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Marangoni convection induced by simultaneous mass and heat transfer during evaporation of *n*-heptane/ether binary liquid mixture

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ABSTRACT

The Marangoni convection induced by simultaneous temperature and concentration gradient during the evaporation process of the binary liquid mixture was observed by means of the optical shadowgraph technique, and its morphology was presented. In order to investigate effects of temperature and concentration gradient on the Marangoni convection, a transient numerical computation was developed and conducted by combining the Volume of Fluid (VOF) numerical method with the continuum surface tension (CSF) method. The details of the local velocity field and concentration distribution of the Marangoni convection was revealed by the simulation, and the reference time when the Marangoni convection took effect to enhance the mass transfer coefficient was acquired. Meanwhile, the Marangoni convection induced by either the temperature gradient or the concentration gradient in this evaporation process was respectively investigated numerically to survey influence of the thermal effect accompanying in mass transfer on the Marangoni convection.

1. Introduction

Interfacial liquid flow phenomenon driven by the surface tension gradient is called as the Marangoni convection. Occurrence of the Marangoni convection can accelerate renewal of the liquid surface and significantly enhance the transfer coefficient of the heat and mass transfer process. It attracts many studies in chemical engineering because it is possible to utilize it to intensify separation operations in chemical industry [1]. Moreover, Marangoni effect is also important in applications with temperature gradients on free surfaces such as crystal growth, welding and glass manufacture [2,3].

Lots of works on the Marangoni convection related to mass transfer have been conducted usually by means of absorption, extraction, and evaporation in the quiescent or laminar flowing liquid [4–6]. With the help of the Schlieren, shadowgraph, particle image velocimetry (PIV) and other optical method, structures of the Marangoni convention emerging in liquid during various gas-liquid or liquid-liquid mass transfer processes were acquired [7–9]. Compared to other optical method, such as PIV, shadowgraph is non-destructive testing while PIV needs to add tracing particles which may influence the flow field structure [10]. In addition, the linear stability theory has been utilized theoretically to acquire the critical condition for occurrence of the Marangoni convection [11,12]. However, due to the complicated nonlinear nature of the Marangoni convection, theoretical predictions from the linear theory were not in good agreement with experimental results, and the current nonlinear theoretical method is not well developed to study the complicated Marangoni convection in details [13,14].

It is difficult to investigate the local velocity field and component concentration distribution of the Marangoni convection in details by means of experimental and pure theoretical methods. However, nowadays, the computational fluid dynamics (CFD) method has been verified to be an effective tool to understand mechanism of the Marangoni convection and its influence on mass transfer since it can acquire the local flowing and transfer information about the Marangoni convection. For example, evaporation dynamics and the Marangoni convection in small heated water droplets was investigated successfully by the CFD method [15]. The details of the Marangoni convection in thin films above heated walls was also acquired numerically [16]. With respect to the liquid-liquid mass transfer, a series of studies was conducted by the two-dimensional (2-D) and three-dimensional (3-D) CFD simulation in order to investigate the Marangoni convection in details and its influence on mass transfer [17–20]. Results from those CFD simulation works showed a good agreement with reality.

It is well known that the surface tension is a function of the concentration and temperature. Variation of the concentration and temperature in liquid during mass transfer processes could results

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Nomenclature

A	gird area, m^2
c_p	specific heat capacity, J/(kg·K)
D	diffusion coefficient, m^2/s
E	energy, J/kg
$\mathbf{g}$	gravity acceleration, 9.81 m/s^2
h	enthalpy, J/kg
ΔH	latent heat of vaporization, J/kg
$\mathbf{j}$	diffusion flux, kg/(m^2·s)
k	thermal conductivity, W/(m·K)
K	mass transfer coefficient, m^2/s
m	mass flux, kg/(m^2·s)
$\mathbf{n}$	normal unit vector to the interface
p	pressure, Pa
T	temperature, K
$\mathbf{u}$	velocity, m/s
V	grid volume, m^3
S_L	mass source item in liquid phase, kg/(m^3·s)
$S_{E,L}$	energy source item, J/(m^3·s)

Greek symbols

α	volume fraction
σ	surface tension, mN/m
μ	viscosity, Pa·s
ρ	density, kg/m^3
ω	mass fraction

Subscripts

L	liquid phase
V	vapor phase
i	component i
q	q phase
1	component 1
2	component 2
I	interface

in emergence of the surface tension gradient as well as the Marangoni convection. Especially for the gas-liquid or vapor-liquid mass transfer process, the thermal effect always takes place while one or several components pass through the interface. Most previous works related to the Marangoni convection during the gas/vapor-liquid mass transfer neglected this accompanying thermal effect for convenience [21–23], or did not study concentration gradient and temperature gradient respectively in single case. Few of works focused on influence of this accompanying thermal effect during mass transfer processes on occurrence and development of the Marangoni convection. However, this coupled thermal effect in mass transfer is important to the Marangoni convection. Lubetkin [24] studied on thermal Marangoni effects on gas bubbles, and showed that there were two factors affecting the surface tension: the direct effect of the temperature and the indirect effect of the temperature coefficient of the solubility. The later determined the concentration which in turn changed the surface tension. Albernaz [25] studied on a suspended droplet under evaporation with Marangoni effects, and showed that Marangoni effects played an important role in maintaining the internal circulation when the superheated vapor temperature was increased.

So far, previous investigation related to the Marangoni convection during the gas/vapor-liquid mass transfer was not focused on the difference of Marangoni convection induced simultaneously by thermocapillary and solutocapillary. In addition, in chemical industry, as the base of the multi-component mass transfer, mass transfer operations of binary components are common. However, most theoretical investigations relevant to the Marangoni convection were carried out by means of the mass transfer of the single component [4,8]. It is worthy of surveying the Marangoni convection in the binary component mass transfer process accompanying thermal effect, especially studying Marangoni convection induced by concentration gradient and temperature gradient simultaneously or respectively.

In this work, the Marangoni convection induced by simultaneous heat and mass transfer during the evaporation process of the binary component liquid was investigated by means of the optical shadowgraph observation and two-phase CFD simulation. By combining the Volume of Fluid (VOF) numerical method with the continuum surface tension (CSF) method, the surface force was incorporated in the momentum equation as the body force, and a transient numerical computation was developed and conducted. Moreover, the Marangoni convection induced by either the temperature gradient or the concentration gradient in this evaporation process was investigated respectively in order to survey influence of the thermal effect on the Marangoni convection in mass transfer.

2. Experiment

2.1. Experiment method

In this work, the shadowgraph optical technique was utilized to acquire flow structures of the Marangoni convection and its configuration is presented in Fig. 1. The divergent light beam emitted from a LED point light source passed through the test box at first, and then the shadowgraph image with the variant brightness was projected on the screen and captured by a digital camera (Cannon EOS 400D) with the high resolution (2816 × 1880). With the help of the divergent light, the shadowgraph image projected on the screen was the magnified image of the actual illuminated medium region where the Marangoni convection emerged [26]. This configuration was different from the image acquired by the common shadowgraph or Schlieren optical technique, which makes use of a parallel light beam to illuminate the medium region. Due to the parallel light beam, the size of the acquired image is the same as that of the illuminated medium region.

Evaporation was carried out by means of a test box as shown in Fig. 2, and it was also utilized to observe the Marangoni convection. The test box was constituted mainly by two same square optical glass plates with the length of 150 mm. There was a narrow

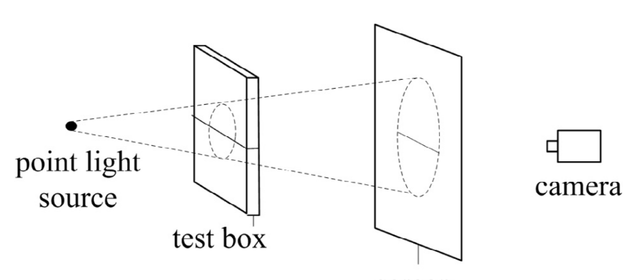

Fig. 1. Sketch of the shadowgraph optical observation.