Two-phase heat transfer correlation for multi-component mixtures in the saturated flow-boiling regime

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Investigations of two-phase heat transfer in the saturated flow-boiling region for multi-component mixtures has led to a proposed new correlation for the heat transfer coefficient where heat transfer of boiling is simply expressed in term of the boiling number. This correlation was tested against the existing data on forced convective boiling heat transfer reported in the literature, giving satisfactory results; the correlation should, however, be tested further against wider data on convective heat transfer coefficients in multicomponent systems. The present lack of such data should be remedied.

Keywords: *heat transfer, two phase flow, multicomponent mixtures, boiling*

Little research has been undertaken on heat transfer in flow-boiling of multi-component mixtures[1].Various correlations are reported in the literature for heat transfer regimes in two-phase flow systems, but there is little data on multi-component mixtures. These regimes include the saturated flow-boiling region. Most of the published work on two-phase convective boiling heat transfer[2-8] deal with either single component or binary systems. Even such data are scarce, and most of those available give insufficient accurate information about the local heat transfer coefficient.

The purpose of this work was to investigate further the heat transfer phenomena in two-phase multi-component and binary mixture systems particularly in the saturated boiling region. Based on the experimental results obtained, a general correlation for the local heat transfer coefficient covering both bubbly and slug flow is proposed. Mixtures of ethanol and gasoline at various compositions were used in the experiments, a choice based solely on practical automotive considerations, for example the heat transfer aspect of two-phase multicomponent flow in vapour lock in fuel lines[9].

Experimental equipment

The experimental equipment comprised principally two basic systems: (1) vertical heated tubes with upward flow and (2) instrumentation and controls. Fig 1 indicates the experimental arrangement. The test section consisted of two identical heaters and Pyrex tubes giving a clear view of the development of the saturated boiling regime.

The function of the first heater was to bring the liquid to its saturation state while the second induced bubble formation; adjusting the mass flow rate and input heat flux gave the required flow patterns. Detailed dimensions of the heated tube are given in Fig 2. The heat transfer results were obtained at various ethanol concentrations in premium grade (C_6–C_8 alkanes) gasoline. The ethanol contained 5% water by volume (azeotrope composition).

The gasoline–ethanol mixtures were prepared on a mole basis measuring pre-calculated amounts of each component to give the required mole percent for the mixtures. The mole fraction of ethanol, also referred to as concentration here, was determined from the total moles of the mixture by:

$$\phi_L = \frac{m_{\text{ethanol}}}{m_{\text{mixture}}} \tag{1}$$

The experimental Reynolds number varied up to $Re_L = 10^4$ and heat flux from 8000 to 20 000 W/m^2.

Twenty iron constantan thermocouples were placed in the centre and on the outside wall of the tube at ten locations at regular intervals of 30 mm to measure the wall and bulk liquid temperatures. The inside wall temperatures were then predicted from the measured outside values using the steady heat conduction equation for a hollow cylinder.

Power input to these tube heating tapes was varied using a Variac transformer and measured with a voltmeter and ammeter. The instrumentation facility included the provision of thermocouple wells at the test section. The output emfs of all thermocouples were measured and recorded by a 100 channel digital data logging system. Mixture flow rate was measured using a precalibrated rotameter upstream of the first test section.

An iterative procedure was used to calculate the varying concentration of ethanol along the heated length of the test section using the phase equilibrium diagram and measured temperature.

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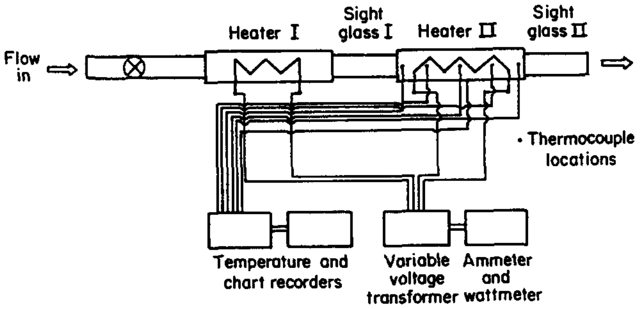

Fig 1 Schematic of the test section

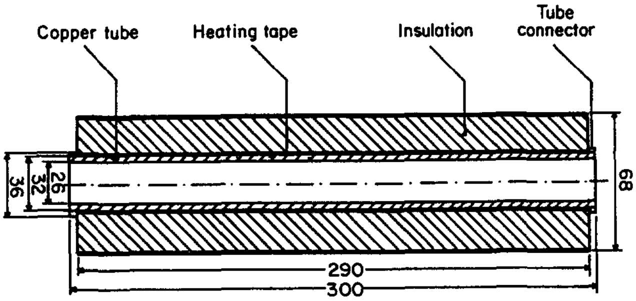

Fig 2 Detailed tube dimensions

Surface and liquid temperature variations

Consider a vertical tube heated uniformly over its length with a low heat flux and fed with subcooled liquid from its base. Fig 3 shows, in an idealized form, the flow patterns considered in the present study. Saturated boiling starts when the fluid temperature equals the saturation temperature, which remains essentially constant over the saturated boiling region for a single-component two-phase flow model.

By contrast, however, the saturation temperature in a multi-component flow system changes continuously along the heated length of the tube as the mixture composition changes. The extent of this saturation temperature change depends on the phase equilibrium characteristics of the mixture. The phase equilibria for a gasoline–ethanol mixture[10] is shown in Fig 4 (gasoline and ethanol form an azeotropic mixture). Such a presentation is only possible if the various components of the mixture are completely soluble in both liquid and vapour phases. Therefore, for mixtures such as gasoline–ethanol, distinctive surface and liquid temperature variations along the saturated boiling region are possible, and depend on the mixture composition.

In contrast to the pool boiling condition, where there is always a mass of liquid mixture of the original composition, the mixture composition in our system changes continuously along the heated section of the tube but is always uniform at and along any cross section of the tube. This condition necessarily implies that bubble growth in the saturated boiling region is not due to the isothermal mass diffusion process, as in the case for pool boiling[11], but to the continuing mixture evaporation process along the heated section. This depends solely on the amount of the applied heat flux, the mass flow rate, and the latent heat of evaporation and composition of the flowing mixture.

Fig 5, obtained experimentally, can be used to verify this postulate and, further, to form a basis for the development of the heat transfer correlation which will be discussed in the next section. Fig 5 shows the mole concentration of ethanol (along the heated section of the tube) as functions of wall superheat and heat flux. The solid and dotted lines indicate constant concentrations of ethanol. The dotted line approximates azeotropic composition.

Depending on the initial mixture composition entering the heated tube (see Fig 4), for a given heat flux

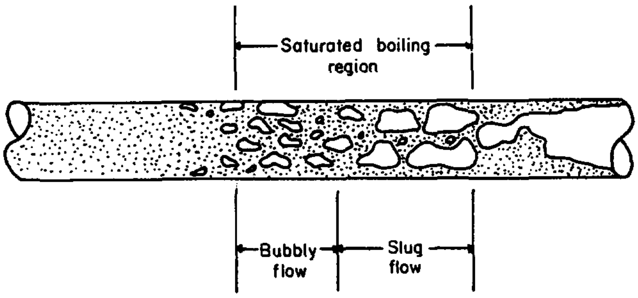

Fig 3 Flow patterns in the saturated boiling region

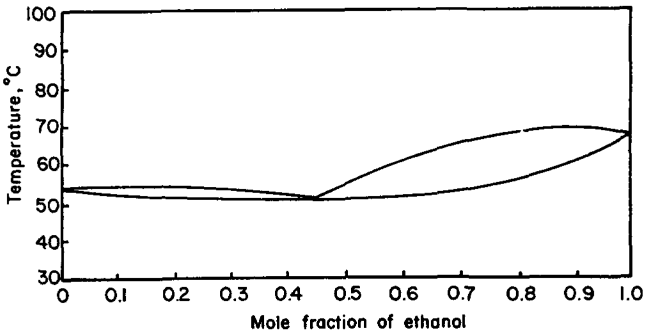

Fig 4 Phase equilibria for gasoline–ethanol mixture

Notation

A	Area
Bo	Boiling number, $Q/A/\rho V h_{fg}$
C_p	Constant-pressure specific heat
D	Diameter of pipe
h_{fg}	Latent heat of evaporation
k	Conductivity
Pr	Prandtl number, $C_p \mu/k$
Nu	Nusselt number
Q	Heat rate
Q/A	Heat flux
Re	Reynolds number, $\rho VD/\mu$
T	Temperature
V	Velocity
α	Vapour void fraction
μ	Viscosity
ρ	Density
ϕ	Mole fraction

Subscript

L Liquid phase

and constant mass flow rate the ethanol concentration progressively varies toward either a larger or smaller value (toward the left or right of the dotted line) as the mixture temperature gradually increases along the heated length of the tube. Therefore, heating a mixture of equal initial composition to give equal final composition at the exit of the tube produces a lower heat transfer coefficient as the heat flux is increased. The slopes of constant concentration lines support this statement.

Other interesting effects may also be observed in Fig 5. Even though increasing heat flux means producing more or larger bubbles, mixture evaporation in the tube reduces the amount of the flowing liquid mass; thus the increasing heat transfer coefficient due to the decreasing liquid hold up generally postulated by many investigators would not result. At lower concentrations of ethanol (lower latent heat of evaporation of the mixture), the evaporating mixture depletes the flowing liquid mass even more to lead to decreasing heat transfer coefficients. To meet the given heat flux, the degree of wall superheat (ΔT) must, therefore, increase. The same result would also be obtained for a constant heat flux condition. The surface and liquid temperature variations along the tube are shown in Fig 6.

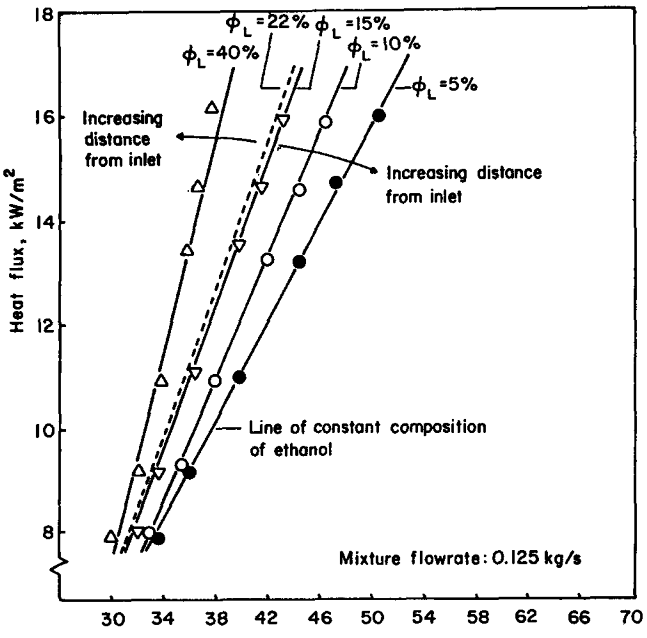

Fig 5 Wall superheat as functions of heat flux and mixture composition

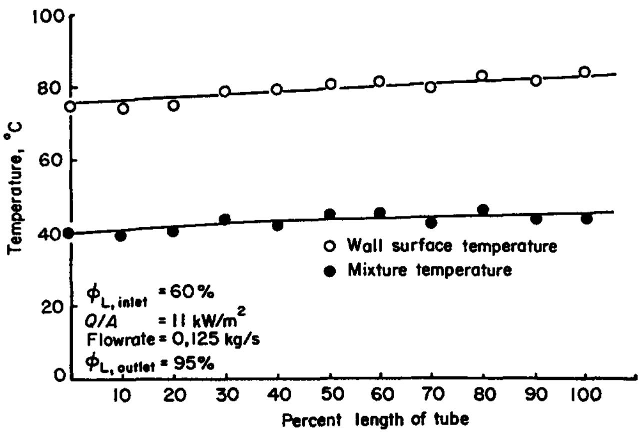

Fig 6 Tube wall and liquid temperature variations

Development of the correlation

Referring to the treatment of McAdams[12] on gravity flow of liquids in a vertically heated tube, the flow patterns considered here are probably the same except for the condition of the unfilled liquid space and the reversed direction of the flow. If such a deduction is correct, then the Reynolds number and the Prandtl modulus of the flow should, in principle, be the same everywhere along the tube provided that no evaporation takes place. Moreover, the two-phase heat transfer coefficient should be simply related to the single-phase heat transfer coefficient by only a flow area factor, as in the case for gravity flow. However, because boiling occurs in our system, this simple relationship might not hold. Nevertheless, many investigators have given the following analogous relationship to account for the effect of the vapour void fraction (α) on the two-phase heat transfer coefficient:

$$Nu_{TP} = \left[\frac{1}{1-\alpha}\right]^n \xi(Re_L)\psi(Pr_L) \tag{2}$$

Even though Lockhart[12] successfully correlates the liquid hold-up parameter $(1-\alpha)$ using the so-called Martinelli parameter, this type of relation, as has been shown previously, may overestimate the two-phase heat transfer coefficient. This has also been verified by many workers. Thus a boiling parameter analogous to the liquid hold-up parameter is introduced instead. The proposed correlation equation then takes the form:

$$Nu_{TP} = \zeta(Bo)\xi(Re_L)\psi(Pr_L) \tag{3}$$

Introduction of the boiling number has basically two significant physical meanings. First, by definition it accounts for the amount of liquid evaporated and, therefore, corrects for the possible change of the liquid flow area due to evaporation. Secondly, it essentially gives the ratio of the mass of the flowing liquid to the mass of the evaporated fluid and, thus, represents the so called liquid hold-up parameter in the Martinelli approach. The mass of evaporated liquid is, strictly, affected by the amount of the applied heat flux and the latent heat of evaporation of the liquid itself which, in this case, are functions of mixture composition and temperature. Obviously, the mixture composition and temperature vary along the heated length of the tube and so does the latent heat of evaporation. Thus it appears that the two-phase heat transfer mechanism in forced convective boiling would be similar for binary or even multi-component mixtures regardless of the different mixture characteristics they might have.

We can therefore conclude that the two-phase heat transfer coefficient for multi-component mixtures should depend on Q/A, h_{fg}, ρ_L, c_L, μ_L and k_L. Applying the Buckingham Pi theorem, the resulting correlation, developed using the experimental data obtained, the two-phase heat transfer coefficient for binary and multi-component mixtures in the saturated boiling region is:

$$Nu_{TP} = 3.2(Re_L)^{0.8}(Pr_L)^{0.8}(Bo)^{0.6} \tag{4}$$

The influence of the Prandtl number on the heat transfer coefficient here is stronger than that typically obtained in single-phase flow, seemingly due to the thermal diffusivity

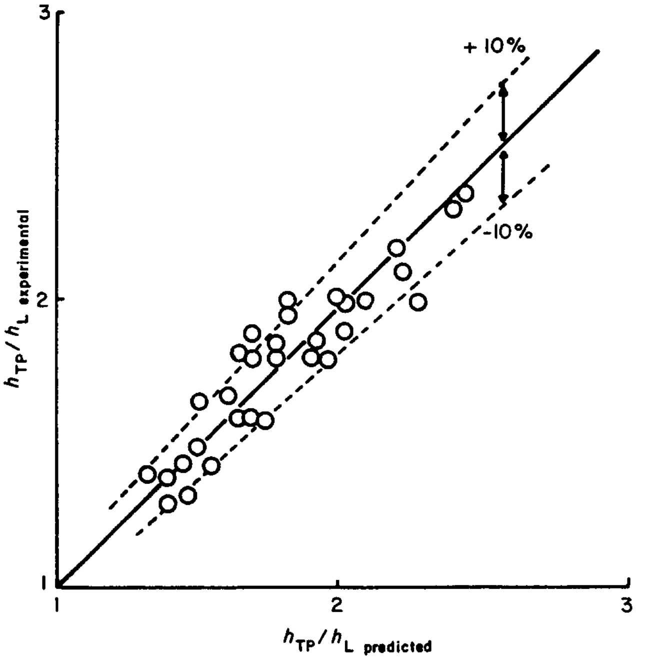

Fig 7 Heat transfer correlation for gasoline–ethanol mixture

effect of the flowing fluid when vapour phase is formed during liquid heating.

The correlation between our experimental heat transfer coefficients and those predicted by Eq (4) is given in Fig 7. However, the present lack of data for multicomponent mixtures limits further verification of the proposed correlation. Work in this area should be continued. Nevertheless, the correlation appears to work well for binary mixtures and pure component systems (Fig 8). The field of application of such systems is considerably wider than that of multi-component systems.

Conclusion

Two-phase heat transfer coefficients in the saturated boiling regime for multi-component and binary mixtures have been satisfactorily correlated by a new function of the type:

$$Nu_{TP}=f(Re_L, Pr_L, Bo)$$

The proposed correlation appears to be practical and simple to use in many designs and engineering applications because one only needs to account for the boiling number. Predictive properties to calculate such a modulus are readily available. In order that the proposed correlation may be tested further, the present lack of data for convective heat transfer coefficients in multicomponent systems must be remedied.

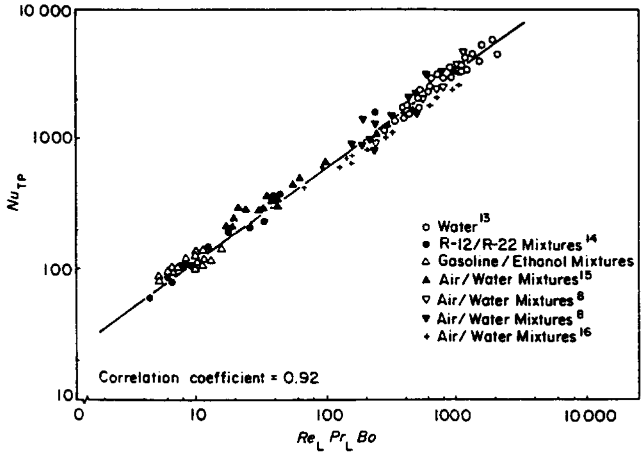

Fig 8 Heat transfer correlation for binary mixture and pure component systems

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