International Journal of Heat and Mass Transfer 121 (2018) 943–951

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Evaporation rate analysis of capillaries with polygonal cross-section

K.M. Schweigler [a],*, S. Seifritz [b], M. Selzer [c,d], B. Nestler [c,d]

[a] Robert Bosch GmbH, Postfach 1355, 74003 Heilbronn, Germany
[b] Robert Bosch GmbH, Renningen, 70465 Stuttgart, Germany
[c] Institute of Applied Materials-Computational Materials Science, Karlsruhe Institute of Technology (KIT), Straße am Forum 7, 76131 Karlsruhe, Germany
[d] Institute of Materials and Processes, Karlsruhe University of Applied Sciences, Moltkestrasse 30, 76133 Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 7 October 2017
Received in revised form 11 December 2017
Accepted 18 December 2017

Keywords:
Capillary evaporation
Phase field model
Computer simulation
Experimental study
Interface shape

ABSTRACT

We present experimental and numerical investigations of liquid evaporating from capillary tubes with round, square and polygonal cross-sections depending on the shape, size and position of their liquid-gas surface. Simulations are based on an Allen–Cahn type phase-field model, where the liquid-gas phase transition is governed by a function of the liquid-gas surface area, the distance of the surface to the entrance of the capillary and the concentration gradient in the gas phase. Experiments are conducted under defined initial and constant conditions. Throughout the whole experiment, temperature, relative air humidity and the weight of the liquid within the capillary tube are tracked continuously. We compare the computational evaporation curves with experimental data for square capillary tubes with inner side lengths of 1, 2 and 4 mm and find that the evaporation rate per cross-sectional area is inversely proportional to their inner side length. Furthermore, the model is applied to square, lens and drop shaped cross-sections and to square and star shaped cross-sections with rough inner walls. The results show that the model is applicable to any cross-section shape of straight capillary tubes and that the presented computational approach captures experimentally measured evaporation profiles very well. These findings are especially relevant for industrial applications such as the drying time of complex components after cleaning.

1. Introduction

Capillary evaporation is essential in many industrial applications. Especially for drying of porous media, for cleaning processes or for curing of lacquer layer on structured surfaces, it is important to know how the liquid wets a three dimensional geometry and how its drying behavior can be described. For over one century, scientists have been modeling evaporation from capillary tubes starting with Stefan in 1871 who described the evaporation behavior of single round capillary tube [1,2]. Hence, evaporation from round capillaries is often called "Stefans tube problem" and can be modeled using Fick's laws of diffusion, where the mass transfer from the liquid/gas-surface is inversely proportional to the length of the considered diffusion path x. Since then, various experiments have been conducted [3–5] that confirm Stefan's model [6].

Though, for capillary tubes with polygonal cross-sections this simple model no longer applies. Due to capillary forces, liquid films can rise in the corners of polygonal tubes up the entrance of the tubes, where their diffusion path to the ambient gas concentration is much smaller. Therefore, the evaporation behavior of capillary tubes with polygonal cross-sections differs fundamentally from the Stefans tube problem and scientists require models that take into account the influence of corner liquid films, also called "liquid fingers". The length of the liquid fingers at which the film detaches from the entrance of the capillary as the meniscus recedes further is called critical film length. Experimentalists have now paid special attention to square and polygonal capillary tubes since they represent the smallest unit of porous media. Chauvet et al. [7] show experimentally that similar drying kinetics to porous media can be obtained from a much simpler system (a square capillary tube) owing to the effect of corner liquid films. The authors expanded the set of investigated tubes with focus on the corners roundedness and found that the critical film length depends strongly on the degree of roundedness of the tubes internal corners [8]. Therefore, they developed a model taking into account liquid corner flow and phase change at the film tip in order to predict the critical film length at depinning. Recently, Keita et al. [9] conducted experiments on a simple glass channel with dominant capillary effects and reported a constant evaporation rate period while the shape of liquid fingers remains intact and they are in contact with the entrance of the capillary. This period is followed by a

---

* Corresponding author.
E-mail address: Katharina.Schweigler@de.bosch.com (K.M. Schweigler).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.090
0017-9310/© 2018 Elsevier Ltd. All rights reserved.

falling rate period, that was due to the thinning of the liquid fingers when the liquid reservoir was exceeded (as they found with the help of FEM Simulations), not due to the depinning as Yiotis et al. [10] assumed. This shows the importance of the right shape of the liquid corner films for evaporation studies.

Already in the middle of the last century, Concus and Finn [11] modeled the shape of the liquid-gas-interface in square capillary tubes. They found a critical contact angle that describes the ability of the liquid to wet the corners of the tube. Son et al. [12] presented lattice Boltzmann simulations that show promising results concerning the shape and length of the liquid fingers in capillary tubes of square and triangular cross-sections. Though, gravitation was not considered because of the small size of the capillaries. Camassel et al. [13] found that the position of the bulk meniscus should scale proportional with time multiplied by a factor. This factor is very sensitive to the liquid distribution within the entrance region of the tube. Camassel et al. emphasize that it is important to appropriately account for the shape of the liquid interface at the mouth of the capillary tube and present a simplified model for a tube of square cross-section that they calibrated with data from three-dimensional simulations.

However, in a wide range of industrial applications, capillaries with arbitrary cross sections, where gravity forces cannot be neglected, are especially interesting. Thus, the current work is focused on the following questions: How does the evaporation rate in capillaries change depending on the liquid/gas surface (denoted as *lg*-surface) shapes and on the size of the capillary tube? Can a basic model be applied to this rather complex evaporation behavior? Therefore experiments and simulations with square capillaries are compared and calibrated with the well described evaporation in round capillaries. We present a phase-field model (PFM) of Allen–Cahn type, where the liquid/gas phase transformation takes place due to a difference in saturation concentration and partial concentration at the entrance of the capillary tube. Phase-field models have been used in the past for the evaluation evaporation processes of liquid into gas atmosphere [14–16]. They were applied especially to liquid/gas interfaces that are open to atmosphere or drops of fluid [17]. To the authors knowledge phase-field models have not yet been applied to evaporation processes in capillary tubes. We propose a basic model that takes into account both, the shape of the *lg*-surface as well as its distance to the entrance of the capillary.

In Section 2, we describe the capillary tubes used in the experiments and introduce the experimental set-up. Then we present the PFM and its adoption to evaporation processes in capillary tubes using an energy density contribution $f_{cap}(\phi)$ and explain the assumptions linked to it in Section 3. The results are presented and discussed in Section 4. Finally, in Section 5 we present our conclusions.

2. Experimental materials and methods

In this section, capillaries and their preparation are described and the experimental set-up for the evaporation rate measurement of capillary tubes is introduced. All tubes were produced by Hilgenberg. They are 50 mm long, 1–13 mm wide and closed at one end. The cross-sections of the investigated round as well as square capillaries are shown in Fig. 1. The measured roundedness of the corners lies between 15 and 74 µm. Details concerning the dimension of the single capillary tubes are presented in Table 1.

Before each experiment, the capillaries are cleaned with n-heptane and n-buthylacetat using a syringe. After every treatment, the capillary tubes are rinsed with pure ethanol to make sure no solvent is being left in the capillary tube. This process is repeated three times. Afterwards, the capillary tubes are dried with a clean nitrogen stream. In the glove box, the capillary tubes are placed vertically on a small stand and filled completely with deionized water at room temperature.

Over time, the mass of the liquid in the capillary, relative air humidity and temperature are tracked within an airtight glove box of 0.5 m^3. Fig. 2 displays a schematic drawing of the experimental set-up similar to the one presented in our previous work [18]. The relative air humidity *RH* is kept constant during all experiments using saturated salt solution of sodium hydroxide (NaOH) in large flat bowls within the glove box. At 295 K, the air humidity adjusts to 17% RH with a maximal deviation of 2%. Four SHT21 sensors from Sensirion placed in the corners of the glove box measure the relative air humidity and temperature throughout the whole experiment. One of the sensors is placed in the proximity of the

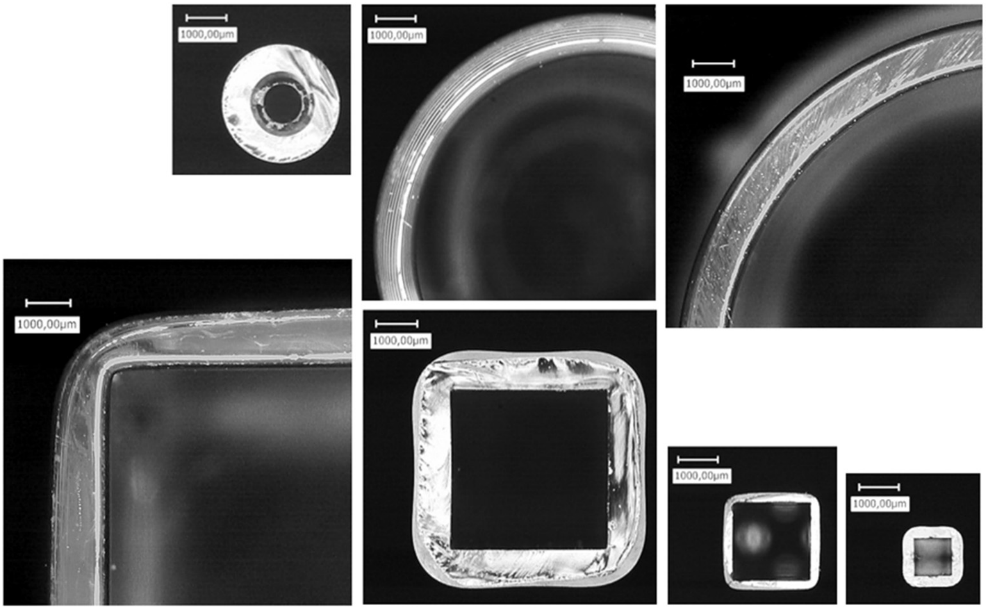

Fig. 1. Microscope images of the cross-sections of the capillary tubes shown with the same magnification. From left to right, the square cross-sections have an inner side length of 13, 4, 2 and 1 mm and the round cross-sections have an inner diameter of 1, 10 and 16 mm. Scale bar represents 1 mm on all images.