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Research Paper

Measuring the average volumetric heat transfer coefficient of a liquid–liquid–vapour direct contact heat exchanger

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HIGHLIGHTS

- Measurements of U_v in a 3-phase spray column DCHE.
- Effect of Q_c, Q_d, D_o, H_v and sparger configuration was examined.
- U_v decreases with D_o and H_v.
- U_v increases with increasing continuous and dispersed phase flow rates.
- Very slight effect of sparger configuration on U_v.

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ABSTRACT

The average volumetric heat transfer coefficient in a spray column liquid–liquid–vapour direct contact evaporator has been experimentally investigated. The experiments were carried out utilising a cylindrical Perspex tube of diameter 10 cm and height and 150 cm. Saturated liquid *n*-pentane and warm water at 45 °C were used as the dispersed and continuous phases, respectively. Three different dispersed flow rates (10, 15 and 20 L/h) and four different continuous phase flow rates (10, 20, 30 and 40 L/h) were used in the study. The effect of different parameters, such as the initial drop size, continuous and dispersed phase flow rates and sparger configuration, on the average volumetric heat transfer coefficient in the evaporator was studied. The results showed that the average volumetric heat transfer coefficient was reduced as the initial drop size increased. Also, both the continuous phase and the dispersed phase flow rates have a significant positive impact on the average volumetric heat transfer coefficient.

1. Introduction

The efficient design of an energy conversion system requires the extraction of the maximum thermodynamic potential of the energy source. This process is carried out by the heat exchanger, where the thermal energy transfers between two different fluid streams. Heat exchangers can be split into two main types: surface types, such as the shell and tube heat exchanger and direct contact heat exchangers, for example, the spray column.

In surface type exchangers, the two fluid streams (hot and cold), are completely separated by a solid barrier through which heat is transferred. Therefore, the ability of this type of exchanger to extract the thermodynamic potential energy is constrained by the heat transfer resistance of the surface. This surface is also exposed to fouling, corrosion and thermal stresses, especially when the exchanger operates over a large temperature range. Practically, such problems are alleviated by different technologies, e.g. using a chemical as a corrosion inhibitor, which raises the operational cost, or the use of more expensive materials of construction, which raises the capital cost. This, of course, hinders the applicability of surface type heat exchangers in low-temperature processes. The capital cost of a traditional surface type exchanger is also high due to the large surface area required to overcome the low heat transfer rate or heat transfer coefficient. The operational cost is high mainly due to the expense of continuous maintenance, fouling and corrosion. These problems and others could be solved by using the second type of heat exchanger i.e. the direct contact heat exchanger. These exchangers bring the fluid streams into direct physical contact and therefore eliminate the need for physical

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Nomenclature

A	cross-sectional area of column, m^2
C_{pc}	specific heat of continuous phase, kJ/kg °C
h_{fg}	latent heat of condensation, kJ/kg
$\dot{m}_d$	dispersed phase mass flow rate, kg/min
$\dot{m}_c$	continuous phase mass flow rate, kg/min
$\dot{m}_v$	dispersed (vapour) mass flow rate, kg/min
Q	heat transfer rate, kW
T	temperature, °C
ΔT_{lm}	log-mean temperature difference, °C
U	velocity of continuous phase, m/s
ΔZ	sub-height along column, m

Subscripts

c	continuous phase
d	dispersed phase
i	initial, or location
o	outlet

barriers. This elimination means that a direct contact heat exchanger has many advantages over the surface type heat exchanger. In practice, it has a very high heat transfer coefficient, especially when it utilises a phase change. Also, there is much less corrosion and fouling and it can be operated with a very low-temperature difference [1]. Therefore, it can be used in different industrial applications, such as water desalination, solar energy applications and power production from low-grade energy resources such as geothermal energy, where surface type heat exchangers are rendered uneconomic [2]. Nevertheless, the direct contact heat exchanger has several obstacles to implementation. The most important are: the two fluid streams must be immiscible to avoid intimate mixing between them, which could be extremely expensive if later purification of the contaminated stream is necessary. Secondly, the two streams must be at the same pressure, which is not a requirement of surface type exchangers.

Only limited attention has been paid to understanding the effective parameters which control the performance of the liquid–liquid–vapour direct contact evaporator. Most of these studies are theoretical, and they concentrate on the temperature distribution along the evaporator and the volumetric heat transfer coefficient. Bauerle and Ahlert [3] studied the volumetric heat transfer coefficient and the holdup ratio of an evaporative spray column direct contact heat exchanger, experimentally. They observed a linear relationship between the volumetric heat transfer coefficient and hold-up ratio, up to a holdup 60%. Beyond this value, the volumetric heat transfer coefficient increased rapidly towards the flooding point and then decreased. The same trend in the variation of volumetric heat transfer coefficient with the column holdup ratio was also found experimentally and correlated by Plass et al. [4]. They concluded that their correlations are an accurate prediction of the volumetric heat transfer coefficient of the direct contact spray column heat exchanger, and they could be used successfully for design or sizing.

Many investigators have pointed out that the volumetric heat transfer coefficient, the holdup ratio and the heat transfer rate are affected strongly by the dispersed phase flow rate, while the continuous phase has no significant impact (e.g., [5–9]). An inverse effect of the initial drop diameter on the average volumetric heat transfer coefficient was observed experimentally by Sideman et al. [10].

Siqueiros and Bonilla [6] illustrated promising results when they studied the inlet and the outlet temperatures of both the dispersed (pentane) and the continuous phases (water) during the direct contact evaporation process. They observed that when the initial temperature (inlet temperature) of the continuous phase ranged between 75 and 88 °C and the inlet temperature of the dispersed phase between 23 and 38 °C, the continuous phase outlet temperature was between 70 and 84 °C and the dispersed phase outlet temperature between 72 and 85 °C. Battya et al. [11] numerically studied the temperature distribution of both the continuous and the dispersed phases along the direct contact evaporator. A general numerical solution was carried out by Core and Mulligan [12], Summers and Crowe [13] and Brickman and Boehm [14]. They investigated the temperature distribution along the height of a direct contact spray column evaporator. Brickman and Boehm [14] concentrated on the possibility of maximising the three-phase, direct contact heat exchanger output by solving the one-dimensional, continuity, momentum and energy equations using a Runge–Kutta technique. Birkman and Boehm's [14] results revealed that the optimal performance is achieved when the dispersed phase is injected at its saturation temperature. Similarly, Coban and Boehm [15] and Jacobs and Golafshani [16] predicted the temperature distribution of the dispersed and the continuous phase along the column height. Tadrist et al. [17] developed a numerical solution including the coalescence of the evaporating drops and carried out experimental measurements of the temperature distribution and holdup ratio in the liquid–liquid–vapour direct contact spray column evaporator.

Analytical models describing a liquid–liquid–vapour heat exchanger are very rare because of the many complex interacting phenomena. In this context, and based on an expression for the heat transfer coefficient for a single drop evaporating in an immiscible liquid developed previously [18], an analytical solution for the local and the average heat transfer coefficient for multiple drops evaporating in a spray column direct contact heat exchanger was developed by Mori [19]. Recently, Mahood et al. [20] have derived analytically the temperature distribution of both continuous and dispersed phases along a three-phase direct contact evaporator. Most recently, Wang et al. [9] accurately measured the interface temperature of the continuous phase, and accordingly they calculated the heat transfer coefficient of *n*-pentane drops evaporating in direct contact with hot water. The temperature driving force for evaporation was accordingly the difference between the interface temperature and the drop saturation temperature. They concluded that the value of the heat transfer coefficient calculated based on the interface temperature was significantly greater than that calculated using the continuous phase temperature. Jiang et al. [21] observed that the effective height of the direct contact evaporator is reduced by up to 25% when using packing material, under temperature differences less than 8 °C. Also, a significant increase in the associated volumetric heat transfer coefficient was recorded.

Finally, Mahood et al. [1,2,23–25] have investigated the heat transfer characteristics of the vapour–liquid–liquid direct contact condenser both experimentally and theoretically. In general, the mass flow rate ratio was noted to have a significant impact on the direct contact heat transfer process with no considerable effect from the initial temperature of the dispersed phase. An increase in the temperature (both transient and steady state) of the continuous phase with height was observed experimentally and predicted analytically [2,22]. Also, the volumetric heat transfer coefficient