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Numerical study of heat and mass transfer of binary mixtures condensation in mini-channels ☆

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ABSTRACT

This work presents a model to study condensation heat and mass transfer characteristics of binary mixtures inside mini-channels. By considering the mass and heat transfer resistances in the vapor phase, the conservation equations of mass, species, momentum and energy are solved using higher order finite element method. The model is validated by comparing the predicted results with experimental data from the literature, in particular for the case of methane/ethane mixtures at different compositions and working conditions in a tube of 1.0 mm in diameter. The results show a reasonably good prediction of the heat transfer coefficient and pressure drop by comparing with these experimental data. The model is then used to study the effect of mass flux, wall heat flux and system inlet pressure on the heat and mass transfer resistances during condensation of binary mixtures.

1. Introduction

Heat transfer and mass transfer during condensation inside mini-channels are of practical interest due to the wide range of applications of compact heat exchangers. In order to achieve optimal designs of heat exchangers involving mini-channels or compact spaces, reliable models of the heat transfer coefficients and pressure drop in mini-channels are needed [1]. In particular, the study of condensation of mixtures is relevant within the liquefied natural gas (LNG) industry.

Many theoretical studies have been done to predict the mass and heat transfer phenomena during multicomponent mixture condensation. Webb and Sardesai [2] discussed two categories of physical models: the equilibrium models which assume that the condensation process follows the condensation curve, such as the Silver–Bell–Ghaly method [3,4]; and the non-equilibrium models based on film theory, such as the well-known Colburn and Drew method [5]. Panchal et al. [6] studied the condensation of ammonia–water mixtures and analyzed three limiting cases, including equilibrium conditions and liquid-phase diffusion of finite and infinite values. Their results were compared with the experimental data for a tube of 25.4 mm in diameter and showed that the vapor-phase diffusion is a controlling mechanism. Koyama et al. [7–9] proposed prediction models to study binary and ternary mixtures and compared the results with experimental data for tubes of inner diameter of 7.9 mm and 8.32 mm. They also compared the heat transfer characteristics of mixtures with R22. Kim [10] assumed constant physical properties and solved the equations of continuity, momentum, energy and diffusion in two dimension. Cavallini et al. [11] tested the method of Colburn and Drew for the design of a tube-in-tube non-azeotropic mixture condenser. They assumed the liquid film was fully mixed and the results showed a reasonably good prediction of the heat flux exchanged for a tube diameter of 8.0 mm. Jin et al. [12] also proposed a prediction model by considering the mass transfer resistances in both the vapor and liquid phases and assuming that the vapor was saturated. Their results presented a good prediction compared with data for a tube of 8.44 mm in diameter. Shah et al. [13] assessed some predictive methods for condensation heat transfer of refrigerant mixtures by using data for diameters ranging from 1.49 mm to 16 mm. Wang et al. [14,15] proposed a similar model to Jin et al. [12] and the model was validated by their own data for tubes of 2 mm and 4 mm in diameter. As it can be seen, most of these studies involve conventional channels, while the research on condensation in small channels is still limited and not many investigations have been done.

The aim of this work is to study the heat and mass transfer characteristics during condensation of binary mixtures in mini-channels. We are interested in the mass transfer resistance in the vapor phase, as the liquid-phase diffusion is not predominant according to previous studies in the literature; and also interested in the heat transfer resistance in the vapor phase, which is not emphasized in most of the non-equilibrium models mentioned before. Moreover, the effect of different parameters on the mass and heat transfer resistances is investigated.

The structure of this paper is as follows. Section 2 presents the mathematical model, including both conservation and constitutive equations. In Section 3, the numerical method for solving the system of equations and the solution procedures are described. The model is validated by comparing the results with experimental data for methane-based binary mixtures in Section 4. Section 5 studies the effect of

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Nomenclature

C_0	initial bulk composition
c_p	specific heat capacity [J/kg K]
D	diameter [m]
f	friction factor
G	mass flux [kg/m^2 s]
h	heat transfer coefficient [W/m^2 K]
i	specific enthalpy [J/kg]
i_{1v}	specific enthalpy of vaporization [J/kg]
k	mass transfer coefficient [kg/m^2 s]
M	condensation rate [kg/m^3 s]
$\mathcal{D}$	diffusion coefficient [m^2/s]
P	pressure [Pa]
P_r	reduced pressure, $P/P_{critical}$
Pr	Prandtl number
Q	heat flux [W/m^2]
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	temperature [K]
V	velocity [m/s]
X	mass fraction of more volatile component in liquid
x	vapor quality
Y	mass fraction of more volatile component in vapor
z	axial coordinate along the pipe [m]

Greek symbols

α	void fraction
δ	liquid film thickness [m]
λ	thermal conductivity [W/m K]
μ	viscosity [Pa s]
Φ	two-phase multiplier
ρ	density [kg/m^3]
τ	shear stress [N/m^2]

Subscripts

1	component 1
2	component 2
eq	equilibrium
I	vapor–liquid interface
l/lo	liquid/liquid only
sat	saturated
t	total
v/vo	vapor/vapor only
w	pipe wall

different parameters on the heat and mass transfer resistances during condensation in mini-channels, and analysis and discussion of these results are covered. Final comments and conclusions are sketched in Section 6.

2. Problem description and present model

The physical model describes a binary mixture flowing in a horizontal pipe, as shown in Fig. 1. When the mixture begins to condense, the less volatile component with the higher boiling temperature (ethane in this case) condenses preferentially. This results in that the vapor mixture at the vapor-side interface locally has a higher composition of the more volatile component (methane in this case) than the bulk vapor.

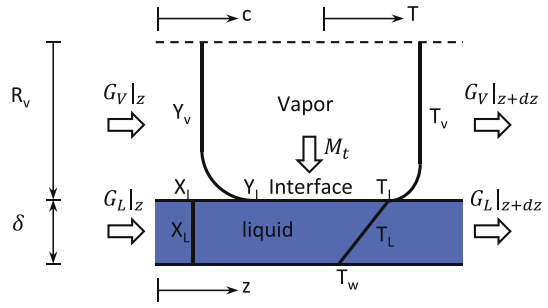

Fig. 1. Physical model.

Meanwhile, the temperature of the interface is lower than the bulk vapor. The physical model includes the heat and mass transfer resistances in the vapor phase, and the heat transfer resistance in liquid phase.

The phase equilibrium diagram of the non-azeotropic binary mixture methane/ethane is shown in Fig. 2. The assumptions for calculation of the mass and heat transfer of binary-component condensation are:

1. The liquid and vapor are locally at the same pressure and the interface is in thermodynamic equilibrium. The vapor-side and liquid-side interface are on the dew and bubble line, as marked in Fig. 2.
2. The liquid phase is well mixed and the mass transfer resistance in the liquid phase is neglected, namely the composition of the more volatile component of the bulk liquid is equal to that at the liquid-side interface.
3. The vapor phase can be either saturated or superheated, so that it can be located at any point of the horizontal line indicated as "vapor" in Fig. 2.
4. The flow is annular and the film thickness is assumed circumferentially uniform.

2.1. Conservation equations

2.1.1. Two-phase flow

The mass conservation equation for the vapor phase can be written as

$$\frac{d}{dz}(\alpha\rho_v V_v) = -M_t \tag{1}$$

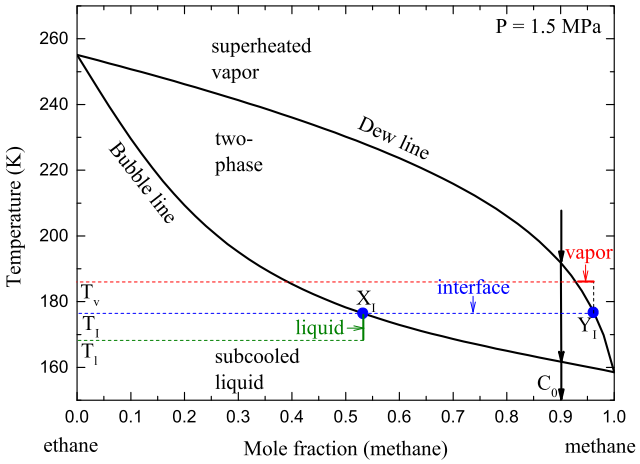

Fig. 2. Phase equilibrium diagram for methane/ethane at 1.5 MPa.