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Falling film break-up and thermal performance of thin polymer film heat exchangers

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ABSTRACT

Polymers as alternate construction materials in apparatus design feature special advantages as column internals or in heat transfer operation when handling corrosive media (resistance to corrosion and fouling, costs). However, high overall heat transfer coefficients can only be realized when applying thin polymer films (25 μm) in combination with a spacer grid. The hydrodynamic characterization of such heat exchangers is necessary in respect to its specific design criteria as well as general understanding of falling film heat transfer enhancement. The falling film break-up propensity of flat polymer surfaces and polymer-spacer combination is investigated and heat transfer with and without phase change is studied and modeled as well. New correlations are proposed for the heat transfer enhancement induced by the spacer grid of the Polymer Film Heat Exchanger (PFHX).

1. Introduction

In handling of corrosive media or fluids with fouling affinity polymeric heat exchangers have been developed and applied in several industrial fields [1–4]. Besides corrosion resistance also the price stability of polymeric materials is of economic importance compared to metallic construction materials. When applying thin polymer films (25 μm) as heat transfer surface, high overall heat transfer coefficients can be achieved [5]. Christmann et al. [6] also proofed the mechanical stability of the apparatus concept for thermal seawater desalination at Multi-Effect-Distillation (MED) process conditions. Dreiser and Bart [7] found that the polymeric heat transfer surfaces provide considerably low mineral scale propensity, even at high overall heat transfer coefficients, as well as an easy cleanability. These beneficial properties contribute to future prospects of industrial applications.

In the past numerous research has been carried out in enhancement of heat transfer processes involving tubes [8,9], but only few investigations on falling film heat transfer enhancement regarding vertical walls are present [10–12]. To gain design criteria for the concept of the polymer film heat exchanger (PFHX) an investigation of wetting phenomena and hydrodynamic boundary conditions is required as well as a characterization of its thermal performance.

Since polymers show considerably different surface properties (roughness, surface energy) compared to stainless steel as a common heat transfer equipment material [13], the wettability needs to be studied in detail before applying existing correlations for falling film break-up propensity. A correlation for the polymer film spacer combination should be developed for hydrodynamic design criteria. The geometrical impact on the heat transfer is investigated as well. An adaption of existing Nusselt-correlations to this apparatus concept fastens the thermal characterization. The results increase the knowledge in falling film wettability prediction (e.g. polymeric column internals) and heat transfer enhancement in general, but also contribute to specific design criteria for the PFHX.

2. Experimental

2.1. Wetting characteristics and falling film hydrodynamics

Besides fluid properties (viscosity, surface tension), surface properties (surface free energy, polarity, topology and roughness) affect the wettability as well [13]. The wettability of the heat transfer surfaces is determined by video-based contact angle measurement (OCA 15 EC, DataPhysics Instruments GmbH). Polyether ether ketone (Aptiv® 1000 series, Victrex plc.) is selected as

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Nomenclature

A	heat transfer area, m^2
b	width of heat transfer surface, m
c_p	heat capacity at constant pressure, J kg^{-1} K^{-1}
d_h	hydraulic diameter, m
g	gravitational acceleration, m s^{-2}
h	heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
Ka	Kapitza number
L	length of heat transfer surface, m
$\dot{m}$	mass flow rate, kg s^{-1}
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
Q	heat flow rate, W
Re	Reynolds number
s	wall thickness, m
U	overall heat transfer coefficient, W m^{-2} K^{-1}

Greek letters

Γ	falling film mass flow per unit of length, kg s^{-1} m^{-1}
η	dynamic viscosity, kg s^{-1} m^{-1}
$\Delta\overline{\vartheta}$	mean temperature difference, °C
$\Delta\overline{\vartheta}_{log}$	mean logarithmic temperature difference, °C
Δh_v	enthalpy of evaporation, J kg^{-1}
θ	contact angle, °
ϑ	temperature, °C
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
σ	surface tension, mN m^{-1}
ω	relative wetted area of heat transfer surface

Superscripts

+	increasing flow rate
−	decreasing flow rate

Subscripts

c	channel
cf	condensate film
cond	condensing
evap	evaporation
exp	experimental
ff	falling film
G	gas
heat	heating
in	inlet
L	liquid
lam	laminar
out	outlet
turb	turbulent
v	vapor
w	wall

Abbreviations

MED	Multi-Effect-Distillation
max	maximum
PEEK	polyether ether ketone
PFHX	polymer film heat exchanger

polymeric heat transfer surface and compared to stainless steel (1.4571 or 316Ti) as benchmark.

Macroscopic wettability is studied in a thermostatted falling film device with an infeed width of 0.2 m. The infeed design including a pre-distributing weir followed by a perforated plate (holes of 1 mm diameter and 2 mm distance) guarantees the homogeneous liquid distribution. The falling film side liquid temperature is controlled through a thermostat and flow rate accuracy is ensured via a gear type pump. Grounding of the whole setup prevents electrostatic charging. With the adjustable pressure difference at the heat transfer surface and the weir inlet geometry the device is conform to the fluid dynamics of the pilot plant heat exchanger. Besides flat surfaces, also polymer film and spacer combinations can be tested. The present spacer consists of rods of 3 mm diameter, which are point welded to a grid (30 × 30 mm). The polymer film only contacts the horizontal rods, since film buckling is very low for the studied process conditions [6].

Dependent on the falling film liquid load the specific wetted area or wetting degree ω, defined as the ratio of wetted to total heat transfer surface area, is determined by optical image analysis (ImageJ, National Institutes of Health). In falling film processes usually a wetting hysteresis can be observed, when decreasing the liquid load after prior establishment of a falling film by stepwise increase of the liquid load. Fig. 1 presents experimental results of the falling film wetting hysteresis for a flat PEEK surface, which yields to the critical liquid loads Γ^+ and Γ^-. Falling film break-up ($\omega < 1$) causes heat transfer drop and enhances fouling [7]. Therefore, the experimental determined critical liquid loads are necessary for efficient PFHX design criteria and a quantification of the stable operating area.

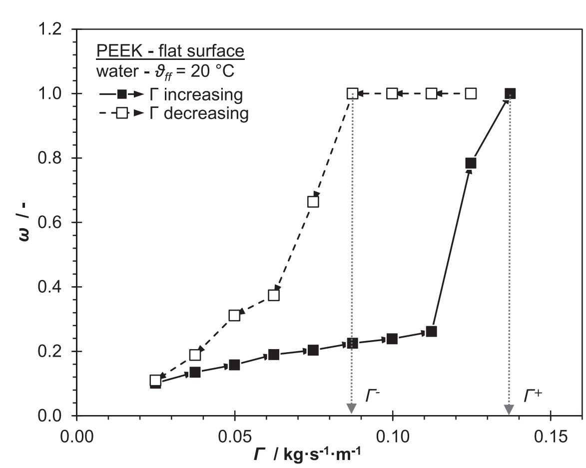

Fig. 1. Experimental wetting hysteresis and critical values for increasing falling film side liquid load Γ^+ and film break-up at decreasing liquid load Γ^- for a PEEK surface.

2.2. Thermal characterization

To study different heat transfer configurations a lab-scale heat exchanger was operated (single-phase heat transfer) as well as a pilot plant heat exchanger (heat transfer with phase change). Water or steam is used as heat transfer media respectively on both sides. The lab-scale heat exchanger possesses a heat transfer area of 0.052 m^2 and allows the investigation of flat heat transfer surfaces as well as polymer foil and spacer combinations. Single-phase