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Study of the hydrodynamic characteristics of a free flowing liquid film in open inclined microchannels

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HIGHLIGHTS

- We study experimentally the falling film hydrodynamics in microchannels.
- It appears that wetting phenomena and contact angle hysteresis affect in a great degree the operation of FFMR.
- We have formulated a generalized correlation for predicting film thickness with reasonable accuracy (± 15%).
- A simplified empirical correlation is also proposed for the prediction of meniscus shape.

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ABSTRACT

A widely used device for continuous contacting in microdevices is the *Falling Film Micro-Reactor* (*FFMR*). The liquid films that are formed in the channels of a *FFMR* are quite stable and have a typical thickness of less than 100 μm. In the present work, a *μ-PIV* system was used for measuring velocity profiles and for estimating the local liquid film thickness in three open inclined microchannels (with width of 1200, 600 and 300 μm). The film thickness measurements were utilized for reconstructing the shape of the interface, while the effect of various fluid parameters (e.g. physical properties, flow rate) as well as geometrical characteristics of the conduit and the inclination angle of the microchannels, on the geometrical characteristics of the liquid phase has been also experimentally investigated. As the correlations that are valid in the macroscale are generally not applicable in the microscale, the aim of the present study is to develop a means for predicting the geometrical characteristics (i.e. liquid film thickness, shape of the gas/liquid interface) of the liquid phase, as well as its mean residence time. Generalized correlations for predicting film thickness and meniscus shape are proposed (accuracy ± 15%) while, by combining these correlations an estimation of the mean residence time can be also made.

1. Introduction

Microreactor technology is a modern, promising trend in chemical engineering that integrates safety with economy. Microreactors are characterized by low reagent consumption, quick system response and multifunctionality, since various unit operations can be combined in a single piece of equipment. Additionally, as both minichannels and microchannels are characterized by high specific areas, heat and mass transfer rates are enhanced compared with conventional technologies and this feature has attracted the interest of chemical and pharmaceutical industries.

In traditional chemical engineering there are various reactors that can be utilized for gas–liquid reactions. There are basically two approaches for bringing two phases in contact. The first is to keep both phases continuously contacting at the interface while the second is to disperse one phase into the other (Ziegenbalg et al., 2010). The most popular device for continuous contacting is the *Falling Film Micro-Reactor* (*FFMR*). In microchannels the liquid films that are formed are quite stable and have a typical thickness of less than 100 μm, while in conventional falling film devices the film thickness is usually between 0.5 and 3 mm (Ho et al., 2011). As such thin films offer a high surface to volume ratio, *FFMRs* have enhanced heat and mass transfer capabilities and are therefore suitable for various gas/liquid applications (e.g. reaction, evaporation and highly exothermic/endothermic processes). To achieve optimal performance of the microreactors, the designer must know exactly how the interplay between flow, mixing, heat

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transfer and chemical reaction works. Due to the small characteristic dimension of the conduit, viscous forces dominate, while inertial forces become less important. In the same time the ratio of surface area to system volume increases and so does the relative importance of surface forces comparing with gravity forces. It is obvious that working in microscale differs from working in macroscale and as a result the operating parameters of a *FFMR* (i.e. liquid film thickness, film velocity, extent of interfacial area) are not expected to be accurately predicted using the well-established design correlations that are valid in the macroscale.

Many recently published papers deal with processes that take place in falling film microreactors and explore the operating parameters which affect the performance of an *FFMR*. For example, Moschou et al. (2012), who investigated mass transfer during the stripping of nitrogen from isopropyl-alcohol and toluene in an *FFMR*, developed two mass transfer models, namely a semi-analytical one based on the mass balance equations and a numerical one solving the hydrodynamics and mass transfer equations. However, in this work it was assumed that the curvature of the film meniscus does not considerably contribute to the increase of the interfacial area and thus both the liquid film thickness and the velocity was estimated using the Nusselt theory. Sobieszuk and Pohorecki, (2010) investigated mass transfer during the absorption of CO_2 by a NaOH aqueous solution and measured the liquid and the gas side mass transfer coefficients. The absorption of CO_2 in a *FFMR* was also studied by Chasanis et al. (2010), who used numerical methods for investigating the relative impact of various process parameters (e.g. gas and liquid phase volumetric flow rates) on absorption performance. Stavarek et al., 2009 via the hydrogenation of a-methylstyrene investigated the hydrodynamics and mass transfer characteristics of a *FFMR*.

Other important studies, concern micro-evaporation and micro-distillation in falling film devices, where heat transfer has to be intensified. Monnier et al. (2012) published a study about the different boiling heat transfer regimes in a micro-exchanger during falling film evaporation of a pure substance (ethanol). Klemm et al. (2011) investigated the evaporation of a 50% aqueous hydrogen peroxide solution in a *FFMR* made of $ALMg_3$ while Kane et al. (2011) published a work about the capability of a *FFMR* to separate a binary mixture of ethanol and n-propanol. In this last study, experimental measurements of heat and mass transfer are analyzed and finally it is proved that the operation of the microcontactor depends essentially on heat flux and feed flow rate. The film thickness has been calculated using the Nusselt correlations. Important information about the operation of a *FFMR* is given in the papers by Zhang et al. (2010) and Monnier et al. (2010) in which the stability of the falling film is investigated. In the first one the flow patterns in a *FFMR* are presented and an empirical correlation for the calculation of the minimum wetting flow rate is also proposed. Al-Rawashdeh et al. (2008), who have numerically studied the design parameters of a *FFMR*, examined the effect of liquid flow distribution, gas chamber height and hydrophilicity and/or hydrophobicity of the channel material on the absorption rate of CO_2 by an aqueous solution of NaOH. Yeong et al. (2006) have conducted experiments in vertical stainless steel microreactors using low surface tension alcohols as working fluids and determined the shape of the interface and the liquid film thickness using laser scanning confocal microscopy. Also Tourvieille et al., (2013) studied the operation of a microstructured falling film at pilot scale with the use of fluorescent confocal microscopy by varying the properties of the solvents used such as viscosity and surface tension. Recently Ho et al. (2011), applied the volume of fluid (*VOF*) model to numerically study the hydrodynamic characteristics of the liquid film (i.e. velocity, pressure and shear stress profiles) as well as the shape of the interface in a 300 width microchannel. However in none of the aforementioned works a general strategy for the design of *FFMR* devices is proposed.

It is obvious that to be able to calculate the mass and heat transfer rates in a *FFMR*, one must know the characteristics of the liquid film, e.g. velocity profiles, extent of the gas–liquid interface etc. Thus the purpose of this work is to experimentally investigate the effect of various fluid parameters (e.g. physical properties, flow rate), as well as geometrical characteristics and inclination angle of the conduit on the geometry of the liquid phase and on the velocity profiles. Since the correlations that are valid in the macroscale are not generally suitable for being applied in microscale, the aim of the present study is also to contribute to the design of *FFMR* devices by proposing correlations suitable for predicting the geometrical characteristics (i.e. liquid film thickness, shape of the gas/liquid interface) of the liquid phase.

2. Experimental setup

The experimental setup (Fig. 1) consists of a fluorescence *μ-PIV* system, the test section that comprises of microchannels and a syringe pump for generating the flow. The test section (Fig. 2) consists of three microchannels of square cross-section with a side width of 1200, 600 and 300 μm. The microchannels were manufactured on a sheet of

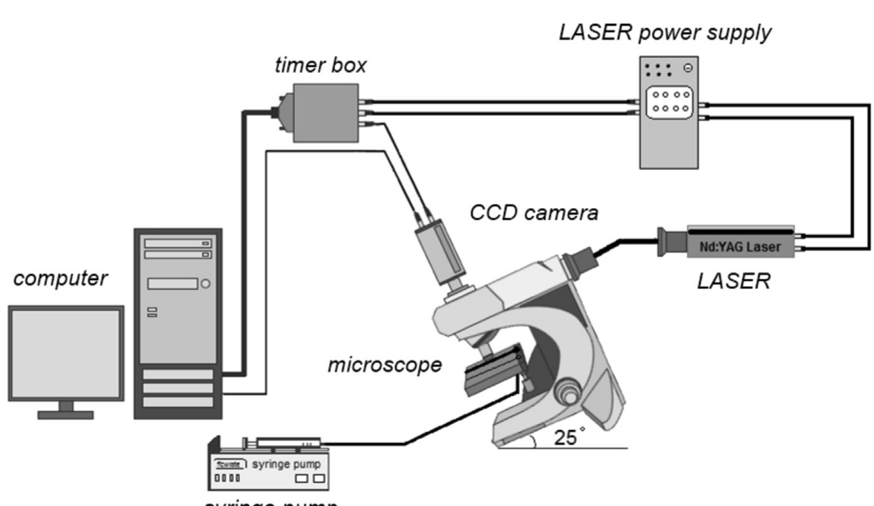

Fig. 1. Experimental set-up.