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Thermal analysis of plate condensers in presence of flow maldistribution

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Abstract

Flow maldistribution in plate heat exchangers causes deterioration of both thermal and hydraulic performance. The situation becomes more complicated for two-phase flows during condensation where uneven distribution of the liquid to the channels reduces heat transfer due to high liquid flooding. The present study evaluates the thermal performance of falling film plate condensers with flow maldistribution from port to channel considering the heat transfer coefficient inside the channels as a function of channel flow rate. A generalized mathematical model has been developed to investigate the effect of maldistribution on the thermal performance as well as the exit quality of vapor. A wide range of parametric study is presented, which shows the effects of the mass flow rate ratio of cold fluid and two-phase fluid, flow configuration, number of channels and correlation for the heat transfer coefficient. The analysis presented here also suggests an improved method for heat transfer data analysis for plate condensers.

Keywords: Condensation; Heat transfer; Mathematical modelling; Phase change; Transport processes

1. Introduction

Plate heat exchangers (PHEs) have been widely used in food processing, chemical reaction processes and many other industrial applications due to their high effectiveness, compactness, flexibility, and cost competitiveness. Generally speaking, PHEs can serve as an alternative to shell and tube heat exchangers for most applications at low and medium pressures. In recent times, plate heat exchangers have been also widely used in application of two-phase processes, both condensation and evaporation [1–5]. Note that PHEs are often called plate condensers when they are used for vapor condensation. Some examples of industrial applications of vapor condensation were described by Wang and Sunden [6]. However, the knowledge about their performance is very limited due to the relative short experience. In order to further expand this application, work must be carried out to improve the understanding and prediction of thermal and hydraulic performance for PHE condensers.

Flow maldistribution in heat exchangers causes deterioration of both thermal and hydraulic performance. According to Mueller and Chiou [7], there are many factors influencing maldistribution in exchangers: mechanical issues (design, tolerances), self-induced maldistribution due to the heat transfer process itself, fouling and/or corrosion, or the use of predisposed flows such as two-phase flows. The flow distribution from a header (manifold) to parallel channels has become of interest in predicting the heat transfer performance of compact heat exchangers especially in PHEs [8–11]. Often, flow rates through the channels are not uniform and in extreme cases, there is almost no flow through some of them, which result in a poor heat exchange performance. The situation becomes more complicated especially with two-phase flows. In a condenser, uneven distribution of the liquid will create zones of reduced heat transfer due to high liquid flooding. Thus, for the design and optimization of compact heat exchangers based on parallel flow technology, the understanding of two-phase flow distribution is of great importance.

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Nomenclature

A	heat transfer area for effective plate, m^2
A_c	cross-sectional area of the channel, m^2
A_p	cross-sectional area of the port, m^2
a	exponent of Re in Eq. (11)
a_1, a_2	exponents in Eq. (11)
c_p	isobaric specific heat of the fluid, J kg^{-1} K^{-1}
H	dimensionless parameter, $H = \frac{c_p \Delta T}{h_{fg}}$
h	heat transfer coefficient, W m^{-2} K^{-1}
h_f	enthalpy of the liquid, J kg^{-1}
h_{fg}	latent heat of vaporization, J kg^{-1}
Ja	modified Jakob number
L	fluid flow length in a channel, m
$\dot{m}$	mass flow rate, kg s^{-1}
m^2	flow distribution parameter
n	number of channels per fluid
N	total number of channels for the both fluids
NTU	number of transfer units
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
r_h	ratio of heat transfer coefficients
rv	ratio of velocities
rh_f	ratio of the enthalpy of liquid to latent heat of evaporation
T	fluid temperature, K
$T_{1,in}$	inlet temperature of the fluid (1), K
$T_{2,in}$	inlet temperature of the fluid (2), K
$r\Delta T$	dimensionless parameter, $r\Delta T(i) = \frac{\Delta T_i}{\Delta T_{uniform}}$
ΔT	temperature difference, $\Delta T = T_{sat} - T_{c,i}$, K
t	non-dimensional temperature $= \frac{T - T_{1,in}}{T_{2,in} - T_{1,in}}$
u	dimensionless volume flow rate in the channels
X	dryness fraction of two-phase fluid
y	space coordinate for the fluid flow, m
Y	non-dimensional flow path coordinate $= x/L$
z	dimensionless flow path coordinate in the port
ε	effectiveness of plate heat exchanger $= \frac{(\dot{m}c_p)_1 (T_{1,out} - T_{1,in})}{(\dot{m}c_p)_{min} (T_{2,in} - T_{1,in})}$

Subscripts

i	ith channel
in	inlet
out	outlet
min	minimum
uniform	the case of uniform flow distribution amongst channels
w	plate
w_i	ith plate
1	the fluid in odd channel
2	the fluid in even channel

Most of the previous research work in PHEs was conducted with the assumption of plug (one-dimensional) flow inside channels and an equal distribution of fluid into the channels from the port. However, it is a well known fact [12] that the flow maldistribution within the plate heat exchanger and particularly from channel to channel plays a major role for the deviation of the performance compared to the idealised case with flow equally distributed among the channels. The effect of unequal distribution of fluid inside the channels was analysed using a numerical technique by Datta and Majumdar [13] and in more detail using an analytical technique by Bassiouny and Martin [14,15]. The flow maldistribution due to port to channel flow has a tremendous effect on heat exchanger performance which has been investigated analytically and experimentally by Rao et al. [16] and Rao and Das [17]. These investigations have been carried out based on the analytical models for single phase flow distribution from port to channel in a PHE conduit by Bassiouny and Martin [14,15]. From the discussion, it is clear that a proper heat transfer model of the plate heat exchanger based on the unequal flow distribution in channels is required. This is not only to analyse the heat exchangers but also to obtain proper heat transfer data from experiments on heat exchangers with multiple channels, which will be stripped by the influence of number of channels or flow configuration used in the experiment. However, all these studies have been carried out for single phase flow in PHE conduits. So far no study has been reported concerning maldistribution effects on the thermal performance for two-phase plate heat exchangers. This is the main inspiration of the present work. In the present work the plate heat exchanger is thermally modelled with unequal flow in the channels taking the distribution suggested by Baussiouny and Martin [14,15]. While carrying out this investigation the heat transfer coefficients inside the channels are assumed to vary according to general correlations for the Nu for both the cooling and two-phase channels.

For two-phase flow distribution in manifolds, authors like Seeger et al. [18] and Lahey [19] have investigated two-phase (vapor and liquid) distribution in single T-junctions. Only a few studies on the topic of two-phase distribution in manifolds have been presented. Nagata et al. [20] conducted experiments on a horizontal manifold with four vertical upward tubes. Recently, Bernoux et al. [21] experimentally studied the distribution of vapor and liquid phases at the inlet manifold of a compact heat exchanger. Two-phase distribution in the channels are obtained by the use of mass flow rate and mass quality measurements in each channel using transparent windows allowing the observation of two-phase flow pattern of refrigerant 113 at different operating conditions. Vist and Pertersen [22]