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Near-zero shear stress experiments with heat flux effects on falling film evaporation inside a vertical tube

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ABSTRACT

Local heat transfer coefficients for falling film evaporation of isopropanol were experimentally measured ($(U_{h,\,95\%}/h)_{max} = \pm 3.5\%$) inside a vertical brass tube ($d_{inside} = 28$ mm) at near-zero shear stress. Zero shear stress experiments with falling film evaporation inside a tube are extremely difficult to realize – not to say they are impossible. In literature respective heat transfer investigations and visual flow observations were mostly done at outside tube surfaces surrounded by an extended volume. For the present investigations at near-zero shear stress a special vapour flow sensor was developed and installed in the experimental tube to locate the level of near-zero vapour velocity. The measurements included film *Re* numbers up to 100, inner wall heat flux up to 12,500 Wm^{-2} without bubble formation in the superheated liquid, and vapour temperatures ranging from 8.5 °C to 36 °C ($Pr_{liquid,\,freesurface} = 14.5–20.8$). The heat transfer measurements were focussed on *Re* number and heat flux effects on falling liquid film evaporation. The basic intension of this paper is a comparison of the evaporation heat transfer measurements with the characteristics in the various *Re* number ranges, and also a comparison with the authors' earlier condensation results as reported in Refs. [1,2]. Thereby influences of *Re*, *Pr* and *Ka* numbers on heat transfer are discussed, correlated (within deviations of ±2.7% from measured data) and compared with the literature.

1. Introduction

Falling film evaporation and condensation inside vertical tubes are found in many industrial applications like heat exchangers and chemical process columns where heat transfer is always affected by the vapour-side shear stress. This acts cocurrent or countercurrent to the liquid film depending on vapour flow direction. The open literature provides lots of heat transfer measurements, both for evaporation and condensation, and also studies of the hydrodynamics of falling liquid films, see, e.g. Refs. [3–10], regarding falling film evaporation [1,2,11–14], for condensation, and [15–22] for the hydrodynamics. For literature concerning wave shape, film structure and frequency see also Philipp et al. (2006) [21] and Gross et al. (2009) [2].

Nusselt (1916) [23] presented the first analytical solution of velocity profile and heat transfer across a smooth laminar film with and without the influences of vapour-side shear stress. These results have been confirmed as the lower limit for condensation and evaporation heat transfer, e.g. by Brauer (1956) [24] and Alekseenko et al. (1994) [17]. Actually, heat transfer was found to be enhanced by wave formation and transition to turbulence. The structure of falling liquid films is usually classified to be laminar, laminar-wavy, and locally or fully turbulent depending on Reynolds, Kapitza and Prandtl numbers. Falling film condensation and/or evaporation heat transfer measurements have been presented and correlated by many scientists, e.g. Refs. [12–14,25,26], mostly for vertical walls and the outside of tubes.

The present authors performed extended reflux-condensation heat transfer measurements with water, ethanol, and isopropanol ($2.6 \leq Pr \leq 55$) inside a vertical tube in the countercurrent flow situation with the focus on shear stress effects [1,14,27,28]. Excellent reproducibility (±1% for water, ±0.5% for isopropanol) was obtained allowing extrapolation of the measured data to zero shear stress [1]. The results have been plotted in terms of the Nusselt number, see Fig. 1, and they have been referred to Nusselt's solution [23]. For getting the wave enhancement factor $F_{wave} = Nu_{experimental}/Nu_{Nusselt\,(1916)}$ as shown in Fig. 2 and [1]. Furthermore the condensation heat transfer data have been correlated for the laminar-wavy range done for three sub-ranges (Eqs. (1)–(3)) corresponding to different wave characteristics as obtained from visual observations [2] (for the definitions, see Eqs. (4)–(8) below):

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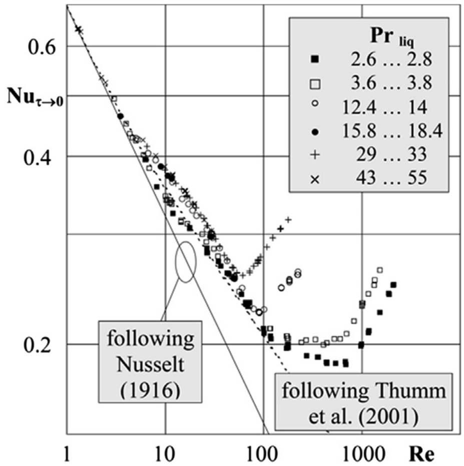

Fig. 1. Condensation heat transfer for the limiting case of zero shear stress in a vertical tube (see also Gross and Philipp (2006) [1]).

$$F_{wave} = 1.028\left(Re\,Ka^{0.09} < 0.8\right) \quad (1)$$

$$F_{wave} = 1.096Re^{0.141}Ka^{0.0126}\left(0.8 \le Re\,Ka^{0.09} < 4.2\right) \quad (2)$$

$$F_{wave} = 1.270Re^{0.040}Ka^{0.0036}\left(4.2 \le Re\,Ka^{0.09} < 7.3\right) \quad (3)$$

where

$$Re = \frac{\Gamma_{liquid}}{\mu_{liquid}} = \frac{\dot{m}_{liquid}}{\pi d_{pipe-inside}\mu_{liquid}} \quad (4)$$

and

$$Ka = \frac{g\mu_{liquid}^4}{\rho_{liquid}\sigma_{liquid}^3}. \quad (5)$$

The Kapitza number (Ka) has been established for classification of the wave activity in falling liquid films. In literature the Ka number was used first with $Re = 0.6075Ka^{-1/11}$ to compile the lower limit for the development of sinusoidal waves (see Kapitza (1948) [29]). Three years earlier, Grimley (1945) [30] suggested $Re = 0.291Ka^{-1/8}$ as the smallest Re number for getting wavy liquid films. The literature contains various Ka number definitions, and Eq. (5) is used e.g. by Chun and Seban (1971) [3], Alhusseini et al. (1998) [26] and VDI heat atlas (2010) [31]. There are, however, different ones like $Ka^* = 1/Ka$ used by Alekseenko et al. (1994) [17], Al-Sibai (2004) [32], and Weise and Scholl (2007) [10]. Further modifications are $Ka^{**} = (1/Ka)^{-1/3}$ and $Ka^{**} = (3/Ka)^{-1/5}$, see Dietze and Kneer (2010) [33] and Sofrata (1980) [34] respectively. Thereby mostly all researchers are using different reference temperatures.

McAdams (1954) [35] and Blangetti (1979) [36] introduced averaged wave factors, $F_{wave} = 1.28$ and 1.15, whereas Labuntsov (1957) [37], Zazuli (see Kutateladze (1963) [38]) and Uehara et al. (1983) [39] found the wave factors to increase with the Re number introducing $F_{wave} \propto Re^{0.04}$, $F_{wave} \propto Re^{0.11}$ and $F_{wave} \propto Re^{0.083}$ respectively. Sofrata (1980) [34], Uehara (1983) [39] and Mitrovic (1990) [40] refined the wave factor calculation by including Ka number effects. In case of laminar wavy film evaporation, Alhuseini et al. (1998) [26] did the same, whereas Chun and Seban (1971) [3] restricted the wave factor calculation on Re number effects similar to Kutateladze's (1963) [38] approach.

Based on additional visual observations of surface waves, the present authors evaluated the effective wave frequency as the leading effect on heat transfer enhancement from slow motion videos for $Re < 100$ [21]. Various characteristic ranges have been obtained from both studies with clear criteria for the transition from a first range (occasional small waves with a limited heat transfer enhancement of about 2.8%, Eq. (1)) to a second (two-dimensional waves with low effective wave frequency, Eq. (2)) and finally a third range (three-dimensional waves with increased effective wave frequency, Eq. (3)) bringing enhancement factors up to 34.5% and 37.5%, respectively ([2,41]).

Heat transfer measurements inside vertical tubes (afflicted by shear stress) are focussed on thermosyphon applications [25,42,43]. Zero shear stress experiments with falling film evaporation inside a tube are extremely difficult to realize – not to say they are impossible. Respective heat transfer investigations and visual flow observations at outside tube surfaces surrounded by an extended volume are easier to handle. Struve (1969) [44], Chun and Seban (1971) [3], Alhusseini et al. (1998) [26], Leuthner (1999) [45] and Leuthner et al. (1999) [6] reported such local heat transfer experiments.

Realization of evaporation heat transfer measurements with near-zero shear stress inside a vertical tube was one aim of the present study. Second aim was to investigate the relation between changes in local heat transfer and film structure depending on Re, Pr and Ka numbers as well as on heat flux effects. The test setup, the vapour flow sensor, the Reynolds number and heat flux effects will now be explained and discussed in detail.

2. Methods

2.1. Experimental setup

An experimental setup which previously has been used for local reflux condensation heat transfer measurements [1,14,46] has been modified for the present evaporation measurements. These modifications enabling both cocurrent and countercurrent vapour flow [41,47].

The experimental plant (Fig. 3) consists of a vertical brass tube with a total length and inner diameter of 4.2 m and 28 mm, respectively. Three cycles are established, one for the liquid and two for vapour, which can be operated independent from each other. Liquid (e.g. isopropanol) is pumped by an infinitely variable gear pump through a mass flow measuring device at a constant temperature (controlled by a thermostat) to the top of the tube where it penetrates a porous sintered steel section. A uniform liquid film is created which flows downward at the inner wall surface with a total hydrodynamic entrance length of about 1580 mm before entering the measuring level. The uppermost part of the tube is surrounded by a water jacket for heating (heating system). The heating water can be fed into three different inlets of the evaporation section, permitting three different lengths of the heating zone. The measuring level for local heat transfer coefficients is located in the lower-most section. The present experiments have been done with the two lower heating lengths and mainly with the thermal entrance length of 740 mm.

For measuring the heat transfer in the measuring level two thin calibrated thermocouples (0.5 mm in diameter) are situated directly underneath the in- and outside surfaces of the thick-walled brass tube each at three points over the circumference (every 120°). Therefore the thermocouples were inserted in axially blind-end bores which were manufactured by spark erosion (150 mm in length and 0.6 mm in diameter). The remaining gap between