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Pool Boiling of Liquids & their Mixtures on Enhanced Surfaces at Sub-atmospheric Pressures

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This paper is an attempt to measure heat transfer coefficient (HTC) for the nucleate pool boiling of liquids and their binary mixtures on a plain as well as copper coated stainless steel tubes at atmospheric and subatmospheric pressures. Basically, it deals with the effect of heat flux, pressure and composition of mixture on HTC for the boiling of methanol, distilled water, and their mixtures on a plain as well as copper coated stainless steel heating tube surfaces. An experimental setup has been designed and fabricated for the study. Experimental results obtained shows that HTC of binary liquid mixtures have different features as compared with that of pure liquids depending upon their vapor-liquid equilibria behaviors at the prevailing system pressure.

1. Introduction

It has been known from the plenty of experimental investigations on nucleate pool boiling of liquids binary mixtures that the boiling HTC of binary mixtures is significantly lower than those of pure liquids. This trend was observed by almost all the researchers for various types of liquid mixtures at different pressures. The explanations of this behavior of mixtures have been summarized by Thome (1983, 1984).

Nucleate pool boiling of binary mixtures is a complex phenomena and variation in system pressure other than atmospheric may also increase its complexity. Many authors have studied effects of system pressure on binary HTC but most of the literature available is either at atmospheric or at super atmospheric pressures. In fact, data available at atmospheric or higher pressures can not be used with confidence to predict the HTC at sub-atmospheric pressures. Though, few recent works Alam et al. (2008) and Prasad et al. (2007) for boiling of pure liquids are available in literature under sub-atmospheric conditions but measured data are scarce for the boiling of liquid mixtures at lower pressures.

Keeping these in view, the present work was aimed to generate experimental data for the boiling of methanol, distilled water and their binary mixtures on plain as well as copper coated stainless steel surface at various pressures.

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2. Experimentation

The experimentation includes saturated boiling of methanol, distilled water and their binary mixtures on an electrically heated horizontal plain as well as copper coated stainless steel heating tube surfaces. The heating tube has been made of AISI 304 stainless steel cylinder having 18 mm I.D., 31.94 mm O.D. and 150 mm effective length. It is heated by placing a laboratory made electric heater inside it. Wall and liquid temperatures were measured by polytetraflouroethylene (PTFE) coated 30 gauge copper-constantan calibrated thermocouples. The thermocouples are placed inside four holes drilled at a pitch circle diameter of 25 mm in the wall thickness of heating tube for measurement of surface temperature. Similarly, thermocouple probes are placed in liquid pool corresponding to wall thermocouple positions in heating tube for the measurement of liquid temperature. A digital multi-meter measures e.m.f. of thermocouples. The compositions of binary liquid mixtures and those of boiling liquid and vapor were measured by using HPLC system. Power input to heater is increased gradually from 240 W to 640 W in six equal steps and pressure from 44.40 kN/m^2 to 97.71 kN/m^2 in five steps. Three thicknesses of copper coating; viz. 22, 43 and 67 μm have been employed over plain heating tube by electroplating technique. The maximum uncertainty associated with the measured value of average HTC is of the order ±1.13%.

3. Results and Discussion

Experimental data for saturated boiling of distilled water, methanol and their binary mixtures on a plain as well as copper coated tube of various thicknesses at atmospheric and sub-atmospheric pressures have been processed to obtain HTC. Analysis of experimental data has shown surface temperature to increase from bottom to side to top of heating tube for a given value of heat flux at atmospheric and sub-atmospheric pressures. However, liquid temperature remains uniformly constant at all values of heat flux for a given pressure. Above observations are consistent for all the liquids of this investigation.

3.1 Variation of HTC with heat flux and pressure on plain surface

Figure 1a is a plot between HTC and heat flux for the boiling of distilled water on plain stainless steel heating tube. The features of this plot are as follows: at a given pressure, HTC of a distilled water increases with heat flux and the variation between the two can be described by a power law, $h \propto q^{0.7}$ and a rise in pressure enhances the value of HTC subjected to a given heat flux. Both the above features are consistent and in accordance with the physics of boiling phenomenon. Possible explanations for these features are available in Alam (2008). Further, these features have also been observed for the boiling of methanol, as can be seen from the plots in Fig. 1b. It may be pointed out that this also corroborates the findings of various other investigators Alam et al. (2008), Prasad et al. (2007), Pandey (1982), Alam (1972), and Tolubinskiy and Ostrovskiy (1969). On the basis of above analysis, a dimensional equation: $h = C_1 q^{0.7} p^{0.32}$ for saturated boiling of liquids has been developed by the method of least squares within a maximum error of ±5%, where, C_1 is a constant whose value depends up on the type of boiling liquid and heating surface characteristics.

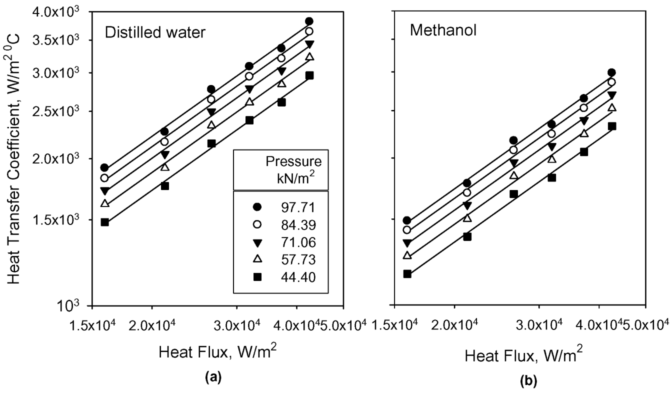

Fig. 1 Variation of HTC with heat flux for boiling of distilled water, and methanol on a plain heating tube with pressure as a parameter

Boiling characteristics representing the variation of HTC of a binary mixture with respect to heat flux and pressure remains the same as those of individual liquids, as evident from Fig. 2. The functional relationship of heat transfer coefficient with heat flux and pressure is same as observed for liquids and therefore a dimensional equation, $h = C_2 q^{0.7} p^{0.32}$ for the boiling of a binary liquid mixture has been developed for atmospheric and subatmospheric pressures.

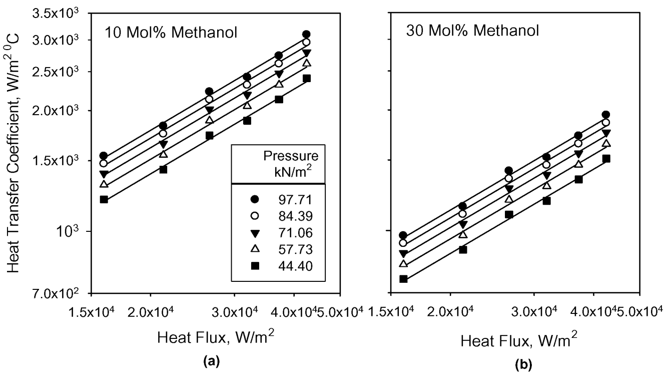

Fig. 2 Variation of HTC with heat flux for boiling of 10 and 30 mol% methanol-distilled water mixture on a plain heating tube with pressure as a parameter

3.2 Variation of HTC of liquid mixtures with composition on plain tube

Figure 3 depicts a typical plot between HTC of a boiling binary liquid mixture and mole fraction of methanol with heat flux as parameter. As can be seen, HTC does not vary linearly with composition but pass through a minimum value corresponding to a composition, turnaround concentration, at which difference between vapor and liquid composition is maximum. Thus, HTC of a boiling binary liquid mixture can not be predicted by the method of interpolation of HTCs of individual components present in the mixture, corroborated by Thome & Shock (1984), Fujita & Tsutsui (1994, 2002), and Sun et al. (2007). This has been due to the occurrence of mass transfer along with heat transfer in the process.

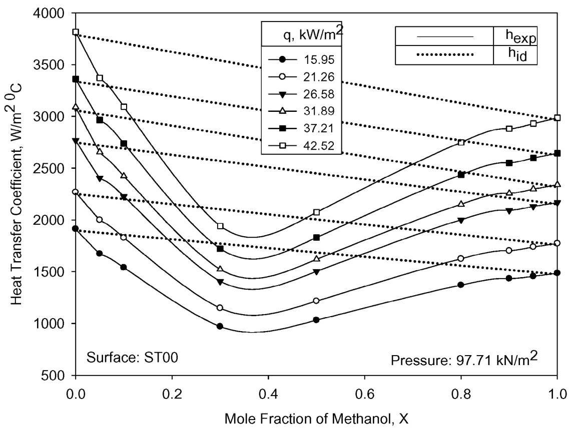

Fig. 3 Variation of HTC, IY-XI with mole fraction of methanol for methanol-distilled water mixtures on uncoated tube at atmospheric pressure

3.3 Variation of HTC of liquids with heat flux and pressure on coated surfaces

Analysis of experimental data for saturated boiling of distilled water on a stainless steel tube coated with copper of various thicknesses at atmospheric and sub-atmospheric pressures have been carried out to establish the effect of operating parameters on HTC of distilled water boiling on coated tubes. Fig. 4 depicts a plot between HTC and heat flux for boiling of distilled water on copper coated tubes and on a plain tube at atmospheric and sub-atmospheric pressures. It reveals that coating of copper on a stainless steel tube enhances heat transfer coefficient for the boiling of distilled water. Further, enhancement is found to depend upon the thickness of coating. However, enhancement for a 43 μm thick coated tube surface is found to be more than any other coated surface of this investigation. These features have also been observed for the boiling of distilled water at subatmospheric pressures. Hence, a 43 μm thick coated tube surface has been selected to conduct experiments for the boiling of methanol as well as various compositions of methanol – distilled water binary liquid mixtures.

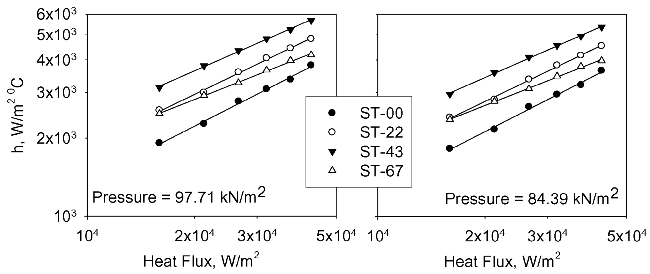

Fig. 4 Variation of HTC with heat flux for boiling of distilled water on copper coated tubes and on a plain tube at various pressures

Boiling of methanol on a 43 μm thick coated tube at atmospheric and subatmospheric pressures has also shown the behavior observed on a plain tube. However, the increase in magnitude of HTC has differed due to difference in physico-thermal properties of methanol and distilled water. On the basis of above, it can be said that coating of copper on a plain tube surface enhances HTC of boiling liquids significantly. Besides, it has also been found that for a given value of heat flux, HTC increases with increase in coating thickness up to a certain value and thereafter decreases. However, increase in HTC is not proportional to increase in coating thickness. Further, the rate of variation of HTC with heat flux depends upon coating thickness. In fact, it decreases with increase in thickness of coating. This continues and therefore, a thick coated heating tube surface may provide HTC lower than that of a plain heating tube surface depending up on the value of heat flux and pressure. At a given value of pressure, HTC of a boiling liquid has been found to vary with heat flux according to power law, $h \propto q^n$, where the value of index, n depends upon the thickness of copper coating and boiling liquid. Consequently, a functional relationship amongst HTC, heat flux and pressure for boiling of liquids on a stainless steel heating tube coated with a given thickness of copper at atmospheric and sub-atmospheric pressures has been established as $h = C_3 q^m p^n$, where the value of constant, C_3 and exponents, m and n depend upon liquid, heating surface characteristics and thickness of coating on heating tube surface.

3.4 Variation of HTC of mixtures with heat flux and pressure on coated surfaces

Heat transfer coefficient of a methanol-distilled water binary mixture on a 43 μm coated tube has been found to be more than that on a plain tube. At a given value of pressure, HTC of a mixture has also been found to vary with heat flux according to power law, $h \propto q^n$. A dimensional relationship, $h = C_4 q^m p^n$ correlating HTC, heat flux and pressure is of the same form as obtained for liquids, where constant, C_4 depends upon the composition of methanol in the mixture, heating surface characteristics and thickness of coating on heating tube surface.

5. Conclusions

i. Analysis of experimental data for nucleate pool boiling of distilled water and methanol on a plain heating tube surface for a wide range of heat flux at atmospheric and sub-atmospheric pressures has shown that HTC of a liquid boiling on a plain tube at atmospheric and sub-atmospheric pressures has been found to be related with heat flux by power law relationship. Raising pressure has enhanced the value of HTC.

ii. The experimental data for the pool boiling of liquid mixtures at atmospheric and sub-atmospheric pressure showed analogous boiling characteristic as that of individual liquids. However, it was found that the value of HTC of binary liquid mixtures is less than that of interpolated value of individual components HTCs.

iii. Experimental data for nucleate pool boiling of distilled water on various copper coated tubes have been generated for different values of heat flux and pressure. Analysis has shown that HTC is related to heat flux by the relationship $h \propto q^n$. The value of exponent n has been found to decrease with increase in thickness of coating. Thus, HTC of distilled water increases with increase in thickness of copper coating on a plain tube. This phenomenon continues up to a particular value of coating thickness and thereafter decreases with further increase in thickness of coating. Enhancement on a 43 µm thick coated tube has been found to be more than 22 and 67 µm thick coated tubes for the boiling of distilled water. Similar observations have also been observed for the boiling of methanol on a 43 µm thick coated tube surface.

iv. The experimental data for pool boiling of liquid mixtures at atmospheric and sub-atmospheric pressure on a 43 µm copper coated tube have shown the same trend as obtained for the boiling of liquids on a plain tube. Further, copper coating does not alter the methanol turnaround concentration. In addition, the correlation developed for boiling of liquid mixtures on a plain tube is also valid for the boiling of liquid mixtures on a 43 µm thick copper coated tube as well.

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