Applied Thermal Engineering 117 (2017) 762–772

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

The effect of Dixon rings on direct contact heat transfer performance: Comparison of counter and co-current evaporation

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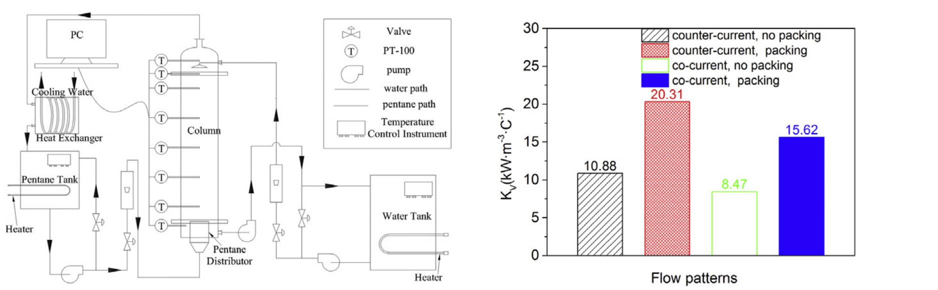
HIGHLIGHTS

- The comparison between counter-current and co-current evaporation.
- The performance of counter-current flow is better.
- The packing can enhance heat transfer effectively.
- The influence factors of evaporation are analyzed.
- The effect of packing on heat transfer performance is analyzed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 August 2016
Accepted 13 February 2017
Available online 16 February 2017

Keywords:
Co-current and counter-current flow
Direct-contact evaporation
Packing
Optimal column height
Volumetric heat transfer coefficient

ABSTRACT

In the experiment, direct contact evaporation in both co-current and counter-current flow were compared with pentane as dispersed phase and water as continuous phase. Dixon rings were also added into the column to enhance heat transfer in those two different contact ways. Axial temperature distribution, optimal column height and volumetric heat transfer coefficient are important parameters to evaluate heat transfer performance. The influences coming from pentane flow rate, water flow rate and inlet water temperature have also been carefully studied. Compared with co-current flow, the optimal column height decreased 15–25% and but heat transfer coefficient increased in the same scale no matter with packing or not in the counter-current condition. The optimal column height was halved and heat transfer coefficient doubled with packing when other factors were the same. Both optimal height and heat transfer coefficient would decrease with the increasing inlet water temperature. Packing in the column was an effective approach to enhance heat transfer performance especially under the condition of low water temperature as well as high water flow rate.

1. Introduction

It is an undisputed fact that the energy crisis has become one of the greatest concerns today. There are two solutions to solve the problem mentioned above. The first method is to develop new energy technologies, such as solar energy [1] and wind energy [2]. Another effective approach is utilizing energy scientifically and supplying energy efficiently based on the idea of sustainability.

As an effective way to use energy, direct-contact heat exchanger was widely studied after its impressive investigation by Sideman et al. [3–8] Direct contact heat transfer has many superiorities such as simple construction, fairly high heat transfer coefficient, negligible fouling and corrosion [9–11]. On account of those merits, it has been applied and researched extensively in crystallization [12],

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http://dx.doi.org/10.1016/j.applthermaleng.2017.02.054
1359-4311/

Nomenclature

Q	heat release ratio of water, kW
Q_{loss}	heat loss ratio of water, kW
C	specific heat, kJ/(kg °C)
C_{pc}	specific heat of pentane vapor, kJ/(kg °C)
m	mass flow rate, kg/s
q	latent heat of evaporation, kJ/kg
ΔT	heat transfer difference, °C
T_{c1}	inlet water temperature, °C
T_{c2}	outlet water temperature, °C
V	volume flow rate, L/h

Abbreviations

DCE	direct contact evaporator

Subscripts

c	continuous phase
d	dispersed phase
b	boiling
v	volumetric
opt	optimal column height

desalination [13], energy recovery from industrial waste [14,15], ice-slurry production [16] and thermal energy storage [17].

As one of the most important applications in the field of direct contact heat transfer, direct contact evaporation also has been the object of study in recent decades. A lot of scholars studied the evaporation process of a single droplet on the micro-level with the aid of high-speed digital camera and cine-photographic technique [13,18–21]. As for swarms of droplets, Smith et al. [11] developed an analytical model for calculating volumetric heat-transfer coefficients for direct-contact evaporation by using single droplet correlations. Song and Steiff [22] presented a model to simulate vaporization height based on the concept of phase space and the population balance equation. Siqueiros and Bonilla [23] investigated the factors that were closely related to volumetric heat transfer coefficient. Song et al. [24] presented a population balance model to predict the volumetric heat transfer coefficient for direct-contact evaporation in a bubble column based mainly on the energy balance and the population balance. Fu et al. [25] investigated the behaviors of drobbles in the experiment of the pentane evaporating in hot water. In general, evaporation in bubble column was well studied in the past few decades.

The evaporation in spray-column was first studied by Sideman and Gat [3]. Battya et al. [26] did a simple theoretical analysis on the contact latent heat transfer in a counter flow spray column. However, there is little study on it owing to flooding and strict operational condition [27]. Seetharamu and Battya [28] investigated the evaporation of R-113 in a stagnant column of distilled water, and developed correlations to predicate heat transfer coefficient. But the limiting condition for keeping hot water stagnant made it unacceptable in practical application. Mori [29] proposed a model to calculate heat transfer coefficient assuming no nucleation. Hameed [30] gave a systematic analysis of evaporation in a spray column, but the assumption that the holdup ratio was constant along the column was far-fetched.

After careful mathematical analysis, Sideman and Moalem [31] pointed out that counter-current was more efficient than co-current operation in direct contact condensation in the column. Park et al. [32] investigated the direct contact condensation in horizontal circular pipe, and found that the overall heat transfer characteristics was better in the concurrent flow.

As an effective device, the packing column was widely studied in the process of direct contact condensation, and played a positive role in the process of heat transfer [33–36]. More recently, in our lab, Jiang et al. [37] investigated the effect of Dixon rings on the performance of direct contact evaporation in bubble column (co-current), and found that packing played a good role in promoting heat transfer. But the experiments just involved the effects of packing on the bubble column. The investments on counter-current flow were not covered. And it is worthy of lucubrating.

In the direct contact heat transfer of volatile liquid evaporation in an immiscible liquid, spray column and bubble column are nearly identical in the operation except flow direction of the continuous phase. In the former, it is co-current flow, while counter-current flow in the latter. So the comparison between those two different operations can provide guidance for choosing suitable contact form in industrial application. Unfortunately, there are little researches on it. At the same time, enhancing heat transfer by utilizing packing in two operations listed above is also worth of investment. And evaluating the effect contributes to our understanding of the influence of packing. In this work, we devote to investigating the heat transfer performance in both co-current and counter-current operations under the condition of adding packing or not, and then making comprehensive and comparative evaluations and analyses.

2. Experiments

2.1. Experimental setup

Taking safe and economic aspects into account, industrial pentane (molar ratio of n-pentane and iso-pentane is 1:1, the physical properties are shown in Table 1) and tape water were chosen as working fluids. Pentane was used as volatile dispersed phase, and water immiscible continuous phase. Before pentane was injected into water by a diaphragm pump, it was preheated to a temperature near the boiling point.

The schematic diagram of the experimental setup is illustrated in Fig. 1. The experimental apparatus mainly consists of four parts, namely direct contact evaporator (DCE), the circulatory system of water and pentane, temperature control system and data acquisition system.

The DCE is the core part of the system. It is a vertical column made of glass and comprised of three parts, including column body and two end sockets. The column body, with height 1000 mm, external diameter 80 mm, thickness 5.5 mm, is the place where pentane changed from saturation liquid to overheated gas. Seven thermometer holes were designed on column body for temperature probes to measure the liquid temperature. Furthermore, in

Table 1
Properties of industrial pentane at 35.8 °C.

Property (at 35.8 °C)	Value
Constituents (molar ratio)	*n*-pentane:iso-pentane = 1:1
Liquid density (kg/m)	610
Gas density (kg/m^3)	2.99
Boiling point (°C)	35.8
Latent heat of vaporization (kJ/mol)	25.42