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Measurements of the contact angle between R134a and both aluminum and copper surfaces

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Abstract

Measurements of quasi-static advancing contact angles of refrigerant R134a on copper and aluminum surfaces are reported over a temperature range from 0 °C to 80 °C. The metal surfaces tested were aluminum (alloy 3003) and copper (alloy 101) plates. Measurements were done using a direct optical observation technique where the liquid meniscus at the surface of a vertical plate was captured using a high magnification camera system. The contact angle of solid–liquid interface was deduced by enhancing and manipulating the digital image using solid modeling software by drawing a tangent line to the meniscus at the intersection location of the solid, liquid and vapor. Values of the contact angle were found to vary between 8.3° and 5.6° for aluminum and between 5.1° and 6.5° for copper when the temperature rose from 0 °C to 80 °C. Maximum standard deviation amongst the measured values of contact angles was 1.3°.

Keywords: R134a; Contact angle; Heat pipes; Refrigerants; Contact angle measurements; Wettability; R134a properties

1. Introduction and background

Contact angle is an extremely important parameter that defines the wetting phenomenon important in several industrial processes as well as in our daily life. It can be used to know how well a fluid will wet a particular surface, penetration of liquids in porous structures, fluid–fluid displacement as well as to characterize solid surfaces [1].

In most of the heat transfer processes involving a two-phase system, vaporization and condensation occurs at the liquid–vapor interface. The energy required for the phase change is transferred through the liquid and/or vapor in contact with the solid boundary of this two-phase system. The way these phases are in contact with the boundary or in other words, the degree to which the liquid or the vapor wets this solid boundary will, as one would expect, affect the heat transfer [2]. The influence of contact angle on nucleate boiling, nucleation site density, bubble departure diameter and the critical heat flux have been well studied [3,4]. Hong et al. [5] studied the effects of surface oxidation which enhances the wettability on pool boiling of R11, and found that oxidation increased the heat transfer coefficient. The influence of contact angle of the working fluid on the performance of heat pipes is evident considering the high heat flux applications for which they are designed.

Recently, R134a has been studied as a candidate fluid for use in heat pipes [6,7]. A heat pipe gives large heat transport rates with relatively small temperature differences by use of evaporation and condensation within a closed system containing a saturated liquid–vapor mixture. The heat pipe absorbs heat in the evaporator section and vaporizes the working fluid. The vapor pressure then drives the vapor to the condenser section where it condenses; thereby transporting the thermal energy through latent heat interactions. The liquid is returned to the evaporator, against a natural pressure gradient, through a porous wick structure. A liquid meniscus formed within the wick creates

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Nomenclature

F	force exerted on a plate
g	gravitational constant
M	mass of a plate
P	perimeter of a plate
RTD	resistance temperature detector
V	volume of liquid displaced
$\Delta\rho$	is the density difference between the two liquid phase and surrounding air.
θ	contact angle
σ_{sv}	interfacial surface tensions at the solid–vapor interface
σ_{sl}	interfacial surface tension at the solid–liquid interface
σ_{lv}	interfacial surface tension at the liquid–vapor interface

the capillary pressure which pumps the liquid back to the evaporator section. This osmotic pressure depends on the contact angle between the liquid and the surface of the wick material. In general, the lower the contact angle, the higher the osmotic pressure. In fact, the exact behavior is that the osmotic pressure varies directly with the cosine of the contact angle. If the capillary pumping head is not larger than the total pressure difference within the heat pipe between the evaporator and condenser sections, the evaporator section will dry out and the heat pipe will fail to operate. One of the basic factors that govern the capillarity or the return of the working fluid from condenser to the evaporator is the contact angle of the working fluid. This makes it is necessary to have the values of contact angle available for a better prediction of the heat pipe performance and optimization of the heat pipe.

The contact angle values for more common working fluids including refrigerants that were developed in 1930s such as R11, R12, and R22 are well reported in the open archival literature [5,8,9]. However, the use of R134a (introduced as a commercial refrigerant in 1990) as the working fluid for heat pipes has given rise to an interest in R134a contact angles, which are not easily found in the literature. Hence, the measurements of contact angle of R134a were undertaken in this work.

2. Measurement techniques

Contact angle θ is defined [2] as the angle between the liquid–vapor interface and the solid surface, measured through the liquid at the point on the surface where all the three phases meet. The familiar Young's equation which defines contact angle is given by Eq. (1) where, σ_{sv}, σ_{sl}, and σ_{lv} are interfacial surface tensions at the solid–vapor, solid–liquid and liquid–vapor interfaces, respectively,

$$\cos\theta = \frac{\sigma_{\mathrm{sv}} - \sigma_{\mathrm{sl}}}{\sigma_{\mathrm{lv}}} \tag{1}$$

The contact angle is not a fluid property but rather a function of the fluid's free surface energy as compared to the solid surface and vapor surface energies [10]. A smaller contact angle means that more of the fluid spreads over an area for a given fluid volume; hence the fluid has a high wettability on that surface. Fluids with $\theta = 0°$ are called highly wetting and with $\theta = 180°$ are called highly non-wetting. In case of heat pipes, maximum capillary pressure is reached when $\theta = 0$ for a working fluid [11].

The familiar Young's equation relates the contact angle, interfacial surface tension, and capillary pressure, to the pore size. Young's equation assumes the solid surface to be ideal (smooth and homogeneous), which is usually not the case. Values of observed (or apparent) contact angles are highly sensitive to the surface finish [1,12,13]. The angle given by Young's equation is also known as the intrinsic contact angle [13]. For surfaces that are real or surfaces that are rough and/or heterogeneous, the contact angle depends on the point where it is measured. Such a contact angle observation is known as the actual contact angle [13]. The angle that is measured in this work is known as the apparent contact angle which is defined as the angle between the tangent to the liquid–vapor interface, as seen by a comparatively low magnification optical device, and the solid surface [13].

Several methods have been proposed and used to measure contact angles depending on the geometry and the materials in question [14–23], each of them with advantages and disadvantages. One of the common methods used is the tilting plate method [14]. In this method a plate is partially immersed in the liquid and the meniscus is formed at both the faces of the plate. The plate is then tilted until the liquid surface on either of the sides is perfectly horizontal up to the solid–liquid interface. The angle of the plate with the flat liquid surface at this point is the contact angle. The accuracy of this method depends on the means utilized to detect the flatness of the meniscus. This method gives good reproducibility however the distinction between advancing and receding contact angles is difficult.

Another well known method is the Wilhelmy Plate method which is a force based method. A plate which is suspended from a balance is brought in contact with a liquid and the downward force exerted by the liquid on the plate is measured [14]. This force is related to the contact angle by

$$F = P\sigma_{\mathrm{sl}}\cos\theta - \Delta\rho g V + mg \tag{2}$$

where P is the perimeter of the plate, σ_{sl} is the liquid surface tension, V is the volume of liquid displaced, m is the mass of the plate, $\Delta\rho$ is the density difference between the fluid's