Energy 93 (2015) 854–863

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Experimental study of direct contact vaporization heat transfer on n-pentane-water flowing interface

Yiping Wang [a, b], Hailing Fu [a], Qunwu Huang [a, *], Yong Cui [c], Yong Sun [b], Lihong Jiang [a]

[a] *School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, China*
[b] *School of Architecture, Tianjin University, Tianjin 300072, China*
[c] *Tianjin University Research Institute of Architectural Design, Tianjin 300072, China*

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form
3 August 2015
Accepted 21 September 2015
Available online 22 October 2015

Keywords:
Direct contact heat transfer
Heat transfer coefficient
Temperature difference
Immiscible liquids
Boiling

ABSTRACT

The direct contact vaporization heat transfer is studied on a small circular interface which is a direct contact interface between the n-pentane injected in a tubule and the immiscible hot water flowing in the channel at the high velocity turbulent state. The interface water temperature is measured by infrared thermograph to obtain the actual driving temperature difference. The effects of water flow velocity and temperature on heat transfer coefficient have been investigated experimentally. In addition, the vapor bubbles characteristics on interface are investigated by visualization research. The results show that the actual driving temperature difference of 8.92 °C is far lower than the traditional temperature difference of 37.9 °C, which causes that their heat transfer coefficients have more than 4 times deviation. The heat transfer coefficient increases as the water flow velocity increases, but decreases with the increase of the driving temperature difference. The n-pentane vaporization rate increases gradually with an increase of water flow velocity and the actual driving temperature difference. The bubbles diameters increase as the water temperature increases, which causes that it is easier to form gas film to reduce the heat transfer coefficient.

1. Introduction

The worldwide energy problems demand the energy utilization efficiency to be increased. Renewable energy such as solar energy, ocean energy etc. has been put into use [1–3]. Many manufacturing processes and most industrial chemical reactions generate heat that must be removed in order to maintain standard operating parameters [4,5]. Therefore, the cooling problem has become an increasing critical problem in concentration photovoltaic systems, heat pump systems, desalination seawater, geothermal heat recovery, thermal energy conversion and storage systems [6–10]. The phase change heat transfer is the most effective method to deal with those problems [11,12]. In recent years, due to the advantages of direct contact heat transfer with lower driving temperature difference, higher effective heat transfer coefficients, fewer scaling problems, a relatively simpler design and no surface corrosion than the traditional heat transfer [13], much attention is devoted to the application of direct contact heat transfer between two immiscible liquids [14,15]. The most important parameter of heat transfer is the heat transfer coefficient, which determines the heat transfer efficiency [16,17].

The direct contact vaporization heat transfer of the conventional stratified flow with two layer of immiscible liquids in horizontal and inclined liquid–liquid systems has been studied in many literature [18,19]. Gollan [20] presented a study of the pentane thin film surface evaporation while flowing co-currently and in direct contact with a laminar water film down a solid plane. A number of mathematical models including an exact formulation and simpler approximate models were considered. The varying thickness of the upper layer was treated by using finite difference techniques. Bentwich [21] analyzed the temperature distribution in a stratified two-phase laminar flow using a Graetz-type solution, and taking into account the discontinuities in the physical properties at the liquid–liquid interface. Nosoko [22] studied the evaporation of single volatile-liquid lenses placed on the surface of a quiescent pool of immiscible, denser, less-volatile liquid. Relatively much work had been done to obtain experimental and theoretical data for stratified flow in laminar systems or stagnant liquid medium because that two layer liquid were easy to be entrained or mixed at

---

[*] Corresponding author. Tel./fax: +86 22 27404771.
E-mail address: huangqw@tju.edu.cn (Q. Huang).

http://dx.doi.org/10.1016/j.energy.2015.09.094

Nomenclature

A	heat transfer area, m^2
D	vapor bubble diameter, mm
D_d	average bubble diameter, mm
H	latent heat of n-pentane vaporization, kJ/kg
K	heat transfer coefficient, $kW/(m^2\ ^\circ C)$
K_i	heat transfer coefficient based on $T-T_{sat}$, $kW/(m^2\ ^\circ C)$
Q	total heat transmission, kJ/s
t	complete vaporization time of n-pentane, s
T	bulk water temperature, °C
T_s	actual surface water temperature, °C
T_p	measured surface water temperature, °C
T_w	measured interface water temperature, °C
T_i	average interface water temperature, °C
T_{sat}	n-pentane saturation temperature, °C
ΔT	actual driving temperature difference, °C
ΔT_m	traditional driving temperature difference, °C
u	water flow velocity, m/s
V	n-pentane vaporization volume, m^3
υ	n-pentane vaporization rate, $kg/(m^2\ s)$
ρ	n-pentane liquid density, kg/m^3

Abbreviations

CMOS	complementary metal oxide semiconductor
IR	infrared
PE	polyethylene

high velocity turbulent state. Some stratified flow models were developed for describing heat transfer across the interface of two independent stirred liquids [23–26], but the agitation interrupted the conduct of experiments and it was difficult to obtain accurate quantitative data [27].

The study of liquid–liquid interface vaporization heat transfer is a vast scientific topic, one can cite the liquid–liquid interface heat transfer of drobble when dispersed phase n-pentane was injected into continuous phase water because the heat transfer taking place at the liquid–liquid interface of drobble mostly had been substantiated by Sideman [28]. In practice, the volatile liquid phase is not always located at the bottom of two phase bubble in the evaporation process as described by theoretical models [29,30]. Simpson [31] observed that the drop oscillated during its rise, which caused the unevaporated liquid to slosh from side to side. Over past years, numerous extensive reviews of experimental and theoretical investigations about the vaporization of an immiscible liquid drop in a continuous liquid were published [32,33]. Sideman [34] also studied the heat transfer coefficient of n-pentane liquid drops evaporating in another immiscible liquid on the assumption that the drop is a sphere with no heat flux across the surface. The driving temperature difference was defined as the difference between the average temperature of the water and n-pentane liquid drop, and the heat transfer area was taken as the area of spheroidal drobble. Simpson [31] defined temperature difference as the difference between the water temperature and butane normal saturation temperature, while the heat transfer area was defined as the equivalent spherical area of the drobble. Kulkarni [35] presented a model to predict the interfacial area and direct contact heat transfer coefficient. The results showed that the volume fraction, mass fraction of the n-pentane liquid and vapor, interfacial area for heat transfer were governed by initial drop size and initial temperature difference between the hot fluid and n-pentane saturation temperature.

The study of interfacial vaporization heat transfer in two immiscible liquid is a significant research topic since key parameters, especially actual driving temperature difference and heat transfer coefficient, are expected to depend on the interfacial heat transfer behavior [36,37]. When n-pentane begins to vaporize by absorbing heat from the liquid–liquid interface, the interface water temperature decreases rapidly, and there will be the difference temperature between the interface water and bulk water. The liquid–liquid direct contact heat transfer interfacial area varies continuously because of the continuing evaporation, system oscillation and sloshing of the unvaporized n-pentane liquid. On the other hand, most of direct contact heat transfer in stratified flow happened on a large interface where the flow velocities are not uniform and unstable especially at the turbulent state. Hence, the change of interface leads to the actual driving temperature difference and heat transfer coefficient cannot be obtained accurately.

To solve this problem, a visualized experiment was fabricated to investigate the direct contact vaporization heat transfer between two immiscible liquids at turbulence flow state. In this work, a special circular interface with small unchanged area was designed to make the water flow velocities uniform on the entire interface. The actual driving temperature difference and heat transfer coefficient are obtained by using this n-pentane-water interface which also could be regarded as the liquid–liquid heat transfer interface of drobbles. The influence factors of heat transfer coefficient are analyzed and the boiling phenomenon is observed when the contact interface constantly updates in the condition of turbulent flow. It is also anticipated that the results obtained in this study will provide a useful method to research the mechanism of immiscible liquids direct contact heat transfer, which will be used for better understanding the future design of gas–liquid–liquid three phase exchangers.

2. Experimental apparatus and design of the test interface

2.1. Experimental apparatus and procedure

The experimental apparatus was shown schematically in Fig. 1. The rectangular flow channel (internal dimensions of 10 mm in

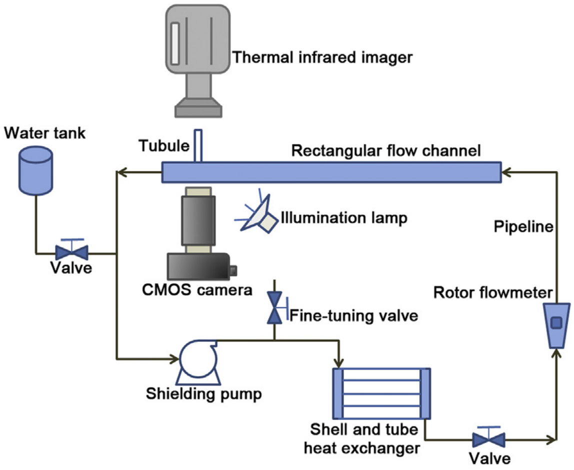

Fig. 1. Schematic of experimental system for the direct contact heat transfer.