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Observation and description of the shape of water bridge retaining between vertical plane surfaces

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ABSTRACT

As the shape of water bridge retaining between vertical fins affects the performance of fin-and-tube heat exchangers, it is necessary to investigate water bridge shape and to develop description methods for water bridge, including those for contact line and contact angles. In this study, a visual experimental apparatus for observing the shapes of water bridges between vertical plane surfaces was designed, and the contact lines and the contact angles for water bridges on 7 types of plane surfaces made of aluminum, copper, stainless steel, quartz glass, acrylic plastics, Teflon and hydrophobic modified copper were measured. The test conditions cover water bridge volumes of 3–21 μL, and plane surface separations of 0.5–2.0 mm. The description method of water bridge shape is presented and compared with experimental data, including the description method of contact line with mean deviation of 2.2%, and the description method of contact angles with mean deviation of 6.1%.

Observation et description de la forme de rétention d'un pont d'eau entre des surfaces planes verticales

Mots clés : Forme de pont d'eau ; Surfaces planes verticales ; Ligne de contact triple ; Angle de contact

1. Introduction

Fin-and-tube heat exchangers are widely used as evaporators in refrigeration systems (Wang et al., 1999, 2012; Zhang et al., 2010), and are usually operated under dehumidifying conditions (Wang et al., 2000), in which the water vapor in the moist air condenses onto the fin surface (Comini et al., 2008; Ma et al., 2007; Yun et al., 2009) and forms small water droplets on the fin surface (Korte and Jacobi, 2001; Qi, 2013). Vertical fins are usually designed for fin-and-tube evaporators to drain the water droplets through gravity. However, it is still possible for the small droplets to grow bigger (ElSherbini and Jacobi, 2004a; Zhuang et al., 2014), and then to form water bridges due to the com-

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Nomenclature

Bo	Bond number
d	separation of solid plane surfaces [mm]
g	gravity acceleration [m s^{-2}]
k	magnification of image [mm pixel^{-1}]
L	length of major axis [mm]
p	distance of border points [pixel]
r	ellipse radius [mm]
V	water bridge volume [μL]
W	length of minor axis [mm]

Greek symbols

β	aspect ratio
θ	contact angle [degree]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
φ	azimuthal angle [degree]
χ	observing angle [degree]

Subscripts & superscripts

A	advancing
h	horizontal
max	maximum
min	minimum
R	receding
v	vertical

bination of big droplets on two adjacent fins (Zhuang et al., 2014). The water bridges may block air flowing through fin spacing, and so deteriorate the heat transfer performance between air and fins (Ma et al., 2007; Min and Webb, 2000; Wang et al., 1997). In order to improve the air side performance of fin-and-tube heat exchangers, the formed water bridges should be discharged promptly.

The shape of the water bridge plays a key role in the discharge of the water bridge from the vertical fin surface (Zhang et al., 2006). The discharge of the water bridge is due to the coupling effect of radial gravity and surface tension (Ahmadlouydarab et al., 2015; Zhang et al., 2006); radial gravity is the driving force of water bridge discharge, which is governed by the contour of the water–air interface of water bridge (Vega et al., 2015); surface tension is the resistance force of the water bridge discharge, which is determined by the contour of the water–fin interface of the water bridge (Vega et al., 2015). In order to evaluate the water bridge discharge characteristics on the fin surface, the shape of the water bridge under the coupling effect of radial gravity and surface tension should be known.

The shape of the water bridge, including the contours of the water–fin and water–air interfaces, can be described by the functions of triple contact line and contact angles (Chen et al., 2011). The water–fin interface represents the plane area surrounded by the triple contact line (ElSherbini and Jacobi, 2004a, 2004b); the water–air interface is the curved surface formed by the rotation of a curve around the contact line, and the slope of the curve is determined by the contact angles along the contact line (ElSherbini and Jacobi, 2006). In order to describe the shape of the water bridge, the functions of the triple contact line and contact angles should be developed.

The triple contact line and contact angles are affected by the forces acting on the water bridge, including the radial gravity and the surface tension (ElSherbini and Jacobi, 2004b, 2006). To develop the functions of the triple contact line and contact angles, the influences of both radial gravity and surface tension need to be taken into account. Existing research on the triple contact line and the contact angles are focused on the water bridge under the effects of surface tension and axial gravity, including the experimental investigations (Chen et al., 2015; Ferrera et al., 2006; Montanero et al., 2002; Petkov and Radoev, 2014; Verges et al., 2001) and numerical models (Acero et al., 2005; Chen et al., 2013; Slobozhanin and Alexander, 1998; Vogel, 1987, 1989).

The existing experimental investigations cover the observation of water bridge contour (Petkov and Radoev, 2014; Verges et al., 2001) and the measurements of contact line and contact angles (Chen et al., 2015; Ferrera et al., 2006; Montanero et al., 2002). Verges et al. (2001) observed the contour of water bridge and investigated the constant mean curvature of contact line by experiments, and the experimental results show that the circular contact line is appropriate for evaluating the shape of the water bridge under the effects of surface tension and axial gravity. Ferrera et al. (2006) employed the theoretical image fitting analysis method to determine the surface tension and the relationship between surface tension and shape of the water bridge. Chen et al. (2015) presented an experimental study of the effect of the contact angle hysteresis on the water bridge profile.

The existing numerical models cover the descriptions of contact line and contact angles (Acero et al., 2005; Chen et al., 2013; Slobozhanin and Alexander, 1998; Vogel, 1987, 1989). The shape of the water bridge can be simply described by a rotational axisymmetric model with a single given contact angle and the absence of gravity (Vogel, 1989). Vogel (Vogel, 1989) analyzed numerically the effect of axial gravity and found the shape of the water bridge was significantly deformed along the axial direction. Chen et al. (2013) developed the water bridge model reflecting the effect of contact angle hysteresis, and found that the water bridge may have two different equilibrium profiles at a given solid plate separation due to the contact angle hysteresis.

The effect of radial gravity on the contact line and the contact angles is different from the effect of axial gravity mentioned in the existing researches. The contact line in the exiting research is considered as a circle (Meseguer et al., 1995), and yet the contact line of the actual water bridge in the heat exchanger will be elongated due to the effect of radial gravity (ElSherbini, 2003). The contact angles mentioned in the existing research are equal everywhere (Akbari et al., 2015); however, the contact angles under the effect of radial gravity vary with the azimuthal angle (ElSherbini, 2003). The functions for water bridges under the effects of surface tension and axial gravity may not be simply applied in the description of the contact line and contact angles of actual water bridges in fin-and-tube heat exchangers.

The purpose of the present study is to experimentally investigate the shape of the water bridge under the effects of surface tension and radial gravity, and to present a method to