International Journal of Heat and Mass Transfer 128 (2019) 469–478

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat flux reconstruction by inversion of experimental infrared temperature measurements – Application to the impact of a droplet in the film boiling regime

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ARTICLE INFO

Article history:
Received 21 February 2018
Received in revised form 24 July 2018
Accepted 17 August 2018

Keywords:
Inverse Heat Conduction Problem
IR thermography
Drop impact
Film boiling
Vapor layer

ABSTRACT

An Inverse Heat Conduction Problem (IHCP) is considered in order to estimate the transient heat flux extracted from a hot solid surface by an impinging droplet. The resolution of the IHCP is made with the so-called quadrupole method, which provides an analytical expression of the temperature and the heat flux at the front surface of the solid wall, where the drop impact takes place. In the experiments, the thermal response of the front surface is recorded using IR thermography. For that, sapphire is chosen as the material of the solid wall, and the front surface is coated with a thin TiAlN ceramic layer (thickness of 300 nm). The latter is highly emissive and opaque in the IR while sapphire is transparent at the same wavelengths. This feature allows the surface impacted by the droplet to be viewed from the bottom by the IR camera. This approach has been implemented to gain some insights into the heat transfer from the solid surface as well as the formation and growth of the vapor film, which appears under the droplet in the regime of film boiling, when the solid temperature is much higher than the boiling temperature of the liquid. Due to the small thickness of the vapor film, heat conduction is predominant in the vapor layer. Hence, the thickness of the vapor film can be deduced from the value of the reconstructed local heat flux, assuming a linear profile of temperature between the liquid interface of the droplet at the saturation temperature and the solid surface measured by IR thermometry.

1. Introduction

Cooling of hot surfaces by sprays, drops or droplets is common in many applications, such as in the quenching of hot metals [1,2], or in the cooling of power electronics [3]. It has driven the attention of many researchers because of the ability of sprays to remove high quantities of heat using limited mass flow rates of liquid coolant.

Reliable assessment of the instantaneous and local thermal power that is removed from a hot surface during quenching by the liquid jet, drops or droplets cannot be made using a fluxmeter, because of both its intrusive character and its inertia, as well as because of the very harsh thermal conditions (transient boiling, with existence of a critical heat flux) that take place on the hot front surface of the solid plate during its cooling. So, most experimentalists use an inverse heat conduction technique [4] based on the temperature responses of thermocouples embedded beneath its front face, or infrared frames taken over its rear face, together with a model describing transient heat diffusion in the plate. It is the case for studying a liquid jet impingement on a moving surface [5] or for investigating impigement of a single droplet on a static surface [6]. In such inverse problems, reconstruction of front face temperature or flux using rear face, or interior, temperature measurements is difficult, because of the low-pass filter role played by heat diffusion through the solid thickness of the material, that makes inversion ill-posed with a need for regularisation [6,7]. In such experiments, it is very interesting to use infrared detectors or cameras, whose signals are not affected by the local temperature conditions, and that do not modify the local transfer of heat in the plate. However, the drawback is to limit measurements to the rear face, because most materials used are opaque in the corresponding spectral interval.

Another solution is to use a transparent or semi-transparent plate, with a thin opaque deposit whose thickness can be neglected from the thermal point of view, over the front face, in order to

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.069
0017-9310/

Nomenclature

a	thermal diffusivity
c	heat capacity of the substrate
d_c	contact diameter of the droplet
d_0	initial diameter of the droplet
DL	digital levels
e	substrate thickness
h	convective heat transfer coefficient
J_i	ith function of Bessel of first kind
n	order of the Hankel transform
q	front face heat flux (in $z = 0$)
q_{drop}	contribution of the drop to the flux extracted in $z = 0$
R	radius of the substrate
r	radial coordinate
s	complex frequency variable for Laplace Transform
T	temperature
T_∞	temperature of the ambient air
z	vertical coordinate

Greek symbols

Δt	calculation time step
α_n	nth root of J_0
δ	thickness of the vapor film
ε	coating emissivity
θ	reduced temperature
κ	thermal conductivity
ρ	density
φ	heat flux imposed for the validation

Subscript/Superscript

SS	steady state
n	nth Hankel mode
sat	saturation condition
vap	vapor
∞	ambient air

directly measure the front face temperature and to get a well-posed inverse problem without the need for some regularisation, which more or less biases the recovered instantaneous and local heat flux. Such a technique has already been tested by two authors [8,9] who used both a sapphire plate. In one of these works [8] no front face deposit was used and the surface temperature map of a 2.5 mm diameter droplet impact was measured by Laser Induced Fluorescence [8]. In [9], a 100 nm-thick platinum film was deposited on the front face of a sapphire plate, allowing temperature measurement on its opposite face through the sapphire which is transparent in the near and short-wavelength infrared regions. This approach allowed to recover the space distributions of the front face temperature first and of the heat flux then, during impingement of a 2.4 mm diameter droplet. However, in this work, priority was given to the experimental results with less details on the inverse heat flux problem and a direct problem solved through a computed simulation software.

In the present paper, one objective is to show that a systematic analytical approach, taking advantage of integral transform solutions [10] by introducing a Laplace transform (variable time) and a Hankel transform (radial space variable), can be implemented, with a good control of the inversion. In what follows, this method will be used to study the impact of a water droplet in the film boiling regime, where a vapor layer is formed almost instantaneously between the droplet and the solid surface where the temperature of the vapor film is much higher than the boiling temperature of the liquid. Under these conditions, the heat flow from the solid wall is particularly small compared to an impact where there is a wetting contact. The heat flux must therefore be estimated with great accuracy to investigate the heat transfer under these conditions.

2. Experimental setup

2.1. Setup

This study focuses on the impact of millimeter-sized water drops onto a solid wall. The experimental bench, presented in Fig. 1, has been developed specifically to achieve drop impact onto a solid surface at high temperature under well-controlled conditions.

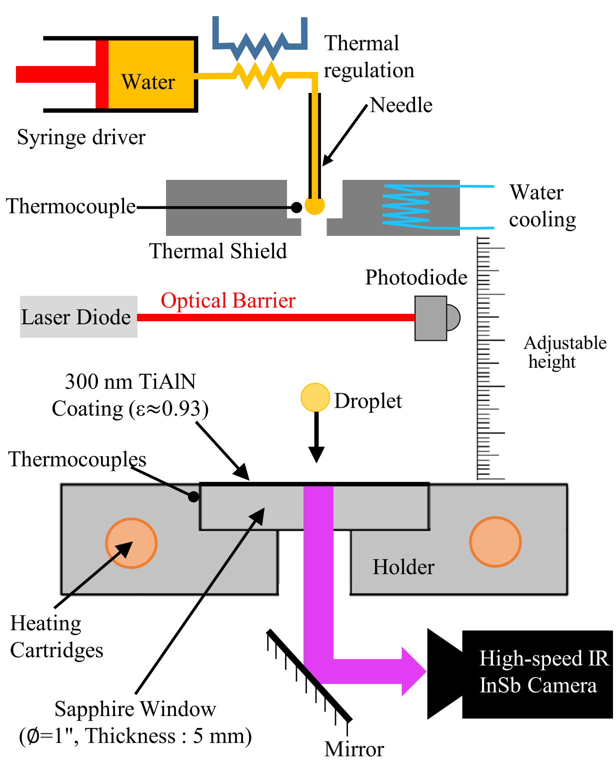

Fig. 1. Experimental setup.

To generate the droplet, water is pushed by a syringe pump across a fine needle (outer diameter 0.4 mm). The spontaneous detachment of the droplet occurs in a very reproducible manner, when the weight of the droplet overcomes the surface tension. This occurs when the diameter of the forming droplet reaches 2.5 mm. During its formation, the droplet is protected from the hot air to avoid its heating by the plume of hot gas rising from the heated solid surface. To that end, the droplet is placed into a small chamber drilled into an aluminium plate regulated in temperature by means of a water-cooling loop. After its detachment from the needle, the droplet impinges onto an optical quality sapphire window which is almost perfectly smooths and flat. This sapphire window