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Investigations of the spreading of falling liquid films in inclined tubes

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ABSTRACT

Starting with an extensive literature review, in this study investigations of the film spreading of falling films inside smooth and structured tubes are presented in dependence of the tube inclination angle ($\beta = 0^\circ$ til 20° from the vertical), mass flow rate and fluid temperature (263.15–293.15 K). Experiments are conducted at isothermal conditions and at partly film evaporation as well. The liquid film is observed visually with a camera which can be moved along the total flow length of the liquid without essential disturbance of the liquid respectively gas flow. The liquid used for the investigations is propane ($Pr \approx 3$, $Ka \approx 20 \cdot 10^{10}$, $Re_{\text{smooth tube}} = 20\text{–}950$). The experiments reveal that the investigated helically structuring of the internal tube surface leads to an improvement of film spreading even for inclination angles up to $\beta = 20^\circ$. Preliminary tests in an open air-water system clearly showed that the groove structure geometry has an influence on initial wetting and film spreading. Further, the results of the calculated capillary transport from two theoretical approaches are compared and adapted to each other.

1. Introduction

Liquid-vapour systems are very popular in a broad range of thermal applications due to their high heat transfer coefficients as stated by Mascarenhas and Mudawar [1]. One category of such systems are falling liquid film evaporators. This technology provides an enormous heat transfer performance and efficiency due to (I) low conduction resistance across the film resulting in minimal temperature differences between the heated and the free film surface, (II) internal fluid mixing by interfacial waves, (III) low pressure drop and (IV) fluid motion by gravity, see Mascarenhas and Mudawar [1], Storch et al. [2]. Therefore this technology is widely used in horizontal and vertical falling film evaporators as applied in chemical and food industries. Further applications are found in the field of so called renewable energy utilization such as sea water desalination, juice concentration, solar and geothermal thermosiphons as stated by Storch et al. [2], Grab [3], Storch et al. [4].

A major restraint for falling film evaporation is the need of a completely wetted surface for getting high efficiency. This requires a vertical alignment of evaporation-tube heat exchangers. Hartley and Murgatroyd [5], Paramalingam et al. [6] and Storch [7] describe that any deviation from the vertical mostly leads to film breakup, i.e. the formation of rivulets and dry patches yield to a reduction in heat and mass transfer.

One technical approach to prevent the instability of a liquid film has, e.g. been introduced by structuring the wall surfaces as described by Grab [3] and Maun [8]. Surface elements like indentations, grooves, ribs, bulges are integrated into a smooth surface as micro and/or macrostructure elements. These may be orientated in longitudinal or transverse direction or as twisted or combined structures. Additionally, special porous or capillary structures and artificial surface roughness are more specific surface shapes.

The present contribution is directed to distribution and spreading of a falling liquid film inside innovative internal helically grooved tubes. This includes cases without and with evaporation from the film surface for propane and water. Furthermore the effects of mass flow rate, vapour temperature and tube inclination are studied. The investigation is aimed to find optimum tube surface structures for a wide range of parameters.

2. Literature

2.1. Film spreading and minimum film thickness

El-Genk and Saber [9] report that the risk of film rupture and dry-out increases by decreasing the film thickness down to a certain minimum. The minimum wetting rate (MWR), minimum Reynolds number and the associated minimum film thickness at the point of the formation of rivulets have been formulated as criteria predicting film breakup in smooth tubes under isothermal conditions, Hartley and Murgatroyd [5]. MWR is the minimum necessary dimensionless liquid mass flow rate to ensure continuous wetting

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Nomenclature

Abbreviations

CMF	coriolis mass flow meter
DI	deionized
FS	full scale
MV	measured value
TC	thermocouple
VDI	Verein Deutscher Ingenieure
WR	wetting rate

Symbols

A_g	perfused groove area (m^2)
Eo	Eötvös number $\left(=\left(g\cdot\rho_{liq}\cdot d_h^2\right)/\sigma_{liq}\right), \equiv$ Bond number (–)
Ga	Galilei number $\left(=\left(g\cdot d_h^3\right)/\nu_{liq}^2\right)$ (–)
I_P^+	specific polar moment of inertia (–)
Ka	Kapitza number $\left(=\left(\rho_{liq}\cdot\sigma_{liq}^3\right)/\left(\mu_{liq}^4\cdot g\right)\right)$ (–)
Po	Poiseuille number, $\left(=128\cdot\pi^2\cdot I_P^+\cdot A_g/U_{trapezoid}^2\right)$ (–)
Pr	Prandtl number $\left(=\left(\mu_{liq}\cdot c_p\right)/k\right)$ (–)
Re	Reynolds number $\left(=\dot{V}_{g,max}/\nu_{liq}\cdot d_h\right)$ (–)
T	temperature (K)
U	perimeter (m)
b	width of groove (m)
d_i	internal diameter (m)
d_h	hydraulic diameter (m)
g	gravitational acceleration (9.81 $m\ s^{-2}$)
h	height of groove (m)
Δh_t	slope of the tube (m)
Δh_V	latent heat of vaporization ($kJ\ kg^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
l_h	helically length $(=l_t/\sin\varepsilon)$ (m)
l_t	length of the tube (m)
$\dot{m}_g$	mass flow rate in groove ($kg\ s^{-1}$)
n	number of grooves (–)
Δp_V	pressure loss (Pa)
$\dot{V}_g$	volume flow in groove ($m^3\ s^{-1}$)
w	velocity ($m\ s^{-1}$)

Greek symbols

Γ	sprinkling dense ($kg\ m^{-1}\ h^{-1}$)
β	inclination angle of tube (°)
γ	groove opening angle (°)
ε	twisting angle of structure (°)
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
θ	contact angle (°)
ν	kinematic viscosity ($m^2\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	surface tension ($mN\ m^{-1}$)
χ	aspect ratio of cross-section $(=h/b)$ (–)

Subscripts

liq	liquid
max	maximum
s	saturation

of the surface. In the literature, various equations are given to calculate these dimensionless quantities, see Ponter et al. [10], Coulon [11], Brauer [12], Hobler [13], Hallett [14].

Approaches are mostly based on the balance of forces at the stagnation point or on the minimization of the total energy whereby the advancing contact angle plays a decisive role, see e.g. Hartley and Murgatroyd [5], El-Genk and Saber [9], Doniec et al. [15], Hoke and Chen [16], Saber and El-Genk [17], Morison et al. [18], Zaitsev et al. [19].

In addition to the wetting properties (liquid, solid material and evaporator surface morphology) and the applied liquid mass flow rate, heat flow density and the resulting evaporation rate have a significant influence on film breakup for non-isothermal conditions. Local differences in film thickness can also be induced due to surface tension and temperature gradients (thermocapillary breakdown or Maragoni effect), see Bohn and Davis [20], Zaitsev and Kabov [21], Gambaryan-Roisman [22], Mendez et al. [23] or by the formation of vapour bubbles in the liquid film (film boiling) as stated by Hoffmann et al. [24]. Influence on the operation of falling film evaporators due to changes in the falling film liquid concentration are investigated by e.g. Lu et al. [25] (water/glycerol mixtures), Pehlivan and Özdemir [26] (water/sugar solutions), Najim et al. [27]. In all of these investigations influences due to variations of the concentration are reported, while Pecherkin et al. [28] (refrigerant mixture R114/R21) didn't find significant effects.

Further by exceeding some critical wall temperature, the Leidenfrost effect may occur. Thereby the surface is covered by vapour inhibiting wetting.

In process industries liquid film breakup is usually avoided (except of Leidenfrost effect) by operating vertical tube evaporators under turbulent liquid film flow conditions, see Storch et al. [2] and Gross and Philipp [29].

2.2. Experimental studies about hydrodynamics, film breakup and heat transfer of falling liquid films

The literature provides lots of experimental investigations concerning falling liquid films and heat transfer measurements. Such investigations are predominantly carried out on flat vertical or inclined plates, on the outside of vertical or horizontal tubes, and only a few on the inside of tubes. Hydrodynamics of falling films were mostly investigated under isothermal conditions, see Alekseenko et al. [30]. There are some investigations for heated liquid films covering V-shaped or U-shaped grooves as reported by Gambaryan-Roisman [22], Aviles [31]. The main aim is always to improve heat and mass transfer of the evaporation processes such as in seawater desalination and in food industry. Film breakup studies are mostly directed to the limiting heat flow density just avoiding film breakup. In the following a short overview of literature for plates and tubes will be given.

2.2.1. Studies with plates

Due to the wide range of applications and favourable experimental conditions there are numerous studies on plates with the focus on the comparison of the hydrodynamics of smooth and structured surfaces including wetting. Smooth plates, e.g. have been studied for single and multi-phase film flow conditions in vertical orientation by Lel et al. [32] and in inclined orientation by Ambrosini et al. [33], Lel et al. [34], Hoffmann et al. [35]. New investigations are focussed, e.g., on thermal entry length and spatiotemporally resolved heat transfer of vertical and/or inclined heated surfaces. Markides et al. [36] state, that the steady-state theory to determine the heat transfer coefficient is not applicable for larger film thickness. The thermal entry length declines in the combination of wavy films and thermocapillary effects, see Chinnov and Abdurakipov [37].