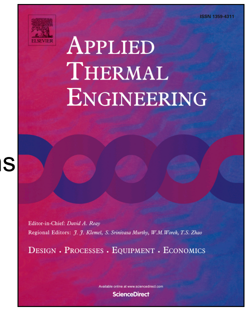
Accepted Manuscript



Thermal analysis of droplet flow: numerical, analytical and experimental investigations

M. Romano, R. Guillaument, C. Hany, J.C. Batsale, C. Pradere

PII: S1359-4311(15)00656-0

DOI: 10.1016/j.applthermaleng.2015.06.096

Reference: ATE 6790

To appear in: *Applied Thermal Engineering*

Received Date: 21 November 2014

Revised Date: 8 June 2015

Accepted Date: 26 June 2015

Thermal analysis of droplet flow: numerical, analytical and experimental investigations

M. Romano[a,c,*], R. Guillaument[b], C. Hany[a], J.C. Batsale[c], C. Pradere[c,**]

[a]LOF, Université Bordeaux 1, UMR CNRS-Rhodia-UB1 5258, 178, A. Schweitzer, 33608 Pessac Cedex, France
[b]ICMCB, Université de Bordeaux, CNRS, UMR 9048, 87 Avenue du Dr. A. Schweitzer, 33608 Pessac Cedex, France
[c]I2M, Département TREFLE, UMR CNRS 5295 site ENSAM Esplanade des Arts et Métiers, 33405 Talence Cedex, France

Abstract

This article reports the thermal behavior analysis of droplet flow for a scenario in which the hydrodynamic and thermal effects are coupled in a cylindrical miniaturized channel; this analysis was performed by comparing numerical, analytical and experimental results. The 3D numerical modeling of the droplet flow was performed using THETIS, a multi-fluid Navier−Stokes solver. A 1D analytical model in Lagrangian space based on a thin-fin thermal approximation was developed. Infrared thermography measurements of droplet flows were used to experimentally determine the temperature fields inside droplets, and these results were compared with those obtained from the simulations and the analytical approach. The originality of this work is the choice of a particular thermal scene to mimic a chemical situation in order to improve understanding and to illustrate the predominant exchanges by model simplification. Furthermore, the results of this study are important for understanding the heat transfer occurring inside droplets for lab-on-chip applications.

Keywords: Millifluidics, Thermal analysis, Infrared Thermography, Hydrodynamics, Multiphase flow, Lagrangian

High lights

- Modeling of droplet flow when thermal and hydrodynamic effects are coupled
- 3D numerical simulation
- Droplet-based Lagrangian analytical modeling
- Experimental measurements of local temperature fields
- Model simplification: understanding the predominant exchange phenomena

1. Introduction

Miniaturized multiphase flows are used in a wide range of applications in fields such as biology, chemistry, and energy production, among many others. In particular, for reaction engineering purposes, the use of segmented flows has increased in popularity in recent years [1, 2, 3]. In addition, the fluid mechanics and hydrodynamics of such miniaturized flows have been studied for both gas−liquid applications [4, 5, 6] and liquid−liquid applications [7, 8]. Several experimental studies have reported coupled thermal and hydrodynamic effects in gas−liquid flows. These studies have primarily reported the influence of the segmentation ratio (i.e., the ratio between the lengths of each segment) on enhancing the heat transfer inside microchannels [9, 10]. Moreover, other studies have applied non-dimensional analysis to describe the observed experimental behavior of such systems [11, 12, 13, 14]. For gas−liquid flows, several studies using numerical and analytical approaches have also been reported [15, 16, 17, 18].

Considering liquid−liquid flows, several studies have considered coupled thermal and hydrodynamic effects. Pradere *et al.* [19] reported experimental and theoretical results regarding such effects inside a microfluidic chip and have concluded that the characterization of these thermal and hydrodynamic effects is difficult to achieve because of the many parameters necessary for a complete thermal description of the flow. Chen *et al.* [20] proposed empirical correlations for liquid-liquid flows through numerical and experimental studies. Moreover, numerical studies have been reported [21, 22], where these works have demonstrated that the effective rate of heat transfer in droplet flow is higher than that in a single-phase flow. Extremely valuable works were published by Eian *et al.* [23] and by Ghobadi *et al.* [24], which concerned experimental and numerical analyses of heat transfer inside liquid-liquid flow. Furthermore, when a chemical reaction occurs inside a liquid−liquid flow, the modeling becomes more complex in terms of the number of coupled effects that occur (hydrodynamic, thermal, mass diffusion effects and heat source)[25].

From an experimental point of view, several publications have reported original techniques to measure coupled phenomena by simultaneous thermal and optical measurements in miniaturized applications [26]. Other promising tools based on micro-electro-mechanical systems (MEMS) have been developed to control, investigate and characterize phenomena occurring in two-phase flows [27]. However, optical imaging tools combined with miniaturized systems have generally proven to be a powerful combination for such analysis [7, 28] due to their good resolution (10 μm), fast acquisition (10 kHz) and high sen-

*Corresponding author e-mail: romano@enscbp.fr
**Corresponding author e-mail: c.pradere@i2m.u-bordeaux1.fr