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Measured and predicted upward flow boiling heat transfer coefficients for hydrocarbon mixtures inside a cryogenic plate fin heat exchanger

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ABSTRACT

Boiling of hydrocarbon mixtures inside plate fin heat exchangers (PFHEs) is most prevalent in many cryogenic processes of petrochemical plants. However, there is very little experimental data and a lack of prediction methods regarding boiling mixtures in PFHEs. This paper established an experimental setup that utilized a single-stage cryogenic cycle to measure the boiling heat transfer coefficients (HTCs) for hydrocarbon mixtures inside a perforated PFHE. The components of the mixtures include methane, ethylene, propane and isobutene. Twenty-seven sets of experiments were conducted under various operating conditions and 261 data points of the boiling HTC were obtained. The experimental conditions cover the mass fluxes of 3.69–19.38 kg m^{-2} s^{-1}, pressures of 1.35–5.22 bar and vapor qualities of 0.05–0.77, which are representative of a wide range of actual industrial conditions. The corresponding heat fluxes only range from 55.7 to 3837.3 W m^{-2}. The experimental boiling HTC varies from 21.4 to 1055.7 W m^{-2} K^{-1}, and it is a strong function of the heat flux. Moreover, twelve existing correlations were assessed by using the present experimental data. The results show that the HTCs predicted by Chen type correlations were not consistent with the experimental results, and a new correlation developed from mini-channel correlations was recommended.

1. Introduction

Plate fin heat exchangers (PFHEs) have been used as the main cryogenic heat exchangers in many petrochemical plants, because of their advantages of a compact structure, high efficiency, a low cost and multi-stream handling capability [1–3]. The applications include liquefied natural gas (LNG) plants [4,5], ethylene separation plants and other hydrocarbon separation plants [6,7], in which the heat transfer fluid is usually a cryogenic mixture with a large temperature glide and its components include propane, ethylene, methane, etc. The heat transfer process inside PFHEs is usually arranged with the upward flow boiling of mixtures in low-pressure channels and the downward flow condensation of mixtures in high-pressure channels. Many studies [8–10] have indicated that the heat transfer performance of the PFHEs significantly affects the thermal efficiency of the cryogenic processes in the above applications. Hence, to improve the design of PFHEs, considerable research related to PFHEs have been focused on flow mal-distribution [11,12], passage arrangement optimization [13,14], optimization design of structure parameters [15,16] and numerical simulation of the thermal and hydraulic performance [17–19]. However, the experimental studies on the cryogenic PFHEs are still rarely constructed because of the high cost and huge measurement difficulty. The lack of experimental data regarding the heat transfer of mixtures in PFHEs hinders the optimal designs and practical applications of PFHEs.

The existing experimental research studies related to the heat transfer characteristics of upward flow boiling inside the channel of PFHEs were mainly focused on pure fluids, such as liquid nitrogen [20,21], CFC114 [22] and propane [23]. They showed that upward flow boiling inside the channel of PFHEs contains the nucleate boiling regime and the convective boiling regime [20–22]. However, the boiling mechanisms for pure fluids insides the channels of a PFHE vary with the operating conditions. The conditions of industrial applications mainly involve convective boiling [23]. For the boiling process of a mixture fluid, considering the changing gas and liquid phase properties, the process inside cryogenic PFHEs will be more complicated. As a result, the existing results of the pure fluids cannot be extended directly to the cryogenic hydrocarbon mixtures.

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Nomenclature

A	heat transfer area [m^2]
B	effective width of PFHE [m]
Bl	Boiling number, $q/(G_m h_{lv})$
Bo	Bond number, $g((\rho_l - \rho_v)d_h^2/\sigma$
C	component mole fraction [%]
C_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
d_h	hydraulic diameter [m]
f	Fanning friction factor
G_m	mass flux [kg m^{-2} s^{-1}]
g_m	mass flow [kg s^{-1}]
H	enthalpy (J kg^{-1})
h	heat transfer coefficient [W m^{-2} K^{-1}]
h_{lv}	latent heat [J kg^{-1}]
L_e	heat exchanger length [m]
l	fin height [m]
M	molecular weight
n	number of passage
P	pressure [Pa]
Pr	Prandtl number, $\mu Cp/\lambda$
Q	heat duty [W]
q	heat flux [W m^{-2}]
R	calculated parameter in the function of W_R
Re	Reynolds number, $G_m d_h/\mu$
Re_v	gas Reynolds number, $G_m x d_h/\mu_v$
Re_l	liquid Reynolds number, $G_m(1-x)d_h/\mu_l$
s	fin spacing [m]
T	temperature [K]
ΔT_g	Temperature glide for mixture [K]
x	vapor quality
U	total heat transfer coefficient [W m^{-2} K^{-1}]
V_n	independent variable in W_R
We	Weber number, $G_m^2 d_h/(\rho_l \sigma)$
W_R	overall uncertainty function
w_n	the uncertainty of V_n

Abbreviations

PFHE	plate fin heat exchanger
HTC	heat transfer coefficient

Greek symbols

δ	fin thickness [m]
μ	dynamic viscosity [N s m^{-2}]
σ	surface tension [N m^{-1}]
η	fin surface efficiency
ρ	density [kg m^{-3}]
λ	thermal conductivity [W m^{-1} K^{-1}]
θ	excess temperature

Subscripts

f	fluid
l	liquid
v	vapor
w	wall
t	top wall
b	bottom wall
h	hot stream
c	cold stream
in	inlet
out	outlet
n	variable
mix	mixture
cal	calculated value
exp	experimental value
cv	convection boiling
nb	nucleate boiling

Because of the mass transfer resistance, the flow boiling mechanism of mixed refrigerants is different from that of pure refrigerants. Thome [24] recommended a method to predict the nucleate pool boiling coefficient of mixed-refrigerants by using a pure refrigerant's nucleate pool boiling HTC modified with the mixture mass diffusion effect. In addition, Silver [25] and Bell and Ghaly [26] proposed a method to evaluate the mass transfer resistance in a mixture's convection condensation. Since then, in many studies of mixture in-tube flow boiling, these two methods have been applied to modify the mass diffusion effect of nucleate boiling and convective boiling, respectively. Ardhapurkar et al. [27–29] assessed the existing flow boiling correlations for pure refrigerants against the boiling experimental data of nitrogen-hydrocarbons mixtures in a 0.835 mm horizontal tube obtained by Nellis et al. [30]. He found that the Silver-Bell-Ghaly correlation [26] and Granryd correlation [31] are more suitable for estimating the mixture's flow boiling HTCs, and the modified Granryd correlation was recommended. Zou et al. [32] measured the saturated flow boiling HTCs of the binary mixtures of R170/R290 in a horizontal tube and proposed a modified correlation based on the pool boiling HTC correlation in their previous work [33]. Rodrigo et al. [34] presented a large set of HTC data for boiling zeotropic mixtures (hydrocarbons and fluorocarbons) with large temperature glides, including cryogenic temperatures. The results indicated that the heat transfer process is driven by the convective boiling, and the Granryd correlation [31] was recommended. Chen et al. [35,36] investigated the flow boiling heat transfer of LNG (liquefied natural gas) in vertical and horizontal smooth tubes at inlet pressures ranging from 0.3 to 0.7 MPa. They noted that their experimental database was well predicted by the correlation of Zou et al. [32].

Nevertheless, for the upward flow boiling of a mixture inside a PFHE employed in the cryogenic cycle, the operation conditions are very different from those in tubes. The flow velocity of a boiling fluid inside a PFHE increases sharply with the increase of vapor quality under low pressure. To avoid an excessive pressure drop, the mass flux of boiling fluids is normally lower than 20 kg m^{-2} s^{-1}. The small mass flux design will cause serious liquid holdup when the fluids at low vapor quality and have a significant influence on the flow boiling regime. Meanwhile, to improve the energy efficiency of cryogenic plants, the temperature difference between the hot and cold streams is small. The effective temperature difference between the boiling mixtures and the wall is even smaller and leads to low heat fluxes (lower than 4000 Wm^{-2}) in the PFHE. Moreover, the hydraulic diameter of the channels in PFHEs can be very small (approximately 2 mm for the PFHE presented in this paper), and should be classified as a mini-channel (the hydraulic diameter range for mini-channel is: 200 um < d_h < 3 mm, proposed by Kandlikar [37]), which is very different from a conventional tube. The flow patterns and boiling mechanisms in miniature/micro channel at large mass fluxes and high heat fluxes have been investigated extensively [38,39]. However, it is still not known whether the nucleate boiling or convective boiling govern the flow boiling heat transfer inside plate fin channels at small mass fluxes and low heat fluxes. Therefore, the boiling heat transfer mechanism and performance of a PFHE with cryogenic mixed refrigerants requires further research.