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Investigation of pillow-plate condensers for the application in distillation columns

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ABSTRACT

Pillow-plate heat exchangers represent a new promising concept which can be, among others, used in distillation as integrated top-condensers. Today, their application in process industries is growing. Pillow-plate condensers were investigated using two experimental set-ups at the University of Paderborn (lab scale) and at Bayer Technology Services GmbH (pilot scale). Condensation experiments at pilot scale were performed using a non-conventional fibre-optic measurement technique for the determination of the condensation channel axial temperature profiles. Cooling-side heat transfer coefficients and pressure drop values were obtained based on the lab-scale measurements and numerical simulations (CFD). These results were compared to calculated values for virtual plain tube bundles. Measured axial temperature profiles as well as the overall and condensation-side heat transfer coefficients are presented. This allows a comparison of the obtained results with conventional geometries.

1. Introduction

Design of new processes and retrofit of existing technologies require a proper choice of the specific heat transfer equipment perfectly fitting to the technological targets. Because of the large diversity of available devices, this is not easy. Plain shell-and-tube or plate (esp. plate-and-frame) heat exchangers have been extensively studied in the past and are widespread in industry; they can be considered as "conventional" equipment. Serth and Lestina (2014) give an in-depth insight into the latest shell-and-tube heat exchanger design principles. Since the fundamental issues have been largely investigated, the research focus has shifted to heat transfer intensification principles (cf. Pan et al., 2013) and structural details. In the meantime, shell-and-tube heat exchanger design methods have become quite reliable, enabling various numerical optimisation algorithms to be applied (cf. Costa and Queiroz, 2008; Asadi et al., 2014; Saeedan and Bahiraei, 2015; Sadeghzadeh et al., 2015). For condensation in shell-and-tube heat exchangers, Serna and Jiménez (2005) and Webb et al. (1997) published relevant practical insights. Serna and Jiménez (2005) investigated a variation of the Bell-Delaware method, which is widespread in the design of shell-and-tube heat exchangers. Webb et al. (1997) gave an experimental comparison of condensers made up of standardised TEMA E and J shell types.

Parallel to the shell-and-tube type, plate-and-frame heat exchangers represent another family of conventional devices. Numerous plate types have been studied for a wide application area, including boiling and condensing systems (cf. García-Cascales et al., 2007). However, the comparatively high condensing media pressure drop and the influence of the geometric variability remains challenging (cf. Arsenyeva et al., 2011). Abu-Khader (2012) gives an overview on recent advances in the field of plate heat exchangers.

As an alternative to conventional units, there exist innovative, promising heat exchanger types, for which only

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Nomenclature

A	area, m^2
d_h	hydraulic diameter, mm
d_{ws}	welding spot diameter, mm
e_i	inner expansion of the pillow plate, mm
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
h_{PP}	height of the pillow plate, mm
i	parameter in Eqs. (4) and (5), –
j	parameter in Eqs. (4) and (5), –
k	parameter in Eq. (4), –
L_{char}	characteristic length, mm
$\dot{m}$	mass flow, kg/h
p_{abs}	absolute pressure, mbar
$\dot{Q}$	heat flow, kW
R_f	thermal fouling resistance, $m^2\,K\,W^{-1}$
s	distance, mm
$2s_L$	longitudinal distance of the welding spots, mm
s_T	transversal distance of the welding spots, mm
u	overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
v	volume fraction, %
w_e	width of the edges, mm
w_{PP}	width of the pillow plate, mm
Greek Letters	
δ_{PP}	pillow plate wall thickness, mm
Γ	mass flux, $kg\,m^{-2}\,s^{-1}$
ζ	Darcy friction coefficient, –
λ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
ϑ	temperature, °C
$\Delta\vartheta_{ln,m}$	log mean temperature difference, °C
Subscripts	
b	bulk
CB	chlorobenzene
CM	cooling medium
cs	cross-sectional
cond	condensation
corr	correlation
exp	experimental
ht	heat transfer
i	inside
in	inlet
m	mean
max	maximum
min	minimum
N_2	nitrogen
o	outside
out	outlet
PP	pillow plate
tot	total
w	wall

very limited basic data has been available. Pillow-plate (PP) condensers represent the latter type. They offer several potential advantages over conventional heat exchangers, for instance, intensified heat transfer, compact, light and pressure-resistant construction, low pressure drop on the product media side, as well as low capital and operating costs. Its application in process industries is growing. However, the implementation of PP condensers is still limited due to the lack of publicly available proven design methods. Until recently, only basic studies by Mitrovic and Peterson (2007) and Mitrovic and Maletic (2011) could be found in the literature, and the existing data on PP geometries, media and operating conditions was insufficient. The data transferability between different PP was also uncertain. This does not allow any reliable design and performance prediction for the PPHE operators. In our group, extensive experimental and numerical studies have been carried out, aiming at overcoming this limitation (Tran et al., 2013a,b, 2015; Piper et al., 2013, 2014b, 2015). Two experimental set-ups have been used complementarily for the determination of pressure drop and overall heat transfer coefficients comprising cooling medium and condensation side. Additional pilot plant measurements have been performed at Bayer Technology Services GmbH (BTS).

2. Pillow plates

The manufacturing of PP consists of the following steps. First, two sheets – usually made of stainless steel – are placed one upon another. Next, these sheets are welded according to a specified welding spot grid to yield a pillow plate, and the latter is then reshaped by using hydroforming. To be used in condensers, several PP are arranged vertically and parallel to each other as a stack, with alternating cooling and condensation channels. The geometrical variability of such a heat exchanger type is extremely high. Fig. 1 shows a sketch of a PPHE along with the designations of the geometrical parameters used.

3. Experimental set-ups

3.1. *Lab-scale plant for the determination of cooling-side (internal) heat transfer and pressure drop*

Heat transfer coefficients of the condenser cooling channel were estimated in a lab-scale plant at the University of Paderborn (UPB). Together with the measured overall heat transfer coefficients, these data permits the heat transfer coefficients in the condensation channels to be determined. A scheme of this set-up is shown in Fig. 2. Here, a PP is heated by dissipating electrical direct current. The heat is absorbed by the cooling medium flowing through the PP, from the bottom to the top. Using seven temperature measuring points along the wall of the PP and two measuring points in the fluid, the mean heat transfer coefficients on the cooling-side can be calculated. Pressure drop is measured along the PP using different pressure measuring points. In this way, both the specific pressure drop of the fully developed fluid flow inside the PP and additional pressure drop caused by the inlet and outlet arrangements can be determined.

3.2. *Pilot plant at Bayer Technology Services GmbH*

A PP condensation pilot plant was built at Bayer Technology Services GmbH (BTS) (see Fig. 3). This plant can be used for the investigation of quite large condensers and high heat fluxes (and hence, high condensate Reynolds numbers). An integrated PP top-condenser (six PP, dimensions 500 × 1800 mm each) was used in a DN600 column with chlorobenzene (CB) in presence of small amounts of a non-condensable component (pure nitrogen, steady operating volumetric flow of 100 $L\,h^{-1}$). The nitrogen volume fractions in the inlet gas–vapour mixtures are given in Section 5. The given inlet values are relatively low, but they increase in a natural way along the