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Heat and mass transfer of binary distillation in a vertical wetted-wall column

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ABSTRACT

In this study, we investigated the effects of partial condensation on the heat and mass transfer rates during ethanol–water binary distillation based on a laminar boundary layer theory applied to a wetted-wall column, as well as the characteristics of the boundary layer behavior on the vapor phase. The thickness of the thermal and concentration boundary layers were shown to decrease with an increase in partial condensation, whereas the heat and mass transfer rates were demonstrated to increase. The results of this study show that the dimensionless rates considered for the convective fluxes $Sh/(1 + \alpha_M)$ and $Nu/(1 + \alpha_H)$ can be determined through a combined application of the laminar boundary layer theory and function $g(\beta)$ of a partial condensation ratio β (mole basis), where β is linearly proportional to v_s/u_∞ (dimensionless velocity), which is a term for the boundary condition at a vapor–liquid interface. A numerical analysis of the experiment data show that both $Sh/(1 + \alpha_M)$ and $Nu/(1 + \alpha_H)$ are approximately proportional to the Reynolds number (Re), and not to $Re^{1/2}$, as is generally the case, under the condition $v_s = 0$. Therefore, we established the functional relationship $g(\beta) = 0.4288 - 0.2844e^{\beta'}$, i.e., the exponential function of β' , which was converted into a mass basis. The modified boundary layer theory was found to be completely self-consistent.

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1. Introduction

In research into continuous gas–liquid contact devices for binary distillation, most studies published after Murphree (1925) and up until the 1950s were carried out from a viewpoint in which a mass transfer relies mainly on its diffusivity. However, Danckwerts et al. (1960) introduced the concept of thermal distillation. The authors suggested

that the plate efficiency of a distillation column might be influenced by the thermal effect from the temperature difference between the vapor and liquid phases, and by the change in the surface tension owing to a liquid composition profile. Such findings laid out the direction of future research for many different scholars. Among them, Moens and Bos (1972) and Yamada et al. (1973) studied the influence of a surface

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Nomenclature

C_p	Mean specific heat at constant pressure [cal/g °C] or [cal/gmol °C]
D	Binary diffusion coefficient [cm ² /s]
F	Dimensionless stream function ($\phi/u_\infty vx$) [-]
g	Function of $F(0)$ or β [-]
k	Thermal conductivity [cal/cm °C s]
J_i	Diffusive flow rate of i component [g/cm ² s] or [gmol/cm ² s]
L	Length of the wetted-wall [cm]
m	Empirical index of $g(\beta)$
N_i	Mass transfer rate of i component [g/cm ² s] or [gmol/cm ² s]
Nu	Nusselt number [-]
Pr	Prandtl number [-]
Q	Total heat transfer rate [cal/cm ² s]
q_s	Sensible heat transfer rate [cal/cm ² s]
r	Mole fraction [-]
Re	Reynolds number [-]
Sc	Schmidt number [-]
Sh	Sherwood number [-]
T	Temperature of vapor phase [°C]
u	x -Component of vapor velocity [cm/s]
v	z -Component of vapor velocity [cm/s]
x	Distance from the lower edge of the wetted-wall [cm]
y	Vapor-phase mole fraction of more volatile component [-]
z	Perpendicular distance from an interface [cm]

Greek letters

α	Flux ratio defined in Eqs. (6) and (7) [-]
β, β'	Molar or mass partial condensation ratio in Table 2 and Eq. (30) [-]
η	Similarity variable of Eq. (14) [-]
θ	Dimensionless temperature in Eq. (18) [-]
δ	Boundary layer thickness [cm]
μ	Viscosity [g/cm s]
ν	Kinematic viscosity [cm ² /s]
ϕ	Dimensionless concentration by Eq. (17) [-]
ρ	Vapor mean density [g/cm ³]
ψ	Stream function by Eq. (14) [cm ² /s]
ω	Mass fraction [-]
Γ	Reflux flow rate [g/s] or [gmol/s]

Subscripts

A	More volatile component
B	Less volatile component
s	Vapor–liquid interface
∞	Vapor free stream or liquid main stream
1	Bottom of the column
2	Top of the column

tension gradient on the surface renewal according to the liquid composition and gas–liquid contact area during column distillation, and concluded that such changes have no significant impact on the distillation process. They noted, however, that the influence of heat transfer, including the effect of the altered liquid composition, on the point efficiency of a distillation column should be reflected when calculating the mass transfer coefficients.

Ruckenstein and Smigelschi (1967) developed a penetration theory based on the heat transfer of a laminar flow layer along an interface

to shed light on the thermal effect associated with the mass transfer rate. However, this theory is applicable only to liquid phases. Scriven (1968) emphasized that the surface dilation and contraction in a fluid interface, which are triggered by the convective diffusion distorting the concentration gradients, have a significant effect on the mass transfer rate.

Many researchers have recently focused on controlling the thermal effects of binary distillation. Ito and Asano (1982) developed theoretical approaches using a laminar boundary layer theory with uniform suction or blowing at the interface to investigate the thermal effects of binary distillation. Rivero (2001) conducted an exergy analysis of adiabatic and diabatic binary distillation of water–ethanol at 1 bar to determine the distribution of the exergy losses inside a column. Rejl et al. (2006) designed a method for determining the distillation heat transfer coefficients on the vapor/gas side and the liquid side in a distillation column. This method consists of fitting the concentration profile along a column obtained through the integration of a differential model with an experimental model. Castellanos-Sahagun et al. (2005) proposed the design of a two-point linear temperature controller for regulating the product compositions in a binary distillation column. This controller recovers the behavior of the exact underlying model-based feedforward-feedback material balance controller, testing two binary columns through simulations using ideal and non-ideal thermodynamics.

Owing to the complexity of the phenomena related to a mass transfer, no experiments have been conducted to separately investigate the aerodynamic resistance of the gas phase and hydrodynamic resistance of the liquid phase at a vapor–liquid interface. Nieuwoudt and Crause (1999) measured mass-transfer coefficients in a short wetted-wall column, and Vivian and Peaceman (1956) have proposed the film theory of liquid-side resistance to gas absorption. Most theoretical studies dealing with this aspect have been based solely on hypotheses, without any experimental evidence. Although some experiment data explaining the mechanisms behind the phenomena of heat and mass transfer in binary distillation are available, further studies with respect to the impact of partial condensation of vapor, induced by the temperature difference between a vapor and liquid, are needed.

In this study, we carried out total reflux distillation experiments on a binary system of ethanol (A) and water (B) in a wetted-wall column using a vertical flat plate in order to investigate the partial condensation induced through the temperature difference between the vapor–liquid interface and the actual vapor stream. We analyzed experimentally the impact of partial condensation on the heat and mass transfer rates by estimating the temperature distribution of the vapor phase inside a column, and by measuring the flow rates and concentrations at the inlet and outlet of the reflux.

2. Theories

2.1. Phenomena related to heat and mass transfer in the vapor phase

Fig. 1 illustrates the heat and mass transfer phenomena under a condition in which the reflux flowing along a vertical flat-plate wetted-wall column for binary distillation is in counter-flow contact with a mixed vapor. The diffusive flow rate (J_{As}) and sensible heat transfer rate (q_s) of component A of the vapor phase in the z -direction of the interface are defined based on the concentration and temperature gradients between the vapor stream and gas–liquid interface, as observed in the following equations.

$$J_{As} = -\rho_s D_s (\partial \omega_A / \partial z)_s \quad (1)$$

$$q_s = -k (\partial T / \partial z)_s \quad (2)$$

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