



Hydrocarbon mixture condensation inside horizontal smooth tubes



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ABSTRACT

The results from an experimental investigation of condensing zeotropic mixtures of hydrocarbons inside horizontal tubes are presented. The trends in heat transfer coefficient with temperature glide, saturation pressure, concentration, mass flux, and quality and tube diameter are discussed with reference to the changing thermodynamic and physical phenomena across the condensing conditions. The modeling techniques most commonly used to account for the non-equilibrium conditions and changes in the bubble and dew point temperatures affecting the condensing heat transfer coefficient are assessed. The degradation in heat transfer coefficient due to mixture effects is most significant at large temperature glides and in the larger tube diameter, and is least significant at higher mass fluxes. The data are analyzed using the Silver–Bell–Ghaly approach as well as the Colburn and Drew framework. The study provides insight into the behavior of zeotropic mixtures during condensation. The conditions that results in the largest concentration changes and cause the greatest degradation in the heat transfer rate are outlined.

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1. Introduction

Condensation of binary or higher order zeotropic mixtures is affected by two factors that effectively reduce the heat transfer rate in condensers. Firstly, as vapor is converted to liquid, there is a non-linear shift in the equilibrium phase concentrations. This change in equilibrium phase concentrations causes a change in the equilibrium temperature, which results in a non-constant condensation temperature (temperature glide, i.e., the difference between the bubble point and dew point temperatures). Thus, the driving temperature ($T_{\text{interface}} - T_{\text{wall}}$) for condensation decreases throughout the condensation process, which reduces the heat transfer rate. Secondly, the components of a zeotropic mixture have different saturation temperatures and mass transfer rates from the vapor phase to the liquid phase. Moreover, the condensation process is a local interfacial phenomenon with the less volatile component condensing more readily than the more volatile component, which results in a concentration gradient in the vapor phase. The concentration gradients in the vapor and liquid phases are often referred to as a non-equilibrium condition. This mass transfer resistance limits the condensation process. Thus, the change in equilibrium condition reduces the overall heat transfer rate and the non-equilibrium condition limits the rate of condensation possible.

The condenser size is highly sensitive to both the temperature difference between the working fluid and the coolant and the heat transfer coefficient. A decrease in either of these parameters results in a greater surface area requirement to achieve condensation of the zeotropic mixture. Thus, knowledge of the development of the equilibrium and non-equilibrium conditions, and whether they are significant considerations during the modeling process is critical in correctly determining the required condenser surface area. This has added importance when the working fluid heat transfer coefficient is the dominant thermal resistance, which is often the case in chemical processing heat exchangers, such as those found in continuous distillation columns.

The non-equilibrium conditions that develop across the tube cross section during condensation experiments can result in inaccuracies in measured heat transfer coefficients. There are few studies on the condensation of zeotropic mixtures in the literature, and fewer still of condensation studies of zeotropic mixtures of hydrocarbons. Fig. 1 shows a map of the published condensation studies conducted using zeotropic mixtures of synthetic and natural working fluids; they are mapped as a function of tube diameter, mass flux and temperature glide. It is clear from the figure that the majority of these studies are for low temperature glides and are generally conducted using a single tube diameter.

The trends in condensation heat transfer coefficient for zeotropic mixtures generally follow the same trends with mass flux, tube diameter, and vapor quality and saturation pressure as pure fluids. The key difference between zeotropic mixtures and pure fluids is the degree by which the equilibrium and non-equilibrium condition

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Nomenclature

Variables

A	area, m^2
C	specific heat capacity, kJ kg^{-1}
D	diameter, m
G	mass flux, $\text{kg m}^{-2} \text{s}^{-1}$
h	heat transfer coefficient, $\text{W m}^{-2} \text{K}^{-1}$
i	enthalpy, $\text{kJ kg}^{-1} \text{K}^{-1}$
k	thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$
L	length, m
$LMTD$	log mean temperature difference, $^{\circ}\text{C}$
m	mass flow rate, kg s^{-1}
MW	molecular weight, kmol kg^{-1}
N	mass transfer flux, $\text{kmol m}^{-2} \text{s}^{-1}$
Nu	Nusselt number, –
P	pressure, kPa
P_r	reduced pressure, –
\dot{Q}	heat duty, W
y	vapor mass quality, kg kg^{-1}
Re	Reynolds number, –
Sh	Sherwood number, –
T	temperature, $^{\circ}\text{C}$
U	overall heat transfer rate, $\text{W m}^{-2} \text{K}^{-1}$
x	liquid mass quality, kg kg^{-1}
X	concentration, kg kg^{-1}
z	fraction of the volatile component of the total mixture condensed

Greek symbols

B	mass transfer coefficient, m s^{-1}
δ	film thickness, m
Δ	change in variable, –
ε	void fraction, –
κ	Ackerman mass transfer correction factor, –
ρ	density, kg m^{-3}

Subscripts/superscripts

avg	average
coolant	pre- and post-condenser coolant water
glide	zeotropic mixture temperature glide, $(T_{\text{bubble}} - T_{\text{dew}})$
i	inner
inlet	inlet to the test section
interfacial	vapor–liquid interface
l	liquid
LM	log mean
o	outer
OT	outer tube
outlet	outlet of the test section
sat	saturation
secondary	secondary loop
subcool	subcooled state
superheated	superheated state
test	test section
v	vapor
wall	test section wall

decrease the heat transfer rate. The trends that have been reported by previous investigators are outlined below.

Several authors [1–6] have studied the effect of mass flux on heat transfer coefficient. Shao and Granryd [4] and Smit and Meyer [5] noted that the condensation rate is affected mostly at low mass fluxes and in the stratified regime. Milkie [3] noted that similar trends in the heat transfer coefficient are observed for mixtures as for pure fluids with mass flux; however, the overall magnitude of the heat transfer coefficient was appreciably lower. Fronk [2] conducted condensation experiments on ammonia–water mixtures flowing through small diameter ($D_h < 3 \text{ mm}$) channels and at low mass fluxes where laminar flow is expected to dominate. He noted that the heat transfer coefficient can be degraded throughout the condensation process for any design conditions.

The effect of concentration on zeotropic mixture condensation is the most widely investigated parameter by researchers [1,2,4,7–11]. Koyama et al. [12], Shao and Granryd [4], Chang et al. [8] and Afroz et al. [7], who have conducted experiments with relatively low temperature glides, e.g., less than 6°C , report that the heat transfer coefficient varies nonlinearly with concentration between the corresponding two pure fluids. The mixture heat transfer coefficient decreases with increasing concentration of one component, reaches a minimum, and then reverses trend with further increases in concentration. Koyama et al. [12] provided an experimental polytropic correlation that models this behavior for mixtures of R22 and R114. Stoecker and McCarthy [10], Tandon et al. [11], Wen et al. [6], Afroz et al. [7], and Milkie [3] noted that the heat transfer coefficient for the mixture generally fell between the values for the two pure fluids. Fronk [2] observed that increasing the concentration of ammonia in water above 0.8 caused degradation in the heat transfer coefficient that was significant enough to cause the heat transfer coefficient to decrease with vapor quality by more than 50%.

While zeotropic mixture concentration can be related to the temperature glide, investigators have typically used fluid concentration as the relevant parameter for assessing the trends in heat transfer coefficient for their chosen fluid combinations. However, the temperature glide is a more informative parameter than concentration for predicting the degree of degradation of the heat transfer coefficient in fluid mixtures, when compared to pure fluid studies. The temperature glide is a more general metric that allows different fluids pairs to be compared. Moreover, the equilibrium modeling technique proposed by Silver [13] and Bell and Ghaly [14] predicts that increasing the temperature glide would result in greater mass transfer resistances and therefore a greater degradation in heat transfer coefficient. Inspection of Fig. 1 shows that the majority of studies have been conducted for relatively low temperature glides, i.e., less than 8°C , with few studies conducted in the mid-temperature glide range ($\Delta T_{\text{glide}} = 6\text{--}15^{\circ}\text{C}$). Even for low-temperature glides such as those conducted by Stoecker and McCarthy [10] ($\Delta T_{\text{glide}} = 3.4\text{--}7.3^{\circ}\text{C}$), Tandon et al. [11] ($\Delta T_{\text{glide}} = 0.4\text{--}2.6^{\circ}\text{C}$), Koyama et al. [12] ($\Delta T_{\text{glide}} = 0\text{--}8.5^{\circ}\text{C}$), Shao and Granryd [4] ($\Delta T_{\text{glide}} = 3\text{--}5.8^{\circ}\text{C}$) and Smit and Meyer [5] ($\Delta T_{\text{glide}} = 0\text{--}6.5^{\circ}\text{C}$), the heat transfer coefficient degraded when compared to the highest pure component heat transfer coefficient. Some mixture concentrations exhibit local heat transfer coefficients lower than both the corresponding pure fluid values, [12]. In the mid-temperature glide range, the studies by Afroz et al. [7] and Milkie [3] noted that the heat transfer coefficient decreased with increasing temperature glide. Fronk [2] is the sole investigator in the literature to have studied condensation of high-temperature-glide mixtures ($\Delta T_{\text{glide}} = 78\text{--}93^{\circ}\text{C}$). He noted that for high-temperature-glide mixtures, the heat transfer coefficient can decrease sharply with increasing quality, creating a local maximum value midway between the vapor and liquid saturation points. For these fluid concentrations, the local maximum

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