International Journal of Heat and Mass Transfer 93 (2016) 872–888

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

An experimental study of spatiotemporally resolved heat transfer in thin liquid-film flows falling over an inclined heated foil

Christos N. Markides *, Richard Mathie, Alexandros Charogiannis

Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering, Imperial College London, London SW7 2AZ, United Kingdom

A R T I C L E   I N F O

Article history:
Received 3 July 2015
Received in revised form 26 October 2015
Accepted 28 October 2015
Available online 18 November 2015

Keywords:
Film flows
Planar laser-induced fluorescence
Infrared thermography
Convection
Unsteady heat transfer
Heat transfer coefficient
Film thickness

A B S T R A C T

This paper describes the development of an experimental technique that combines simultaneous planar laser-induced fluorescence (PLIF) and infrared (IR) thermography imaging, and its application to the measurement of unsteady and conjugate heat-transfer in harmonically forced, thin liquid-film flows falling under the action of gravity over an inclined electrically heated-foil substrate. Quantitative, spatiotemporally resolved and simultaneously conducted measurements are reported of the film thickness, film free-surface temperature, solid–liquid substrate interface temperature, and local/instantaneous heat flux exchanged with the heated substrate. Based on this information, local and instantaneous heat-transfer coefficients (HTCs) are recovered. Results concerning the local and instantaneous HTC and how this is correlated with the local and instantaneous film thickness suggest considerable heat-transfer enhancement relative to steady-flow predictions in the thinner film regions. This behaviour is attributed to a number of unsteady/mixing transport processes within the wavy films that are not captured by laminar, steady-flow analysis. The Nusselt number *Nu* increases with the Reynolds number *Re*; at low *Re* values the mean *Nu* number corresponds to 2.5, in agreement with the steady-flow theory, while at higher *Re*, both the *Nu* number and the HTC exhibit significantly enhanced values. Evidence that the HTC becomes decoupled from the film thickness for the upper range of observed film thicknesses is also presented. Finally, smaller film thickness fluctuation intensities were associated with higher HTC fluctuation intensities, while the amplitude of the wall temperature fluctuations was almost proportional to the amplitude of the HTC fluctuations.

1. Introduction

Liquid films falling under the action of gravity are classical free-surface flows that are either directly encountered in or representative of a wide range of industrial applications, including wetted-wall absorbers, heat exchangers, condensers, evaporators and reactors. The practical interest in these flows arises primarily from their high surface-to-volume ratios and excellent heat and mass transfer characteristics. It therefore comes as no surprise that extensive theoretical [1–4], numerical [5–9] and experimental [10–13] efforts have been devoted to their study over the past decades. The extraction of reliable *detailed* experimental data has, however, proven particularly challenging owing to a number of challenges inherent to these flow systems, such as the restricted fluid domains under observation (often sub-mm) and the intermittent nature of the moving and wavy interface. The present investigation is motivated by the strong demand for detailed, spatiotemporally resolved hydrodynamic and heat-transfer data in planar falling-film flows. This information is necessary for the purpose of improving our fundamental understanding of these important flows, and also for furthering the development and validation of advanced analytical tools and numerical modelling codes, by providing sophisticated closures for accurate and reliable predictions. Beyond this fundamental interest, the availability of the information can also prove valuable in our efforts to appreciate the transport capabilities of these flows and our in-depth understanding of the associated underlying heat-transfer mechanisms, which can then be harnessed in practical situations to improve performance and reduce the size and cost of equipment.

This paper describes a simultaneous application of optical-diagnostic techniques for the provision of the aforementioned spatiotemporally resolved heat-transfer information in thin liquid-films flowing down an inclined heated foil. Optical techniques are recognized as advanced measurement tools, capable of providing detailed, non-intrusive multi-dimensional information on concentration, phase, temperature, velocity and

---

* Corresponding author.
E-mail addresses: c.markides@imperial.ac.uk (C.N. Markides), richard.mathie@cantab.net (R. Mathie), ac1005@ic.ac.uk (A. Charogiannis).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.10.062
0017-9310/

other scalar and/or vector fields with high spatial and temporal resolution. As a result, they are becoming increasingly prevalent in scientific and engineering research and development fields. In particular, the heat-transfer community is moving gradually towards experiments that can combine heat-transfer measurements such as of temperature, heat flux, heat-transfer coefficient (HTC) and in a few cases the velocity field within the fluid domains, thus moving towards a comprehensive understanding of their associated interactions leading to a particular heat-exchange performance.

Specifically, the experimental technique reported here, namely PLIF-IR, involves a combination of laser-induced florescence (PLIF) and infrared (IR) thermography, and was developed in order to enable simultaneous measurements of the film free-surface height relative to the solid substrate (film thickness), the film free-surface and solid–liquid substrate interface temperatures, and the instantaneous heat flux exchanged between the liquid film and the heated substrate. By extension, the acquired data allow the estimation of local and instantaneous HTCs, and an investigation of their variation as a function of important flow parameters. Another important aspect of this effort is our specific interest in developing an experimental methodology that allows the explicit study of unsteady and conjugate heat-transfer [14,15]. In these problems the temperature *and* heat flux at the solid–liquid interface (wetted substrate side) both time-vary, and it is necessary to measure directly these variations. To address this challenge, the employment of a thin metal foil as a substrate enables IR measurements at its underside (un-wetted substrate side) to provide temperature and heat flux information on the wetted solid–liquid surface.

A considerable body of previous research has been dedicated to the development of a variety of experimental measurement techniques and their adaptation to the study of isothermal film-flows. Relevant experimental methodologies can broadly be classified as conventional or advanced, depending on the practice employed towards retrieving the desired data, primarily focusing on recovering the interface shape (film thickness and wave dynamics) and mass-transfer characteristics (entrainment, reposition, etc.). Examples of the former, (i.e. conventional, non-optical methods) are hot-wire anemometry (HWA) [16,17], electrical conductivity [18,19] and capacitance probes [20,21]. Such measurement approaches have played an important role in improving our understanding these flows and have contributed to many advancements made in this field, yet they are associated with certain challenges; in some cases they are intrusive, can suffer from spatial or temporal resolution limitations, are by and large point-measurements, and often involve complex and cumbersome calibration procedures, thus progressively favouring the implementation of non-intrusive optical methods.

Amongst a plethora of relevant optical-diagnostic techniques, fluorescence-based methods have proven to be very effective and are therefore popular amongst researchers engaging in film-flow investigations. These methods employ a tracer (either occurring naturally in the flow or an added chemical substance) that is excited using a laser source. Fluorescence-based methods can be further classified as laser-induced fluorescence (LIF) imaging or planar laser-induced fluorescence (PLIF) imaging. The primary difference between the two is that LIF utilizes the fluorescence intensity, measured at or near the incident light direction, to quantify the film thickness along a line, over a one-dimensional (1-D) or two-dimensional (2-D) domain. PLIF on the other hand relies on planar illumination across the flow field and imaging from the side, and can be used to directly identify the extent of the liquid domain, and to resolve with a higher level of detail, resolution and accuracy 1-D spatiotemporal film thickness variations along the illuminated plane. Consequently, one or both film boundaries need to be identified in raw PLIF images in order to measure the spatial extent of the film. Another advantage of the latter approach (PLIF) is that the fluid-flow domain is visualized directly, allowing for spatiotemporally resolved velocity or temperature data to be obtained simultaneously with the film thickness. Examples of experimental investigations employing LIF imaging are reported in Refs. [22,23], and more recently by Alekseenko et al. [24]. PLIF-based studies are presented in Refs. [14,25–27] in various multiphase/interfacial flows.

Beyond isothermal film-flow investigations, fluorescence-based methods using temperature-sensitive markers have been employed when evaluating the thermal performance of microchannel devices and other microfluidic systems [28,29], as well as plate heat-exchangers in the presence of oscillating flows [30,31,9]. Temperature measurements with an absolute accuracy of 0.5 K, or better, have been reported [28,32,33]. Compared to isothermal film-flows, the study of diabatic (heated/cooled) film-flows which entail liquid-temperature measurements is more demanding, owing to the fact that the liquid is often in physical and thermal contact with a hot solid-substrate which is typically metallic and opaque. Illumination of the liquid domain from the solid side is unfeasible in such a configuration, with the (intermittent and disturbed) liquid free-surface providing the only optical access to the liquid domain. In this case, refraction at the wavy interface results in strong beam-steering that must be accounted for by post-processing correction algorithms. Such measurements are also subjected to the restrictions noted earlier, and any available studies are consequently limited to single-point measurements.

Amongst others, the excellent efforts at RWTH Aachen University [34,35] to conduct simultaneous film-thickness and temperature measurements by employing diacetyl fluorescence and phosphorescence imaging are worthy of mention. In more detail, time-varying local HTCs were reported at the measurement position (point), suggesting a strong correlation between the film thickness and heat transfer (+80% enhancement ahead of the wave and −40% deterioration below the wave crest). Unfortunately, the particular experimental effort was restricted to a narrow flow parameter range ($Re = 126$), and the role of important experimental parameters on the wave regime and HTC performance was not within its scope. Furthermore, the results were recovered on the assumption that the velocity within the film is well-described by the theoretical parabolic Nusselt profile (for 1-D, laminar and fully developed steady-flow dominated by the balance of gravity and viscosity only). Deviations from this profile on account of two-dimensional (2-D) and three-dimensional (3-D) unsteadiness have, however, been confirmed [10,27], which suggests that additional experiments to confirm these findings are necessary.

Further improvements to our insight into the complex and unsteady flow phenomena associated with thin films and their link to heat-transfer performance can be attributed to the extensive body of experimental research carried out at the Kutateladze Institute of Thermophysics of the Siberian Branch of the Russian Academy of Sciences [36,12,37–39] and at the Institute of Thermophysics of the Technical University of Darmstadt [40–43]. The experimetnal efforts at Kutateladze aimed at examining the process of rivulet formation due to thermocapillary convection, employing a wide range of optical techniques including IR thermography, particle velocimetry, shadowgraphy and LIF. In Ref. [12], a range of locally (non-uniformly) heated falling film flows between $Re = 300$ and $Re = 500$. Even when low heat fluxes were imparted onto the vertically falling water films, significant thermocapillary effects were observed. Non-uniform heating was also employed in Ref. [36] to induce the formation of a horizontal bump-shaped free-surface deformation across the film, which was found to transition to a rivulet pattern above a critical heat input. By depositing Aluminium particles onto the liquid surface, a highly non-linear 3-D flow was revealed, while a stagnation point was identified at the top of