International Journal of Thermal Sciences 115 (2017) 112–124

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

A new method for reducing local heat transfer data in multi-microchannel evaporators

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ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form
16 November 2016
Accepted 23 January 2017
Available online 10 February 2017

Keywords:
Local heat transfer coefficients
Multi-microchannel evaporator
Temperature filtering techniques
Heat conduction models
Inverse heat conduction problem

ABSTRACT

Measuring the strong local variation in heat transfer coefficients in multi-microchannel evaporators is related to the inverse heat conduction problem (IHCP). As the local flow heat transfer coefficients change greatly in magnitude from single-phase liquid at the entrance to a peak in slug flow and then to a minimum at the transition to the onset of annular flow and finally a new substantial rise up to the outlet, a significant heat spreading occurs due to the heat transfer process itself, and this has to be accounted for when processing the data. Until now, IHCP has not been introduced in the experimental study of heat transfer in such evaporators when reducing local experimental data. In this paper, a new method for processing experimental local heat transfer data by solving the 3D IHCP is proposed. This method is then applied and validated using two sets of single- and two-phase flow experimental data obtained with infrared (IR) camera temperature measurements. The 14 400 raw pixel temperatures per image from the IR camera are first pre-processed by a filtering technique to remove the noise and then to smooth the data, where the IR camera has undergone a prior inhouse pixel by pixel insitu temperature calibration. Three filtering techniques (Wiener filter, spline smooth, and polynomial surface fitting) are compared. The polynomial surface fitting technique was shown to be more suitable for the current type of data set. Then the 3D IHCP is solved based on a finite volume method using the TDMA (Tridiagonal Matrix Algorithm) solver with a combination of Newton-Raphson iteration and a local energy balance method. Furthermore, the present 3D TDMA method (named as 3D TDMA) is compared with three other post-processing methods currently used in the literature, among which the present one is found to be more accurate for reducing the local heat transfer data in multi-microchannel evaporators.

1. Introduction

The experiments on flow boiling in multi-microchannel evaporators aim to measure the local heat transfer coefficients at the interface between the wall and the fluid along the flow channels. However, only the heat flux and the temperature at the test section backside can be directly measured, whilst the heat spreading due to the gradient in the local saturation temperature and the significant variation in the heat transfer coefficient along the channels needs to be accounted for. In particular, as the local flow heat transfer coefficients change greatly in magnitude from single-phase liquid at the entrance to a peak in slug flow to a minimum at the transition to annular flow and then a new substantial rise up to the outlet, a significant heat spreading occurs due to the heat transfer process itself, and this has to be accounted for when processing the data. Accurate multi-microchannel evaporator data are of paramount importance to the building and validation of prediction methods used to simulate the local temperatures in a CPU or GPU, which must remain below their operating limit.

In such experiments, normally the heat flux is provided by a DC electrical microheater sputtered on the test section backside. The backside temperature traditionally is measured by thermocouples [1] or resistance temperature detectors (RTDs) [2]. These standard techniques provide the temperature measurements with a point value or a spatial averaged value, which is regarded to be zero-dimensional in terms of spatial resolution. Such data are usually reduced assuming that only 1D heat conduction occurs to obtain local heat transfer coefficients. Hence this technique falls short when monitoring the temperature information with high spatial variation.

Infrared cameras are able to provide "high definition" temperature measurements and are becoming more widely implemented

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.01.023
1290-0729/

for microscale heat transfer study [3–8]. Compared to standard techniques, the IR camera tends to be superior due to several merits such as non-intrusive measurements, truely two-dimensional temperature maps, high frequency acquisition, etc. For instance, the non-intrusive technique avoids any interference on the temperature fields, the high resolution temperature map enables one to quantitatively evaluate the axial heat conduction, and the high frequency acquisition allows for transient thermal measurement. A pixel by pixel inhouse calibration also allows the IR temperature accuracy to become equivalent of those of thermocouples.

From the perspective of theoretical heat conduction models, the directly measured temperatures and heat flux on the test section backside are respectively considered to be the Dirichlet and Neumann boundary conditions while the desired heat transfer coefficients on the opposite side (on top) are the Robin boundary condition. The problem of determining the heat transfer coefficients at the top boundary from the temperatures and heat flux measured at the bottom boundary and other boundary conditions by solving the heat conduction equation is regarded as an inverse heat conduction problem (IHCP) [9]. The principal difficulty in solving IHCP is due to its sensitivity to noise in the input temperature data. This noise incurs oscillations in the heat flux field since it is magnified while calculating the Laplacian term, or the second derivative of the temperature in the heat conduction equation.

To our knowledge, so far two solution strategies have been proposed in the literature to overcome such problems: (1) an iterative regularization scheme [10–14], and (2) a pre-filtering of the raw temperature data [15–17]. The former iterative scheme was first implemented in Ref. [10]. This method is based on the least square error between the measured and simulated temperature data. A regularization parameter is involved in the least square formula. A proper selection of this parameter is able to cope with the noise in the input raw temperature data to further alleviate oscillations in the final solution. In this regard, the most general example is the iterative regularization scheme coupled with a conjugate gradient method [18]. However, this method for solving IHCP is only practical for traditional temperature sensors which provide limited numbers of input and output data [9] Instead, for applications with a large number of input temperatures from an IR camera, this method has shown to be cumbersome due to its expensive computational cost [19]. As an alternative, pre-process filtering of the raw temperature data has proven to be efficient at handling such large noisy data [15,16]. The pre-process filtering technique is therefore adopted in our present work. In this second approach, recently three filtering techniques (an ideal low-pass filter, a Gaussian filter, and a Wiener filter) have been compared in Ref. [16] with respect to an example of heat source restoration in a thin plate. They found that the consecutive implementation of the Wiener filter yielded the most suitable results. In their work, the 2D heat conduction model was built assuming a constant temperature distribution along the thickness direction due to a very low Biot number ($\ll 1$). It is worth noting that the filtering technique appears not to be suitable for the case of a limited number of measurement points obtained by thermocouples or RTDs.

Until now only a few researchers have considered the IHCP when reducing their flow boiling heat transfer data in minichannels. Poniewski and co-workers [20,21] have applied IHCP to flow boiling in single small diameter tubes when using liquid crystals to obtain high resolution external temperature fields. Luciani et al. [22] applied the inverse method to reduce the local flow boiling heat transfer data of HEF-7100 in single minichannels under normal, hyper-, and microgravity. The boundary element method was implemented to resolve the inverse heat conduction problem in 2D and 3D models to characterize the local wall heat flux and temperature.

So far, the concept of IHCP has not been introduced into the experimental local heat transfer data reduction in multi-microchannel evaporators. In most experimental studies, a 1D heat conduction model was employed to calculate the heat transfer coefficients using the measured temperature data at the backside of the test section without any iteration [1,4]. The 1D model only considers the heat conduction through the thickness direction, assuming no heat spreads in the axial direction, which is only suitable for small spatial temperature variations. The axial heat conduction was evaluated in a non-uniform heat flux study using diode temperature sensors by the local 2D energy balance method [23]. That allowed a better determination of the net local base heat flux than a 1D approach. However, a 1D heat conduciton model was still used to conduct the calculation up to the wall temperature using this adjusted base heat flux. Also, a full 2D model was implemented by Costa-Patry and Thome [2] using an array of 35 silicon diode temperature sensors to study flow boiling of refrigerants in a multi-microchannel evaporator with a non-uniform heat flux, i.e. hot spot(s) in the imposed heat flux. However, they only considered the 2D heat condution from the bottom to the top without any iteration. This is referred from now on as the “direct” method. Recently, a 3D heat conduction model was solved directly from observations at the back of a multi-microchannel test section to characterize the local heat transfer coefficients, without any iteration or resorting to IHCP [8].

In order to implement and validate the 2D conduction model used in their dynamic modeling of multi-microchannel evaporators [24], the authors introduced an iterative approach to solve the 2D heat conduction problem by using a guessed heat transfer coefficient profile at the top boundary and the known base temperature profile as the investigator [25]. However, three shortcomings remained in their work: (1) the heat transferred in the widthwise direction (perpendicular to the flow) was ignored (i.e. 2D only), (2) the local fluid temperature is needed, (3) the iteration with the guessed Robin boundary condition at the top appears to be much more time-consuming than the direct method of [8]. In the present work, we aim to provide a more practical and precise data processing method by solving the 3D IHCP for obtaining the local heat transfer data in multi-microchannels (single- and two-phase cases). This method is validated using two sets of single- and two-phase flow experimental data tests for a multi-microchannel test section. In the experiment, the IR camera was employed as the temperature sensor. Due to the high resolution of the IR temperature map, an improved way to determine the lateral boundary conditions is introduced. To remove the noise in the raw temperature data, three filtering techniques are employed: Wiener filtering, spline smoothing, and polynomial surface fitting. In the new method, the direct 3D heat conduction problem is solved firstly using a finite volume method (TDMA algorithm) with a guessed Dirichlet boundary condition at the top (instead of the time-consuming Robin boundary condition of [25]). Then a Newton-Raphson method is used to optimize the new footprint temperature array. Finally, the local energy balance method is employed to determine the local heat flux at the top boundary. As a final test, three heat conduction models used in the current literature to reduce the experimental data are reviewed and compared with the new proposed method to demonstrate why it is important to go to this much detail to get accurate local heat transfer results.

2. Case descriptions

Two cases of experimental data composed of single- and two-phase flow were selected to validate the new method. The experimental facility used to acquire the data was the same as