CHARACTERIZATION OF HEAT TRANSFER FLUIDS BY SURFACE TENSION AND CONTACT ANGLE MEASUREMENTS

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Abstract

It is required in heat transfer applications that a coolant fluid makes and retains contact with the surface being cooled. This phenomenon is called surface wettability. Surface tension and contact angle measurements are effective tools used to measure the degree of surface wettability of liquid coolants.

In this work, we carried out surface tension and contact angle measurements of pure and binary mixture: water, ethylene glycol and water-ethylene glycol were studied on a polished steel substrate in a closed environmental chamber at various temperatures. We reckon from our results that heat transfer properties of coolant fluids can be tuned by surface tension and contact angle measurements.

Key words; Contact angle, Heat transfer, Surface tension

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Introduction

A coolant is a fluid which flows through or around a device to prevent its overheating, transferring the heat produced by the device to other devices that use or dissipate it. The effectiveness of a coolant fluid lies in its ability to make and retain contact with the surface being cooled which is usually at higher temperature. Water is an abundant and inexpensive coolant fluid, although the heat transfer properties of water is enhanced when mixed with ethylene glycol, the mechanism responsible for this enhancement remains a subject of interest. Enhanced heat transfer properties of pure and mixed fluids cannot be fully explained by known factors like ballistic phonon transport and Brownian motion [1]. There remains other possible explanations such as heat conduction due to surface wettability and spreading enhancements, convection induced by interfacial tension reduction, etc.

Surface wettability phenomenon is a playground where chemistry, physics and chemical engineering intersect. Surface chemistry is of key importance in determining wetting behaviour of substances, and a large research effort has been put into modifying the surface chemistry of various solids in order to obtain specific wetting properties [6]. In this research however we focused our attention on the modification of liquid composition to get desired properties.

Coolants with high wettability would spread quickly on the heated surface depending on its surface chemistry and the chemical composition of the liquid. A hydrophobic surface tends to avoid or minimize contact with liquids while a hydrophilic surface promotes contact, causing the liquid to spread easily.

Mathematical Formulations

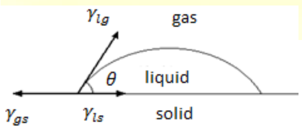

Fig.1. Droplet of water on ideal surface: γ_{lg} = Liquid-gas/vapour interfacial tension, γ_{gs} = gas/vapour–solid interfacial tension, γ_{ls} = liquid-solid interfacial tension and θ = the contact angle.

For a liquid drop on a solid substrate in equilibrium state, there are three different phases present (Fig.1). Therefore there are three surface tensions that need to be considered: solid-liquid, liquid-gas/vapour and solid-gas/vapour. Young's equation [7] gives the relation between the equilibrium contact angle θ_{eq} the drop makes with the surface and the three surface tensions as:

$\gamma_{gs} = \gamma_{ls} + \gamma_{lg}\cos\theta_{eq}$ ……………… (1)

Here all the surface tensions are defined for a homogeneous and chemically inert surface when the three phases, solid, liquid and gas (i.e. saturated vapour of the liquid), are at least in mechanical equilibrium (force balance) with each other. If the three tensions are known, the wetting state of the fluid follows directly. If $\gamma_{gs}<\gamma_{ls}+\gamma_{lg}$, a droplet with a finite contact angle minimizes the free energy of the system; partial wetting will be formed. On the other hand, if $\gamma_{gs}>\gamma_{ls}+\gamma_{lg}$, complete wetting will occur and contact angle = 0. The distinction between the different wetting states is usually made by considering the spreading coefficient:

S= $\gamma_{gs} - (\gamma_{ls} + \gamma_{lg})$…………….. (2)

When S > 0, the liquid wets the surface completely (complete wetting). When S < 0, partial wetting occurs.

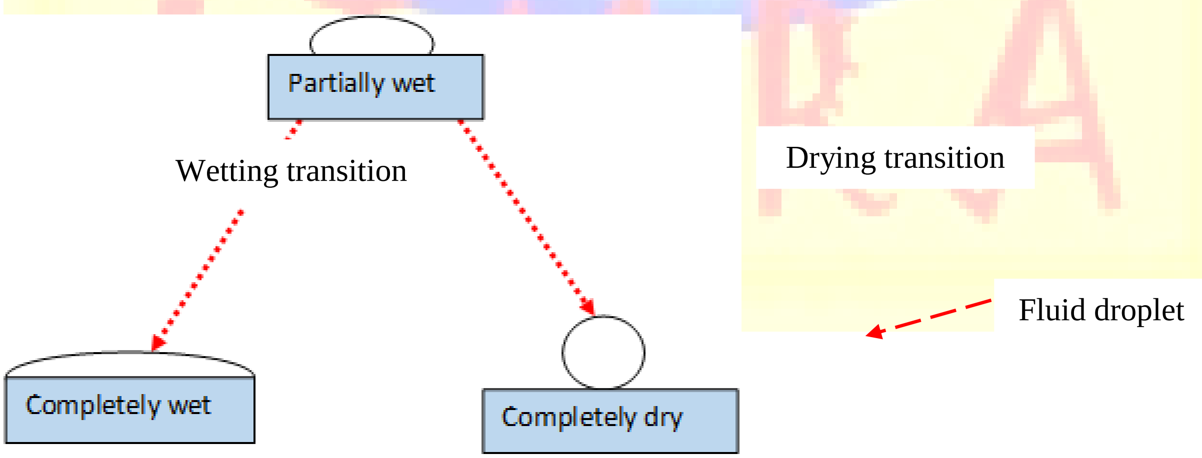

Fig.2.The three wetting states that may exist in any three-phase system.

Conclusively, it is not possible to measure the surface tension of solids, equation (1) is largely dependent on liquid-solid interfacial tension γ_{ls}which depends on the liquid composition.We shall henceforth use interfacial tension to mean surface tension between two surfaces, the fluid sample and the polished steel substrate.

Experiment Methodology

Distilled water and ethylene glycol used in this experiment were supplied by Sigma-Aldrich Co. LLC Chemicals Limited.

Surface Tension and Contact Angle Measurements

We carried out in situ determination of surface tension and contact angle using our multipurpose goniometer. Sessile drop fitting method was used because it can be applied to Young-Laplace equation for quick calculation of interfacial tension since the needle diameter and density of the drop are known. For static contact angle greater than 30^0, interfacial tension was calculated separately to get reliable results.Measurements were carried out in a closedenvironmental chamber at 20, 25, 50, 70 and 80^0C respectively.

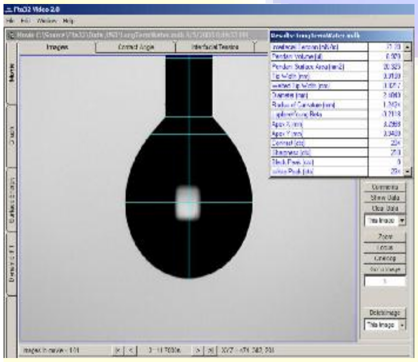

Fig.3. Simultaneous determination of interfacial tension and contact angle.

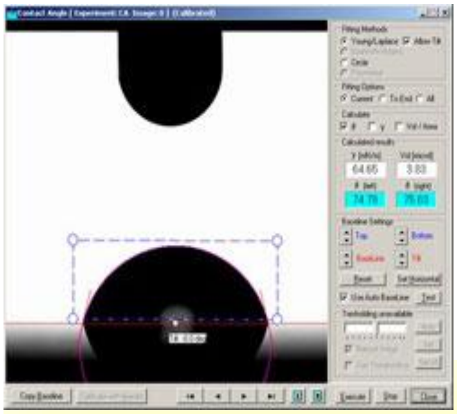

Fig.4. Screen capture of fluid drop on polished steel

Results and Discussions

At constant temperature of 20^{0}C the interfacial tension of distilled waterwas determined to be ≈71.83mN/m (fig.5), interfacial tension of 25vol% water-ethylene glycol at 20^{0}C ≈ 60.0mN/m (fig.6) and interfacial tension of pure ethylene glycol at 20^{0}C ≈ 51.0mN/m (fig.7). We reckon that ethylene glycol reduces the surface tension of water to a degree that is dependent on its concentration by volume.

Next, we determined that high interfacial tension causes water to be attracted to itself, which is why water beads-up on a slick surface, and in effect we measured contact angle at various temperatures for pure and binary components of samples.

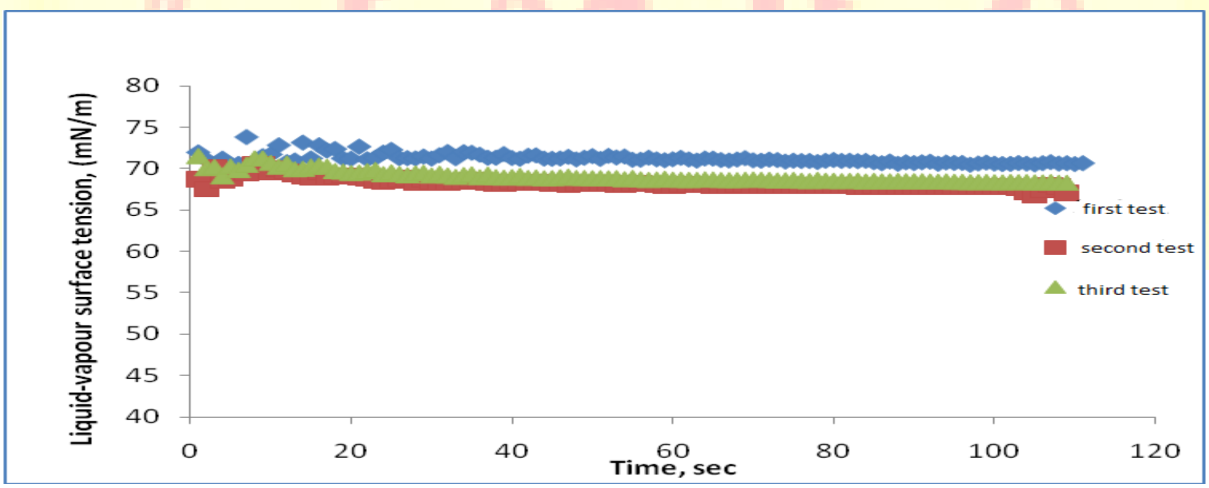

Fig. 5. Interfacial tension of distilled water at 20^{0}C.

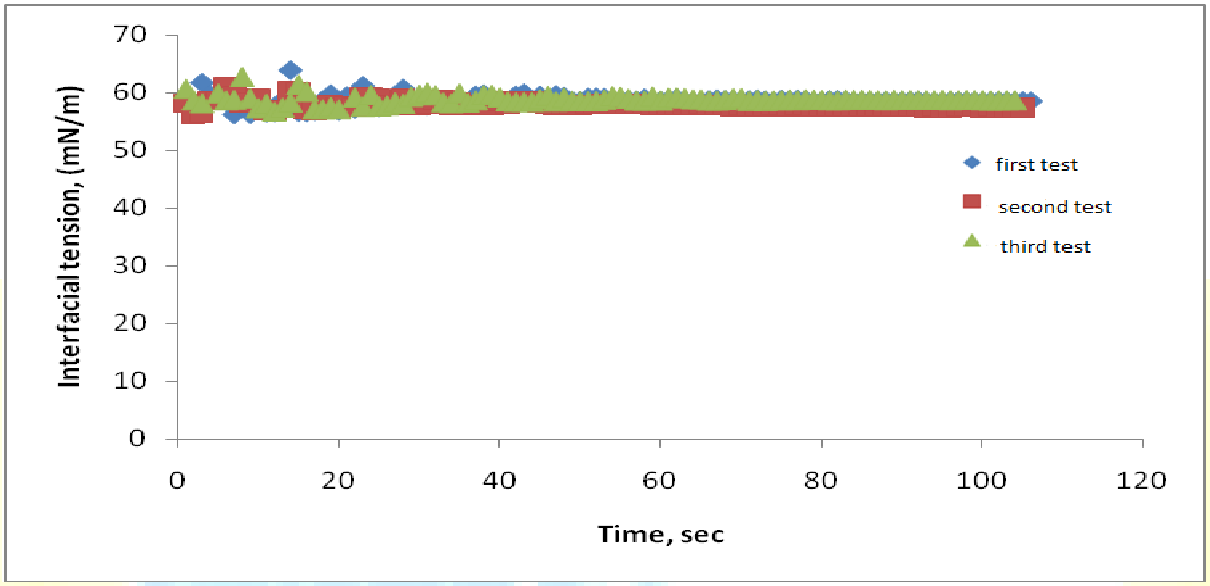

Fig. 6. Interfacial tension of 25vol% water-ethylene glycol mixture at 20^0C.

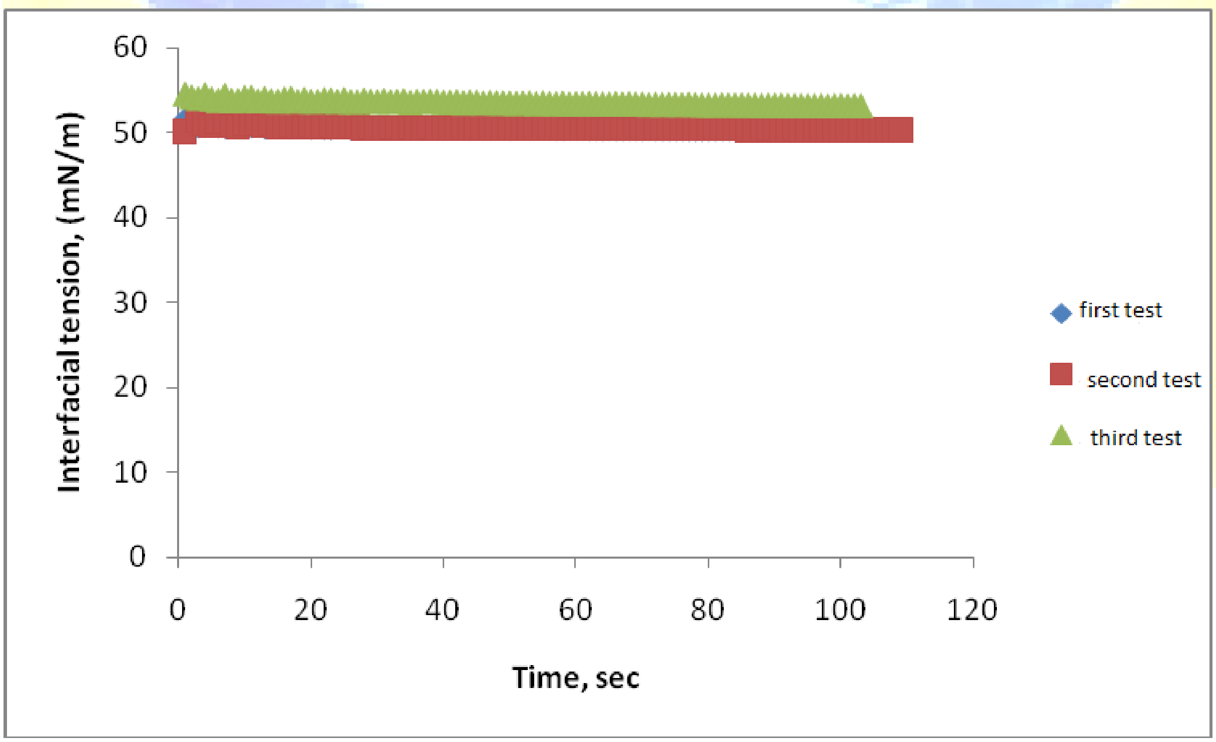

Fig. 7. Interfacial tension of pure ethylene glycol at 20^0C.

Temperature Dependence of Static Contact Angle

Contact angle is equal to the inverse of surface wettability and is a measure of the effectiveness of heat transfer, the higher the contact angle the less wettable a coolant fluid is. Temperature dependence of the static contact angle was investigated by measuring the contact angle at different temperatures. The result was analysed graphically for each sample tested.

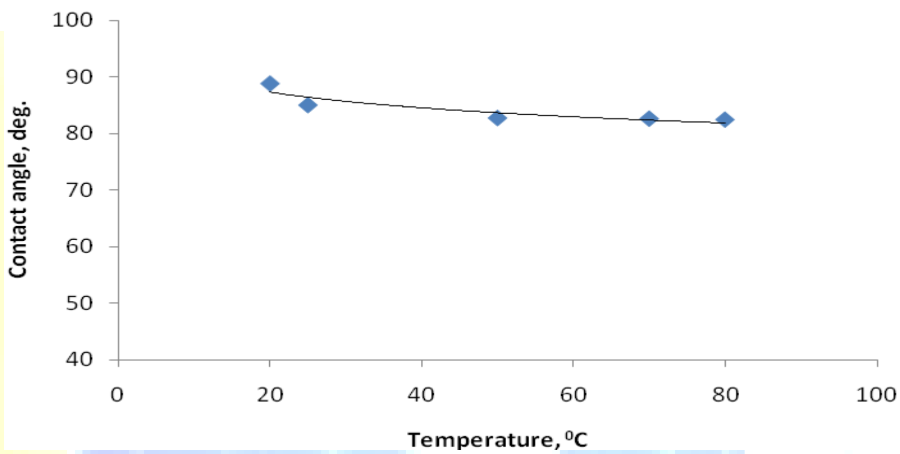

Fig.8. Contact angle of distilled water measured on polished steel substrate.

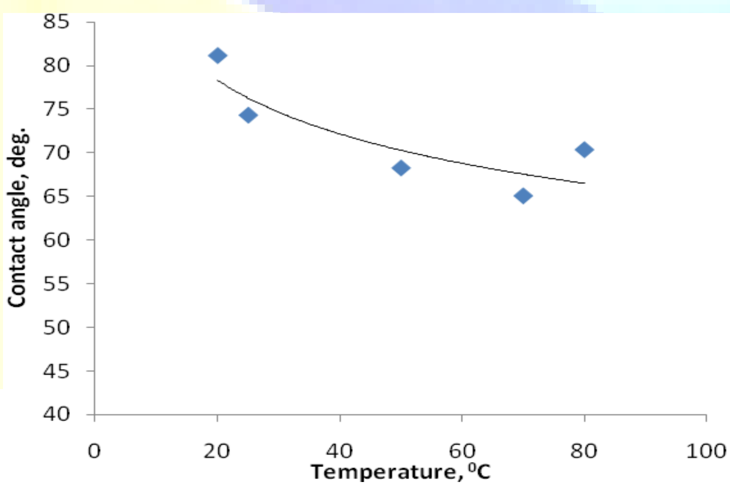

Fig.9. Contact angle of pure EG measured on polished steel substrate

From the test result of pure fluids on polished steel, ethylene glycol proved more wettable than pure water, evident in reduction of static contact angle which validates its use as a medium for convective heat transfer, for example in liquid cooled super computers.

Mechanism of heat transfer enhancement of water using ethylene glycol

The effect of ethylene glycol on the surface wettability of water was investigated by measuring the time-dependent static contact angle of pure water, ethylene glycol and water-ethylene-glycol base fluids on polished steel template at 20^0C for 180 seconds.

Table 1. Experiment test conditions for pure water, EG and WEG.

Sample	pH	Contact angle, deg.
Pure water	7	88
EG	7	71
25%vol. WEG	7	85

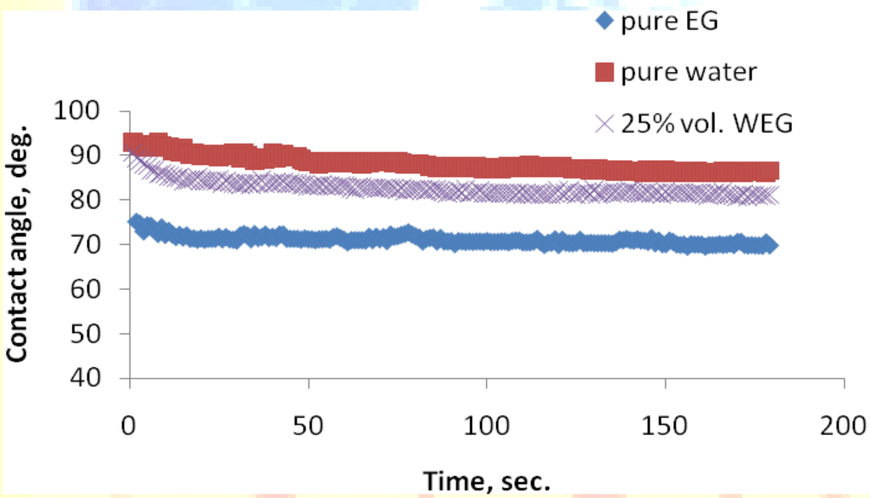

Fig.10. Measured values of contact angles as a function of time for pure water, ethylene glycol and mixed water-ethylene glycol.

To understand the dramatic enhancement of wettability of water by mixing water with EG, Young's equation cosθ = $(\gamma_{gs} - \gamma_{ls}) / \gamma_{lg}$ was considered, which relates the static contact angle to the adhesion tension $\gamma_{gs} - \gamma_{ls}$ and the interfacial tension γ_{lg}. The interfacial tension of distilled water at 20^0C is ≈71.83mN/m (fig.5), interfacial tension of ethylene glycol at 20^0Cis ≈ 51.0mN/m (fig.6) and interfacial tension of water-ethylene glycol at 20^0Cis ≈ 60.0mN/m (fig.7).So Young's equation predicts higher contact angle for water which is in reasonable agreement with this result, (see fig.8). Contact angle of pure EG was calculated to be 71^0 and 25%vol WEG 85^0 and distilled water 88^0. Depending on the concentration of ethylene glycol in water by volume percent, the wettability of water is enhanced. If the heater surface is not smooth, the effective solid-liquid contact area differs from the smooth contact area.

Conclusions

Our result shows that surface tension and contact angle measurements are effective tool that can be used to characterize and optimize heat transfer properties of coolants among other parameters. Ethylene glycol was found to improve the surface wettability of water by reducing the surface tension of water and the interfacial tension between water-ethylene glycol and the polished steel substrate used as the heater surface.

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