CONVECTIVE HEAT TRANSFER OF BINARY MIXTURES
UNDER FLOW BOILING CONDITIONS

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Abstract

The present study represents part of an effort in considering the replacement of ethylene-glycol/water mixtures with propylene-glycol/water mixtures for engine cooling in automotive application. Experimental results are presented for the heat transfer coefficient under flow boiling conditions for water and mixtures of water with ethylene-glycol and propylene-glycol. The range covered includes the single-phase non-boiling region through the fully developed subcooled flow boiling region to saturated boiling. Since there are no predictive methods available in literature for subcooled flow boiling of binary mixtures, a preliminary comparison with pure component correlations is presented in the fully developed boiling region. Further work is being undertaken to extend the methodology to the partial boiling region and the significant void region.

NOMENCLATURE

\( \alpha \) = heat transfer coefficient, W/m\(^2\)K

\( \text{Bo} \) = boiling number = \( \frac{q^*}{Gi_f} \)

\( C_0 \) = convection number, \((\frac{\rho_G}{\rho_L})^{0.5}((1-x)/x)^{0.8}\)

\( c_{p,L} \) = specific heat of liquid, J/kgK

\( D_{12} \) = mutual diffusion coefficient of 1 in 2 in liquid phase, m\(^2\)/s

\( \frac{dT}{dx} \) = slope of the bubble point curve for the mixture

\( F_{fl} \) = fluid surface parameter

\( G \) = mass flux, kg/m\(^2\)s

\( \Delta h_{LG} \) = latent heat of vaporization, J/kg

\( q^* \) = heat flux, W/m\(^2\)

\( r \) = radius, m

\( T \) = temperature, K

\( T_{1,2} \) = measured temperatures at radial positions, \( r_1 \) and \( r_2 \)

\( V_1 \) = volatility parameter, \( \frac{c_{p,L}}{k} \left( \frac{k}{D_{12}} \right)^{1/2} \frac{dT}{dx}(x_1 - y_1) \)

\( x_1 \) = mass fraction of more volatile component in liquid phase

\( y_1 \) = mass fraction of more volatile component in vapor phase

Subscripts

\( f \) = bulk fluid

\( \text{fl} \) = fluid

\( \text{LO} \) = liquid only

\( \text{nb} \) = nucleate boiling component

\( \text{NBD} \) = nucleate boiling dominant

\( \text{sat} \) = saturation value

\( \text{TP} \) = two phase

\( \text{w, wall} \) = wall

INTRODUCTION

The objective of this paper is to present experimental data on flow boiling from the subcooled boiling region to the saturated boiling region. Using this data base, various predictive schemes will be evaluated. The data includes single and binary component mixtures.

With the greater emphasis on performance, there has been an increased interest in achieving higher heat transfer coefficients by the use of boiling heat transfer. An area of considerable activity is low-pressure flow boiling. Internal combustion engines are cooled with ethylene-glycol/water mixtures operating at approximately two atmospheres and encompassing the heat transfer regimes from single phase through saturated boiling. Advanced nuclear reactor systems provide emergency core cooling in the pressure range of one to two atmospheres. Computer manufacturers are involved in investigations using boiling heat transfer to cool high dissipation components.

Although a large body of work exists for saturated boiling, subcooled boiling under flow conditions requires additional investigation. The purpose of the present study is to present experimental results obtained for binary mixtures.
under operating conditions representative of engine cooling systems. The broader purpose of the experiments is to compare the thermal performance of aqueous mixtures of propylene-glycol and ethylene-glycol. Although ethylene-glycol/water mixtures have performed satisfactorily in internal combustion engines, leaks from automotive cooling systems are responsible for accidental human and animal exposures. Ingestion of ethylene-glycol can be harmful or fatal even in relatively small doses. Propylene-glycol is less toxic than ethylene-glycol and possesses very similar heat transfer characteristics, and, therefore, appears to be an ideal replacement. The resulting boiling heat transfer data base can provide a resource to evaluate heat transfer coefficient prediction methods.

In addition to the mixture data, a limited amount of data for water was also obtained. The test conditions provide results from single-phase flow, sub-cooled boiling, and saturated boiling. The resulting data base contains approximately 7500 test points. Although most of this data was obtained at a fixed mixture concentration of 50/50 by volume, a limited amount of data was obtained for 70/30 and 30/70 aqueous mixtures for both coolants.

BACKGROUND

Experimental data for flow boiling with mixtures under subcooled conditions is limited. A number of studies are reported in literature for flow boiling of mixtures under saturated conditions. Among the predictive methods available in literature for saturated flow boiling of mixtures, those presented by Jung [1], Bennett and Chen [2], and Kandlikar [3] are noteworthy. Jung [1] presented extensive results for refrigerant mixtures and based upon this data developed a correlation scheme involving 25 constants. Bennett and Chen [2] developed a correlation based upon the widely used Chen [4] correlation for saturated boiling. Kandlikar [3] extended his theoretical model developed for pool boiling of binary mixtures (Kandlikar [5]) to flow boiling and compared his correlation with available data for refrigerant mixtures with good agreement.

Although ethylene-glycol/water mixtures have been used as engine coolants for over fifty years, there is very little heat transfer data available in the open literature. In an automobile cooling system, the working fluid is generally a mixture of water and either ethylene-glycol or propylene-glycol. The normal mixture concentration is 50/50 by volume. Finlay et al. [6] presented experimental results for an ethylene-glycol/water mixture covering an operating range appropriate to automotive engine cooling conditions. Most of the data were obtained under constant pressure conditions using a copper test section. Some data were also obtained for other test section materials including cast iron and aluminum, and for constant flow-rate operation. These results showed reasonable agreement with analytical predictions based upon the Chen correlation at low surface heat fluxes. However, at higher fluxes under subcooled boiling conditions, the same model tended to under-predict the surface temperature.

McAssey, Stinson, and Gollin [7] presented test results comparing propylene-glycol/water and ethylene-glycol/water mixtures for a range of conditions similar to those existing in normal engine operation. For the range of test conditions, the resulting data spanned the spectrum from single-phase convection to saturated boiling. These investigators concluded that the overall performances for both coolant mixtures were very similar. This paper also presented comparisons between analytical predictions, again based on the Chen correlation, and experimental results. In general, the analytical results under-predicted the surface temperature when the difference between the surface temperature and the fluid temperature exceeded 60°C.

Bhowmick, Branchi, McAssey, and Gollin [8] presented additional data on both fluid mixtures for a wider range of conditions. In their work, the inlet velocity was varied from approximately 0.4 m/s to 2.5 m/s and the surface heat fluxes reached a maximum of 1.8 MW/m². In addition, comparisons were presented between experimental results and analytical predictions based upon the Chen correlation. The experimental results showed that both mixtures had similar thermal performances. In general, the analytical results under-predicted the measured wall temperature by a significant margin.

Bhowmick et al. [9] presented comparisons between predicted results and experimental data for water and aqueous mixtures of ethylene-glycol and propylene-glycol. Although the Chen [4] correlation provided the best approximation to the experimental results, the method tended to over-predict the heat transfer coefficient. Using water data obtained as part of the engine test program, a revised Chen correlation was developed. The revision involved a modification to the S factor in the Chen correlation. With this revised correlation, the authors showed improved predictions for both ethylene-glycol and propylene-glycol mixtures.

Kandlikar [10] presented a method to predict subcooled boiling of a pure component. It was based on the saturated flow boiling correlation developed by Kandlikar [11]. Three regions were identified under subcooled flow boiling after the onset of nucleate boiling (ONB): partial boiling region, fully-developed boiling region, and significant void-flow region. The criteria for identifying each region along with the correlations for specific regions were also presented. These correlations showed good agreement with published experimental data for water and several refrigerants.

In the present work, Kandlikar's [10] model for subcooled flow boiling in the fully developed boiling region is extended to the binary mixtures. The onset of nucleate boiling and partial boiling region will be covered in the follow up work of this investigation.

DESCRIPTION OF TEST FACILITY
Flow Loop

The flow loop consisted of a test section, pump, accumulator tank, rejection heat exchanger, and required piping. Figure 1 presents a schematic layout of the test loop. For this program, the loop was operated in the controlled flow mode. In this mode of operation, the test section is provided a constant volumetric flow-rate under all operating conditions. Since most of the pressure drop occurs across the control valve, changes in the test section pressure drop due to heating have a small effect on the flow-rate to the test section. The bypass line around the test section was installed to allow operation on the constant-head portion of the pump performance curve and to reduce the vapor content of the fluid entering the heat exchanger. Table 1 identifies the types of instruments used in the experiment. The primary flow-rate instrument was a
Table 1 Instrument Accuracy

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Type of Instrument</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>E-type thermocouple</td>
<td>+/- 1.2 °C</td>
</tr>
<tr>
<td>Pressure</td>
<td>Pressure gauge</td>
<td>+/- 1% F.S.</td>
</tr>
<tr>
<td>Pressure Drop</td>
<td>Differential pressure transducer</td>
<td>+/- 0.25% F.S.</td>
</tr>
<tr>
<td>Test Section Flow-rate</td>
<td>Turbine flowmeter</td>
<td>+/- 0.50% of reading</td>
</tr>
<tr>
<td>Loop Flow-rate</td>
<td>Rotometer</td>
<td>+/- 0.75% F.S.</td>
</tr>
<tr>
<td>Power Input</td>
<td>Voltage and current measurement</td>
<td>+/- 1% of reading</td>
</tr>
<tr>
<td>Test Section Fluid</td>
<td>E-type thermocouples</td>
<td>+/- 1.2 °C</td>
</tr>
</tbody>
</table>

turbine flow meter (FL-1) located upstream of the test section. Test section inlet pressure and temperature were measured by a pressure gauge (P-1) and a thermocouple (RTD-1) respectively. A similar arrangement (P-2 and RTD-2) located downstream of the test section was used to measure exit conditions.

![Figure 1 Schematic of the flow loop](image1)

Figure 1 Schematic of the flow loop

The accumulator tank was used to maintain the system pressure. Pressure control was accomplished by means of adjusting the liquid level or the argon pressure. An argon blanket was maintained in the top of the accumulator tank and the pressure in this region was adjusted using an external argon supply. The tank also contained a heater to control the test section inlet temperature. The accumulator tank also produced a constant head source for the loop pump, which was a centrifugal pump capable of producing 0.3 m³/min. at 400 kPa. A control valve located upstream of the test section was used to provide the required flow to the test section. After leaving the test section, the bypass and the test section flows combined before entering the heat exchanger.

**Test Section**

The test section (shown in Fig. 2) was constructed from a 114 mm diameter aluminum cylinder with a length of 165 mm. The horizontal flow channel consisted of a 9.53 mm diameter hole drilled along the centerline of the cylinder. The test section was heated by ten cartridge heaters located on a 97.9 mm diameter circle. Each heater was capable of producing 1,000 watts at 120 volts. By operating at slightly higher voltages, it was possible to dissipate approximately 11 kW in the test section.

![Figure 2 Test section](image2)

The test section was connected to the flow loop by means of inlet and exit calming sections, which have the same inside diameter as the test section. The upstream calming length and the test section each had an L/D ratio of 17:1. This ratio was considered to be sufficient to provide fully developed flow to the heated length. In order to minimize heat loss from the system, the entire flow loop and test section were insulated. The insulation on the test section consisted of over 200 mm of fiberglass insulation.
The test section temperatures were measured by 20 B type thermocouples, mounted at five axial stations along the cylinder (see Fig. 2). Using two thermocouples on the same radial line, the surface temperature can be calculated using Eq. (1).

\[ T_{wall} = T_1 + (T_2 - T_1) \frac{\ln(r_0 / r_1)}{\ln(r_2 / r_1)} \]  

(1)

All thermocouple measurements were made in the same horizontal plane. This arrangement provided two essentially equal surface temperature measurements at each axial location.

**Instrumentation**

The instrumentation for this program was chosen to determine various test parameters and test section temperatures. Test section flow-rates were measured with turbine flowmeters and rotometers. The rotometers were calibrated using a weigh tank with the mixtures at the required operating temperature of 85 °C. The turbine flowmeters were then calibrated against the rotometers. A high temperature thermocouple calibrator was used to calibrate each sensor over the complete operating range. Table 1 presents an estimate of the overall accuracy of the instruments used in these tests.

Since the present study involves the prediction of heat transfer coefficient, the uncertainty in the measurement of this quantity must be examined. The experimental test program was designed to simulate normal engine operating conditions, and, therefore, the fluxes and wall temperatures are quite high. Figures 3 and 4 present surface heat flux versus measured wall temperature for a typical set of test conditions for the binary mixtures. The two parameters determining the heat transfer coefficient are the measured power and the temperature difference (\(T_{wall} - T_{fluid}\)). The power measurement bias error is ±2%. Using the ±1.2 °C uncertainty in temperature measurement, Fig. 5 shows that the uncertainty in \(T_{wall} - T_{fluid}\) varies with flux. In the range of interest above 250,000 W/m² flux, the bias error is ±10%. The total bias error is, therefore, ±12%.

In developing these data, a reference test was established and repeated several times. Figure 6 presents data for propylene-glycol/water obtained over a two month period...
at the same nominal test conditions. This figure shows that most of the data falls within or very close to the 95% confidence level. Using these results as the precision error, the overall uncertainty in heat transfer coefficient is ±13%.

DATA BASE

The experimental results were obtained for a range of conditions representative of internal combustion engine cooling system conditions for both normal and abnormal operation. The normal aqueous equilibrium mixture recommended by engine manufacturers for both ethylene-glycol and propylene-glycol is 50/50 by volume. However, it was recognized that this mixture concentration recommendation was not necessarily followed by the end user. Therefore, tests were performed at two other concentrations to examine the effect on coolant performance. In addition to the two binary mixtures, experiments were conducted with 100% water.

DISCUSSION

The theoretical approach presented here combines the saturated flow boiling model for mixtures by Kandlikar [3] and subcooled flow boiling for pure components by Kandlikar [10]. As stated earlier, only the fully developed boiling region is investigated.

Saturated flow boiling heat transfer with binary mixtures was classified by Kandlikar [3] into three regions depending on the level of suppression as defined by a volatility parameter, V1.

Region I

Near azeotrope region, V1< 0.03, is applicable where the effects of mass diffusion are insignificant, as is the case with azeotropic mixtures.

αTP.B = larger of αTP.B,NBD (2)

αTP.B,NBD and αTP.B,CBD are given by eqs. (3) and (4) respectively using mixtures properties.

αNT.B = 0.6683Co -0.2 (1 - x) 0.8 αLO
+ 1058.0Bo 0.7 (1 - x) 0.8 FpαLO (3)

αTP.CBD = 1.136Co -0.9 (1 - x) 0.8 αLO
+ 667.2Bo 0.7 (1 - x) 0.8 FpαLO (4)

Fp in eqs. (3) and (4) is a fluid-surface parameter related to the nucleation characteristics which is taken as the mass fraction averaged value for the pure components. The single-phase heat transfer coefficient αLO is obtained from the Petukhov and Popov [12] and Gnielinski [13] correlations. For further details, refer to Kandlikar [3].

Region II

Moderate diffusion-induced suppression region, 0.03< V1<0.2, and Bo 10^4, includes the region where mass diffusion effects begin to affect the heat transfer. Here, the nucleate boiling is suppressed and heat transfer is well represented by the following correlation developed for the CBD (Convective Boiling Dominant) region given by eq. (5).

αTP,B = αTP,CBD

Region III

Severe diffusion-induced suppression region, a) for 0.03< V1<0.02 and Bo<10^4, and b) V1>0.2;

αTP,B = 1.136Co -0.9 (1 - x) 0.8 αLO
+ 667.2Bo 0.7 (1 - x) 0.8 FpαLO (6)

The mass diffusion effects further reduce the heat transfer given by the CBD equation, eq. (4), through a mass diffusion factor Fp applied to the nucleate boiling component as seen in eq. (7).

FD = 0.678 ± 0.014Co /

Instead of using the interface concentrations xLs and yLs, the equilibrium liquid and vapor concentrations may be used in Eq. (7) for simplicity. In the fully developed region of subcooled boiling, Kandlikar [10] presented the following correlation, which is rewritten in Eq. (8) in terms of the wall minus fluid temperature difference.

αTP = 1058.0Bo 0.7 FpαLO (Tu - Tw) / (Tu - Tf) (8)

In Eq. (8), the coefficient 1058 corresponds to the nucleate boiling term in the nucleate boiling dominant equation given by eq. (3). Kandlikar and Bulut [14] extended the model presented in eqs. (2)-(7) to the fully developed region of subcooled boiling with mixtures as given by the following equation.

Equation (9) is expected to apply in the moderate diffusion-induced suppression region. An additional factor Fp would be applicable where diffusion-induced suppression is
The present work falls under moderate diffusion induced suppression region as indicated by Kandlikar and Murat [14]. Figure 7 presents a comparison for pure water data with predictions based upon Eq. (9) with the convection dominant coefficient. In the fully developed region, the agreement is reasonable. Figure 8 presents a comparison between prediction and experiment for all flow rates. Except for a few points, all the data could be predicted within ± 20%. Note that some of the data points fall under partial boiling region where a more detailed scheme presented by Kandlikar [10] is applicable.

Figures 9 through 12 show comparisons between prediction, in the fully developed boiling region, from Eq. (9) and experimental data for two binary mixtures, ethylene-glycol/water and propylene-glycol/water. Each mixture had the same equilibrium concentration of 50/50 by volume. In general, the predictions based upon Eq. (9) provided fair agreement for the ethylene aqueous mixture. In Figs. 11 and 12 for the propylene-glycol/water mixture, it can be seen that the approach significantly under-predicts the heat transfer coefficient when compared to the experimental data. Several factors must be considered. The fluid-surface parameter, $F_l$, severe.
was taken as unity, which may not be true for this mixture. Also, the mass diffusion effects may not be as severe, and a constant between 667 and 1058 may be appropriate. Work is continuing on the calculation of diffusion suppression factors.

Figure 13 presents a comparison of prediction and experiment for all the ethylene-glycol/water data at 129 kPa and 205 kPa. Except for the partial boiling region, the agreement is very good, within ± 25%.

CONCLUSIONS

Experimental results are obtained for subcooled flow boiling of water and aqueous mixtures of ethylene-glycol and propylene-glycol under a range of conditions generally encountered in automotive engine-cooling applications. The experimental results are compared with the existing predictive methods. Since there are no methods available for subcooled flow boiling of mixtures, a preliminary comparison is carried out following the model developed by Kandlikar and Mulut [14], which combines the methodology presented by Kandlikar [10] for subcooled boiling of pure components and by Kandlikar [3] for saturated flow boiling of mixtures.

The pure water data could be predicted within 30 percent accuracy using the single-phase correlation and the fully developed boiling correlation, Eq. (9). Further improvement is expected by incorporating specific correlations given by Kandlikar [10] in the partial boiling region.

Equation (9) with an $f_3$ of unity was also shown to yield good results for a 50/50 by volume mixture of ethylene-glycol/water. For the propylene-glycol/water mixture, this approach tended to under-predict the heat transfer coefficient over a range of operating conditions. Estimation of accurate fluid-surface parameter, and further evaluation of diffusion effects for this mixture are expected to improve the results.

Finally, additional operating conditions and mixture concentrations are being investigated.

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REFERENCES


