International Journal of Multiphase Flow 40 (2012) 56–67

Contents lists available at SciVerse ScienceDirect

International Journal of Multiphase Flow

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

Measurement of two-phase flow and heat transfer parameters using infrared thermometry

Tae Hoon Kim, Eric Kommer, Serguei Dessiatoun, Jungho Kim *

University of Maryland, Department of Mechanical Engineering, College Park, MD 20742, USA

ARTICLE INFO

Article history:
Received 30 September 2011
Received in revised form 28 November 2011
Accepted 28 November 2011
Available online 9 December 2011

Keywords:
Infrared thermography
Heat transfer distribution
Two-phase flows
Droplet evaporation flow boiling
Liquid film thickness

ABSTRACT

A novel technique to measure heat transfer and liquid film thickness distributions over relatively large areas for two-phase flow and heat transfer phenomena using infrared (IR) thermometry is described. IR thermometry is an established technology that can be used to measure temperatures when optical access to the surface is available in the wavelengths of interest. In this work, a midwave IR camera (3.6–5.1 μm) is used to determine the temperature distribution within a multilayer consisting of a silicon substrate coated with a thin insulator. Since silicon is largely transparent to IR radiation, the temperature of the inner and outer walls of the multilayer can be measured by coating selected areas with a thin, IR opaque film. If the fluid used is also partially transparent to IR, the flow can be visualized and the liquid film thickness can be measured. The theoretical basis for the technique is given along with a description of the test apparatus and data reduction procedure. The technique is demonstrated by determining the heat transfer coefficient distributions produced by droplet evaporation and flow boiling heat transfer.

1. Introduction

Definitive understanding of phase change heat transfer mechanisms remains elusive due its sensitivity to many variables, but also due to a lack of reliable local information that can enable models to be tested. Although point measurements or area averaged measurements of variables such as local film thickness and heat transfer have been made, techniques whereby these quantities can be measured over large areas are generally lacking. Point or average measurements may be appropriate at very low heat fluxes where insignificant evaporation occurs and the flow regime does not change, but such measurements are insufficient for model validation.

Techniques that have been used in the past to measure local film thickness have utilized capacitance sensors, conductance probes, confocal microscopes, and other techniques such as reflectance (e.g., Coney, 1973, Klausner et al., 1990, Han and Shikazono, 2009, and Shedd and Newell, 1998). The heat transfer has usually been measured using thermocouples welded to the tube walls or by resistively heating the walls and measuring the average wall temperature. The authors are not aware of any techniques whereby liquid film and heat transfer distributions in flow boiling are measured over relatively large areas with high resolution. If the heat transfer distribution along the walls of a tube could be measured, it could be used to verify models of the heat transfer variations predicted by models of slug flow, wavy annular flow, annular flow dryout, etc. For example, a three-zone model of elongated bubble evaporation in microchannels was proposed by Thome et al. (2004) and Dupont et al. (2004). The model assumes that heat is transferred to a liquid slug, an elongated bubble, and a vapor slug (Fig. 1). Heat transfer to the elongated bubble is thought to occur through the thin liquid film between the vapor and the wall. The bubble frequency, liquid film thickness, and heat transfer to the liquid and vapor slugs are obtained from correlations. The globally averaged heat flux was measured and used for model verification. Much stronger verification of the model can be made if measurements of the local heat flux were available to verify the heat transfer rates before, during, and after passage of the bubble.

In flow regime based models (e.g., Kattan et al., 1998a,b,c), the local flow boiling heat transfer coefficients are predicted based on the tube perimeter fraction wetted by liquid. For example, for a horizontal stratified flow in a circular tube, the local heat transfer coefficient is given by

$$h_{tp} = \frac{r_i\theta_{dry}h_{vapor} + r_i(2\pi - \theta_{dry})h_{wet}}{2\pi r_i} \quad (1)$$

where h_{wet} is assumed to be composed of a nucleate boiling component and a convective component in a power law form:

$$h_{wet} = \left(h_{nb}^3 + h_c^3\right)^{1/3} \quad (2)$$

For annular and intermittent flow, $h_{tp} = h_{wet}$. The local void fraction needed to evaluate liquid and vapor velocities is calculated using correlations (e.g., Rouhani and Axelsson, 1970). Again, verification of these models can benefit greatly from measurements of the local heat transfer distribution in the various regimes.

* Corresponding author. Tel.: +1 301 405 5437.
E-mail address: kimjh@umd.edu (J. Kim).

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doi:10.1016/j.ijmultiphaseflow.2011.11.012

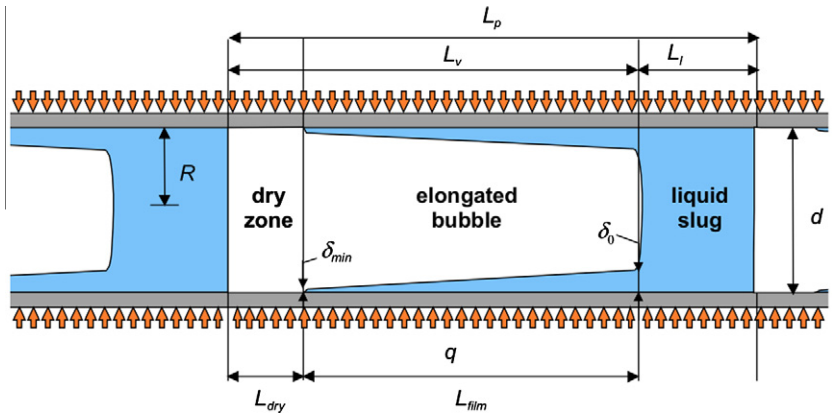

Fig. 1. Three-zone heat transfer model for evaporation in a microchannel from [1]. L_p is the total length of the triplet. L_l, L_{dry} and L_{film} are the length of the liquid slug, the dry zone and the liquid film trapped by the bubble, respectively. The internal radius and diameter of the tube are R and d while δ_0 and δ_{min} are the thicknesses of the liquid film trapped between the elongated bubble and the channel wall at its formation and at dry out.

The objectives of this paper are to describe and demonstrate an IR thermometry based technique whereby the local heat transfer produced by two-phase flows can be measured with high spatial and temporal resolution. The application of the technique to the measurement of liquid film thickness is also described. IR thermometry is an established technology that can be used to measure temperatures when optical access to the surface is available in the wavelengths of interest, and has been used to measure heat transfer distributions during pool boiling heat transfer. Golobic et al. (2009) and Stephan and co-workers (e.g., Schweizer and Stephan, 2009) used an IR camera to measure the heat transfer distribution under single nucleating bubbles as they grew on a thin metal foils. Stephan has recently begun using a thicker CaF substrate in place of the thin film in order to increase the heat capacity of the substrate (Fischer et al., 2011) so it is more representative of real surfaces. Gerardi et al. (2010) used a high speed IR camera in conjunction with a video camera to measure bubble behavior on an ITO heated sapphire substrate. The IR camera measured the temperature distribution at the ITO surface, while a video camera was used to visualize the fluid behavior. Krebs et al. (2010), Shen et al. (2010) and Mani et al. (2012) used IR thermography to study flow boiling in microchannels, droplet evaporation, and jet impingement, respectively. In these studies, an IR camera was used to view through a silicon substrate to visualize in great detail the temperature distribution at the silicon/water interface. Sefiane et al. (2008) used IR thermography to visualize the spontaneously occurring hydrothermal waves within evaporating methanol, ethanol, and FC-72 droplets.

In the present work, a midwave IR camera (3.6–5.1 μm) is used to measure the temperature variations within a multilayer consisting of a silicon substrate coated with a thin thermal insulator that is partially transparent to IR. The insulator amplifies the temperature variations and provides a strong signal for the IR camera. Since silicon is largely transparent to IR radiation, the temperature of the inner and outer walls of the multilayer can be measured by coating selected areas with a thin IR opaque film. The fluid used (FC-72) is also partially transparent to IR over a broad range of wavelengths, allowing the flow to be visualized and the film thickness to be measured. The theoretical basis for the technique, a description of the test apparatus and data reduction procedure, and experimental validation are presented in the sections below.

2. Theoretical background

Consider the multilayer wall consisting of a silicon substrate onto which polyimide tape (polyimide layer + acrylic adhesive) is attached as shown schematically on Fig. 2a. An opaque black paint that is much thinner than the other layers is applied to the top of the polyimide tape. The black surface is exposed to a two-phase flow. The polyimide tape is necessary to measure heat transfer coefficient distributions of the expected magnitude since the high thermal conductivity of the silicon substrate would simply smear out any temperature variations through substrate conduction, reducing both the magnitude of the temperature differences as well as the spatial resolution.

To obtain the heat transfer coefficient at the fluid-wall interface, the temperature gradient within the polyimide tape is required. If the time-varying temperatures of the black surface $T_{s1}(t)$ and $T_{s2}(t)$ are known, the instantaneous temperature profile within the multilayer can be obtained through an unsteady heat conduction simulation. If the polyimide tape is thin compared with the spatial resolution of the camera and the temperature gradient is much larger in the x-direction than in the y- and z-directions, a 1-D heat conduction assumption can be used. The 3-D heat conduction equation must be used otherwise. Assuming 1-D heat conduction, the governing equations within the layers are given by

$$\rho_{si}c_{p,si}\frac{\partial T}{\partial t} = k_{si}\nabla^2 T + \dot{q}_{si} \tag{3a}$$

$$\rho_{A}c_{p,A}\frac{\partial T}{\partial t} = k_{A}\nabla^2 T \tag{3b}$$

$$\rho_{P}c_{p,P}\frac{\partial T}{\partial t} = k_{P}\nabla^2 T \tag{3c}$$

and the system is subject to the boundary conditions $T = T_{s1}(y,z,t)$ at $x = 0$, $T = T_{s2}(y,z,t)$ at $x = L_{Si} + L_A + L_P$.

Consider now the calculation of the black surface temperature $T_{s1}(t)$. This temperature is not directly available since the energy measured by the IR camera consists of emission from the black surface, emission from each of the layers (which depends on the temperature profile within them), and reflection from the surroundings. Since the optical properties of the polyimide and adhesive are similar, they are treated as a single layer in the radiation calculation as indicated in Fig. 2b. The total energy measured by the camera (E_c) is the sum of the energies emitted by each layer within the spectral bandwidth of the IR camera (λ_1–λ_2):

$$E_c = \rho_{\infty-c}E_\infty + \varepsilon_{Si-c}E_{Si} + \varepsilon_{T-c}E_T + \tau_{s-c}E_s \tag{4}$$

where $E_\infty = F_{\lambda_1-\lambda_2}\sigma T_\infty^4$ is the blackbody radiation due to the surroundings, $E_{Si} = \int_0^{L_{Si}} \alpha_{Si}F_{\lambda_1-\lambda_2}\sigma[T_{Si}(x)]^4\exp(-\alpha_{Si}x)dx$ is the energy emitted by the silicon that reaches the Si-∞ interface,