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Investigation of Flow Patterns and Heat Transfer in Gas-Driven Thin Liquid Films

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ABSTRACT

Gas-driven liquid films are a promising candidate for heat up and evaporation of liquids in an efficient way. Many industrial fields benefit of this type of treatment, because of an intensive heat transfer, such as upcoming modern combustion chambers, reboilers, condensers or cooling applications, while gas-driven films represent a complex interaction of two fluids. The state of the film flow and the complex transport mechanisms owing to the interaction at the liquid-gas interface can have significant influences on the overall heat transfer performance, film stability, rupture and wetting process. One advantage of gas-driven liquid films is the stability against film rupture, since close to the film rupture conditions the shear force at the liquid-gas interface guides the liquid along the flow direction and promotes the wetting of the solid wall. In this study, gas-driven thin liquid film flows on unstructured and structured heated walls are investigated experimentally. The effect of different inlet temperatures of both the fluids on the heat transfer rate and the flow pattern is determined. Another aim of the present study is to give insight to the complex flow mechanisms and wetting behaviour of gas-driven thin liquid films on undulated surfaces fabricated as microgrooves. The gas and liquid Reynolds number are varied between 0 to 84000 and 80 to 1900, respectively. Measurements on wall temperature distribution are performed and Nusselt numbers are calculated. By using a high-speed infrared camera, the flow pattern of the liquid is recorded for different experimental parameter configurations revealing the wetting behaviour, flow patterns and rupture of the thin liquid layer. The measured results disclose that using shear at the interface of a thin liquid governs the film stability and heat transfer. An increase of interfacial shear leads to a highly wavy film flow, which is characterized mostly by 3-dimensional surface structure (see Figures below). Another major finding is that at small liquid mass flow rates, the gas flow does not have significant influence on the heat transfer enhancement. The dominance of the gas flow comes more into account at elevated film flow rates.

INTRODUCTION

Thin liquid films driven by a turbulent gas stream can be found in many technical applications such as cooling systems used in chemical industry, gas scrubbing, thermal processes and cooling systems (Ebner et al., 2004, Chu and Dukler, 1974, Jurman and McCready, 1989, Guerreri and King, 1974). Compared to an evaporating liquid film which is basically driven by gravitation (falling film), a vaporizing liquid layer sheared through a turbulent gas stream (gas-driven film) represent a promising method in terms of high evaporation rates and hence increased heat transfer. Another advantage of gas-driven liquid films is the stability against film rupture, since close to the film rupture conditions the shear force at the liquid-gas interface guides the liquid along the flow direction and promotes the wetting of the solid wall (Kabov et al., 2011). In such liquid-gas flow configuration the thermo-hydrodynamic process is rather complex and is therefore not well understood. Due to the fact, that numerical simulations or theoretical models rely on these mechanisms, experimental investigations are necessary in order to delineate this complex thermo-hydrodynamic phenomenon and to provide validation data to the theoreticians.

The aim of the present study is to give insight to the complex flow mechanisms and wetting behaviour of gas-driven thin liquid films on undulated surfaces fabricated as micro-grooves. Therefore, an experimental setup has been used with high-resolution cameras monitoring the wetting behaviour, flow patterns and rupture of the thin liquid layer at varying operating parameters. Moreover, the cooling performance of gas-driven films has been determined for similar operating conditions. This paper gives an extraction out of a large spectrum of measurements performed in this study.

EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

In Fig. 1 the experimental channel for the investigation of hydrodynamics and heat transfer in gas-driven liquid films is shown schematically. Tab. 1 incorporates the operating parameters used in this study. A vertically aligned heated copper tube represents the main element of the experimental configuration, which has an annular cross section in flow direction. Air flows in at the inlet of the channel and passes through a flow straightener. Simultaneously deionized water exits the film distributor and covers the tube surface as a uniform thin layer.

Table 1. List of experimental parameters.

$T_{Gas,in}$	= 30°C, 100°C
$T_{Liq,in}$	= 25°C, 75°C
p_{abs}	= 3 bar
q_W	= 15 Wcm^{-2}
Re_{Liq}	= 30 - 1900
Re_{Gas}	= up to 84000
Pr_{Liq}	= 6.128 – 2.386
Pr_{Gas}	= 0.713 – 0.707
λ_{Liq}	= 0.6072 – 0.6669 Wm^{-1}K^{-1}
μ_{Liq}	= $0.89 \cdot 10^{-3} - 0.37 \cdot 10^{-3}$ kgm^{-1}s^{-1}
μ_{Gas}	= $18.74 \cdot 10^{-6} - 21.96 \cdot 10^{-6}$ kgm^{-1}s^{-1}

The liquid film is heated with a pre-set heat flux at the wall using a heating cartridge mounted inside the tube. The liquid film and the gas flow concurrently towards the exit of the channel. Once the liquid film approaches the end of the tube, it is extracted out of the channel through a drainage. In order to provide optical access to the liquid film flow, quartz and calcium fluoride windows are assembled in the channel. The inlet of the liquid is defined at the coordinate $z = 0$ mm. The inlet temperature of the liquid $T_{Liq,in}$ has been measured at the location $z = -15$ mm using a thermocouple dipped into the liquid while the liquid outlet temperature $T_{Liq,out}$ has been detected inside the liquid collected in the drainage. The measurement of the inlet temperature of the gas flow $T_{Gas,in}$ is performed in the gas stream at $z = 0$ mm. The relative humidity of the gas has been measured at the connecting supply line to the flow channel. The relative humidity ranged between 2 % and 5 %. To determine the wall temperature distribution in z-direction, thermocouples have been soldered into the wall of the tube, 1.55 mm under the liquid-wall interface (see Figure 2). A distance of $\Delta z = 5$ mm has been kept between each thermocouple tip in flow direction. The dimensions for the micro-structured surface are given in Figure 3. The overall uncertainty in temperature measurement by the thermocouples after the calibration is ±0.92 K. For the present investigation, the inlet temperatures of the liquid and the gas streams have been fixed at $T_{Liq,in} = 25$°C and 75°C, $T_{Gas,in} = 30$°C and 100°C. The gas absolute pressure has been kept constant at 3 bar. The liquid mass flow rate is measured using a Coriolis mass flow meter with an accuracy of ±0.15 % of the reading and the gas mass flow rate is measured by the means of a thermal mass flow meter with an uncertainty of ±1.5 % of the measurement range. To investigate the film dynamics, an Infrared camera has been frontally focused on the tube surface at $z = 45$ mm (Budakli et al., 2012).

SELECTED RESULTS

Fig. 4 shows the Nusselt number results of the measurements, in which a heat flux density of 15 W/cm² was set. In the range of small liquid Reynold numbers ($Re_{Liq} < 180$), the influence of Re_{Gas} is on Nu_m is rather low, whereas with increasing Re_{Liq} the influence becomes significantly stronger. This effect reduces with decreasing liquid mass flow and thus increasing wall temperature, resulting in a lower heat transfer coefficient. Visible is a change of the curve shape in the area between $54000 < Re_{Gas} < 68000$, which in the range $240 < Re_{Liq} < 700$ leads to a remarkable jump in the Nusselt number leads. This effect can be attributed to the change of the liquid flow, for example, due to the transition to more turbulent waves and an intensification of the momentum transfer perpendicular to the flow direction.

In Figure 5 the Nusselt numbers for a liquid inlet temperature of 75°C at 15 W/cm² heat flux for varying liquid and gas Reynolds numbers are presented. To note, additional to the gas-driven film flow measurements, data on falling film at comparable operating parameters have been collected. The increased Re_{Liq} resulted due to the reduction of the liquid viscosity. Starting at gas Re_{Gas} of 54000, the gas flow has a much greater influence on the heat transfer, which is reflected in the Nu trend. Nu continuously increases with decreasing fluid mass flow (Re_{Liq}) for $Re_{Gas} \geq 68000$. In contrast, the area where the convective heat transfer rises with decreasing Re_{Gas} becomes smaller and the increase shifts to lower Re_{Liq}. It can be assumed that the flow pattern in the range between $40000 < Re_{Gas} < 54000$ changes and intensifies the heat transport. Furthermore, this trend can be probably justified by the effect of partial wetting, since at elevated gas velocities the liquid film ruptures due to strong interfacial shear. The question is whether the increased heat transfer is governed by heat convection between the low temperature gas and the wall, the intensified mixing of the liquid film.

IR images about the film dynamics along the micro-structured surfaces is displayed in Figure 6 for a heat flux density of 15 W/cm² and $Re_{Liq} = 400$. One can recognize clearly non-wetted areas for $Re_{Gas} = 54000$ while at higher gas flow rates ($Re_{Gas} = 68000$), this phenomena intensifies and the rate of liquid-wetted area becomes smaller, hence the crests of the microstructures are more exposed to the air flow. Higher shear at the liquid-gas interface leads to significant wave formation, with an intense mixing in the liquid film and thus probably to a stronger partial wetting before and after the wave crest. Through this temporary, partial wetting is on the one hand a heat transfer from the wall into the gas flow possible, on the other hand it leads to the formation of a 3-phase contact line, which is causes significant improvement of the heat transfer. Additionally, the strong deformation of the liquid film can contribute to the convective heat transfer through intensification of the mixing mechanism within the liquid bulk.

CONCLUSIONS

In this study, gas-driven thin liquid films have been investigated experimentally at different operating parameters on micro-structured surfaces. The measured results reveal that using shear at the interface of a thin liquid governs the film stability and heat transfer. An increase of interfacial shear leads to a highly wavy film flow, which is characterized mostly by 3-dimensional surface structure. Another major finding is that at small liquid mass flow rates, the gas flow does not have significant influence on the heat transfer enhancement. The dominance of the gas flow comes more into account at elevated film flow rates.

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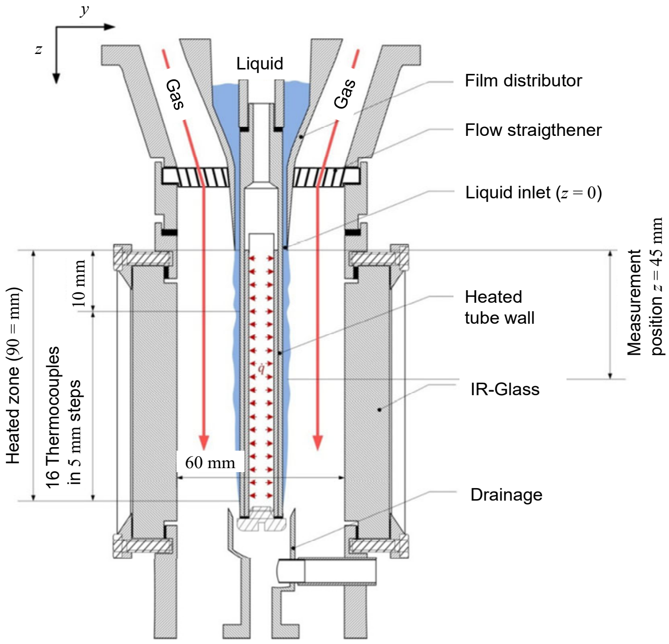

Figure 1. Experimental test section for gas-driven thin liquid films.

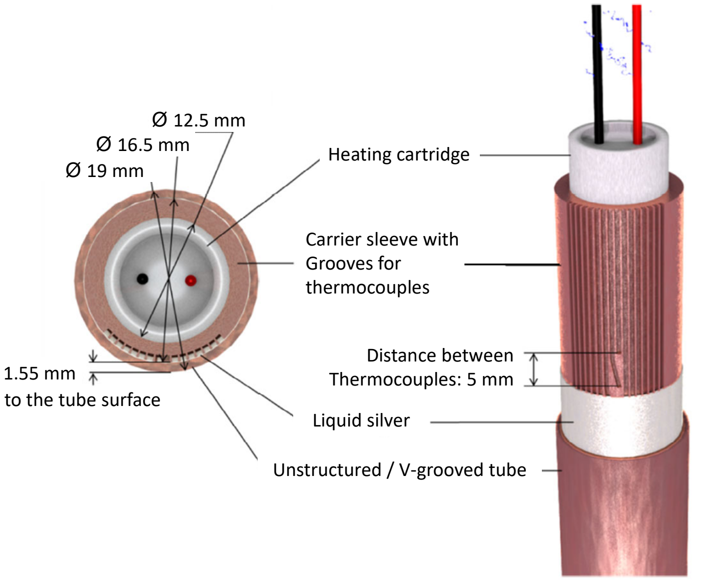

Figure 2. Copper tube configuration with heating cartridge and sleeve for thermocouples.

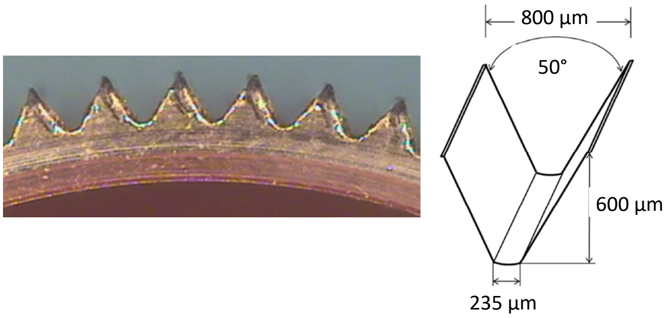

Figure 3. Micro-structured tube: left) Cross-section of V-grooved surface, right) Geometric dimensions.

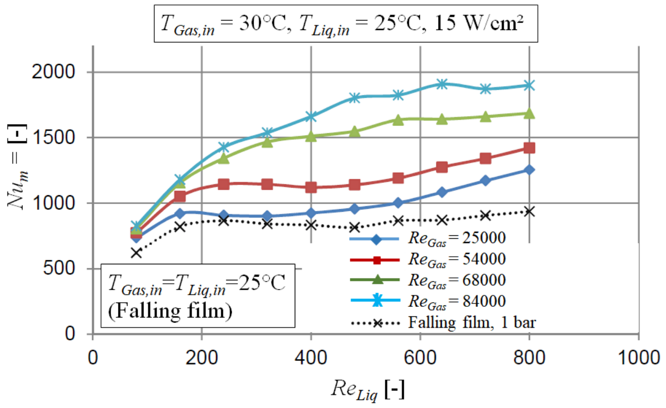

Figure 4. Average Nusselt number at 15 W/cm² depending on Re_{Liq} and Re_{Gas} for $T_{Gas,in}$ = 25°C, 30°C and $T_{Liq,in}$ = 25°C.

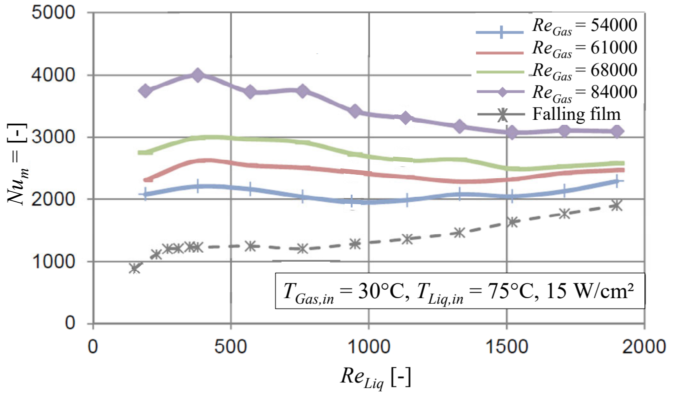

Figure 5. Average Nusselt number at 15 W/cm² depending on Re_{Liq} and Re_{Gas} for $T_{Gas,in}$ = 30°C and $T_{Liq,in}$ = 75°C.

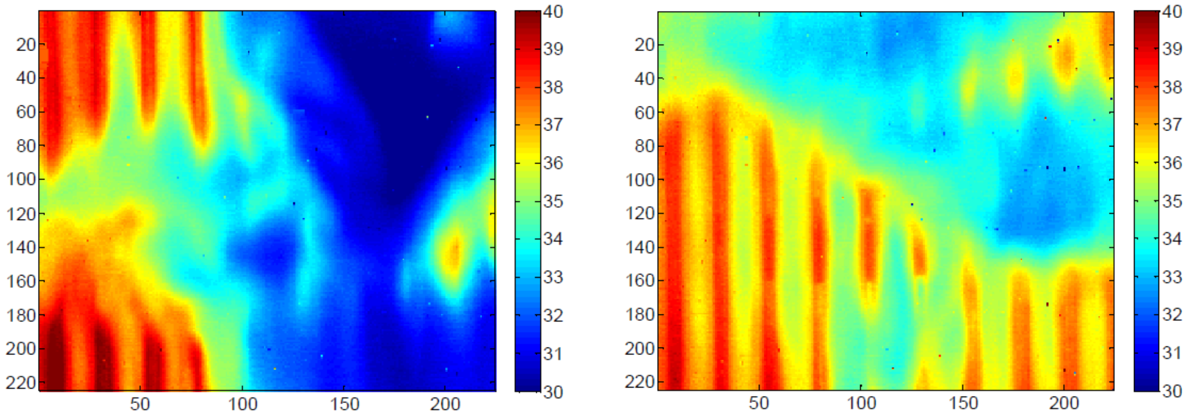

Figure 6. IR images for Re_{Gas} = 54000 (left) and Re_{Gas} = 68000 (right), Re_{Liq} = 400, 15 W/cm² for $T_{Gas,in}$ = 30°C and $T_{Liq,in}$ = 25°C.