-2}	4, 8, 15, 23 kg cm^{-2}	[17]
R-113	7.29	0.214	9.8 bar	5.6, 9.8, 13.35 bar	[13]
			8 kg cm^{-2}	4, 8, 16 kg cm^{-2}	[17]
R-114	7.00	0.214	9 bar	6, 9, 12 bar	[16]
			10 kg cm^{-2}	6, 10, 15 kg cm^{-2}	[17]
Water	41.12	0.186	$0.25-0.45p_c$		[8]
			49 bar	29.5, 49, 73 bar	[14]

Table 3. Comparison of experimental and predicted values
of saturation pressure at which maximum heat flux at second
boiling crisis occurs

Fluid	Reduced pressure at which $(MFBHF)_{max}$ occurs	
	Experimental	Predicted
R-114	0.18 to 0.274	0.214
Methane	0.2 to 0.3	0.294
Ethane	0.4	0.267
Propane	0.27	0.253
n-Butane	0.2 to 0.3	0.248

Note: Source of experimental data for R-114 is ref. [16];
for other liquids ref. [10].

some disagreement between different sources of data
[11,12], our predictions being closer the data of
Sciance et al. [11].

A significant deviation between predicted and
experimental data is observed in the case of water.
The value of p^* for water is found to be 41.12 bar,
i.e. $p_r^* = 0.186$. The experimental data of Kazakova
as given by Lienhard and Schrock [8] shows that
the maximum PNBHF occurs in the range of
$0.25 < p_r < 0.45$. The data of Avksentyuk and
Malykh [14] (not shown in Fig. 1) shows that
maximum PNBHF occurs at $p_r = 0.22$.

From the data for nitrogen in Fig. 2 it may be
seen that $(PNBHF)_{max}$ occurs nearly at the same p_r
irrespective of the geometry of the heating surface.
For a majority of liquids the increase in PNBHF at
p^* over that at normal pressure is of the order of
250%. Thus, it can be deduced that if the bulk satu-
ration pressure is maintained at p^* the largest quantity
of heat can be transferred without changeover to film
boiling compared to that at any pressure whatever the
heating surface characteristic may be.

The data for pool boiling of hydrocarbons [10] has
shown that MFBHF (heat flux at the second boiling
crisis) also goes through a maximum in the range of
$0.3 < p_r < 0.4$. Table 3 shows a comparison of ex-
perimental data and predicted values for methane,
ethane, propane, n-butane and R-114. The agreement
is fairly good, with the exception of ethane.

4. CONCLUSIONS

This paper gives a method for predicting the ther-
modynamic state of bulk liquid at which maximum
heat fluxes occur at the two boiling crises. These data
should be of use in determining the pressure of a liquid
pool to ensure maximum heat transfer in the nucleate
boiling regime. This pressure is independent of
the boiling surface characteristics. The predictions
are reasonably well corroborated by experimental

data. Although the data are presented for only a few
selected liquids, the method can be extended to
other liquids as well.

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DETERMINATION DE LA CONDITION DE SATURATION DU LIQUIDE POUR LES FLUX DE CHALEUR MAXIMAUX DE CRISE D'EBULLITION

Résumé—On présente une méthode de prédiction de l'état thermodynamique du liquide saturé à coeur, pour lequel l'ébullition nucléée atteint son maximum et l'ébullition en film son minimum dans l'ébullition en réservoir. Les données de pression et de température de saturation en valeurs absolues et réduites sont tabulées pour différents liquides cryogéniques et des réfrigérants hydrocarbures et halocarbures. On observe que la condition maximum de flux de chaleur critique en ébullition nucléée correspond à la séparation intermoléculaire au potentiel attractif maximum qui en retour peut être déterminé à partir des données de densité de liquide saturé. Les prédictions sont bien vérifiées par les données expérimentales disponibles dans la bibliographie.

DIE BESTIMMUNG DER BEDINGUNGEN FÜR DIE GESÄTTIGTE FLÜSSIGKEIT ZUR ERZIELUNG MAXIMALER WÄRMESTROMDICHTEN BEI DER SIEDEKRISE

Zusammenfassung—In dieser Arbeit wird eine Methode zur Berechnung des thermodynamischen Zustandes der gesättigten Flüssigkeit vorgestellt, bei dem beim Behältersieden die maximale Wärmestromdichte bei Blasensieden und die minimale Wärmestromdichte bei Filmsieden maximal werden. Die Daten in Form des Sättigungsdruckes und der Sättigungstemperatur werden sowohl in absoluten als auch in relativen Größen für unterschiedliche Kühlflüssigkeiten, Kohlenwasserstoffe und hologenierte Kohlenwasserstoffe (Kältemittel) aufgelistet. Es wurde beobachtet, daß die Bedingungen für die gesättigte Flüssigkeit zur Erzielung eines Maximums der kritischen Wärmestromdichte mit denen der intermolekularen Entfernung bei maximaler Anziehungskraft übereinstimmen. Diese Bedingungen können aus den Daten der Dichte der gesättigten Flüssigkeit ermittelt werden. Die Berechnungen werden durch die experimentellen Daten in der verfügbaren Literatur belegt.

ОПРЕДЕЛЕНИЕ УСЛОВИЯ НАСЫЩЕНИЯ ЖИДКОСТИ В ОБЪЕМЕ ДЛЯ МАКСИМАЛЬНЫХ ТЕПЛОВЫХ ПОТОКОВ ПРИ КРИЗИСАХ КИПЕНИЯ

Аннотация—Предложен метод расчета термодинамического состояния насыщенной жидкости в объеме, когда тепловые потоки для пика пузырькового и минимума пленочного кипения достигают максимума при кипении в большом объеме. Результаты в виде абсолютных и приведенных значений давления и температуры насыщения представлены для различных криогенных жидкостей: углеводородов, галоидоуглеводородных охладителей. Замечено, что условие для максимального критического теплового потока в случае пузырькового кипения соответствует межмолекулярному разделению при максимальном потенциале притяжения, который, в свою очередь, может быть определен из данных по плотности насыщенной жидкости. Расчеты хорошо подтверждаются экспериментальными данными, имеющимися в литературе.