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Research Article

Effect of Various Parameters on the Temperature Measurements in a Three-Phase Direct Contact Condenser

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Abstract

*An experimental investigation of heat exchange for a three-phase direct contact condenser has been carried out by utilising a short Perspex tube of 70 cm in total height with a 4 cm inner diameter. Only the 48 cm was chosen as an active direct contact condenser. Pentane vapour with three different initial temperatures (*40°C, 43.5°C, and 47.5°C*) and a constant water temperature* (19°C) *were implemented as dispersed and continuous phases, respectively, with different mass flow rate ratios. The experimental results demonstrated that the continuous phase outlet temperature increases with an increasing mass flow rate ratio. On the other hand, the continuous phase temperature decreases when increasing the continuous mass flow rate. The dispersed phase initial temperature slightly affected the direct contact condenser output, which confirms that the latent heat of condensation is dominant in such a heat exchange.*

Keywords: *Three-phase direct-contact condenser, condenser temperature output, mass flow rate ratio effect, temperature distribution*

1. Introduction

In a three-phase direct contact heat exchanger both hot and cold fluids are completely immiscible and one of them undergoes a phase change phenomena. In this case, it is not necessary to use barriers to separate the working fluids in the exchanger. Subsequently, a high heat transfer rate, little or no corrosion and/or fouling issues, low cost, and, finally, high heat exchange efficiency are possible. These beneficial features and others assist such exchanger type usage in different industrial applications, such as water desalination by direct contact freezing, power generation utilising geothermal heat sources, and emergency cooling in nuclear and chemical reactors (F. Dammel & H. Beer, 2003, R. Wanchoo, S. Sharma and G. Raina, 1997, R. Wanchoo, 1993).

In general, the direct contact condenser design relies on the thermodynamic situation of the dispersed phase, which is saturated or superheated, and on the condensation process, whether it takes place by drops, bubbles, or thin film (G. F. Hewitt *et al*, 1993). For the saturation case, the flow direction of the fluid streams (concurrent or counter-current) does not have a significant advantage in the heat transfer process, as it is useful only when the dispersed phase contains non-condensable gas or when utilizing gravity for phase separation purposes. Among those, the bubble-type three-phase condenser is relatively high efficiency, simpler in design, simpler in construction, and lower in cost. However, direct contact condensation takes place through an empty column; therefore, the possibility of an unpleasant flooding phenomenon is relatively high. This phenomenon includes when the continuous phase is completely held up by the dispersed phase or the dispersed phase is swept backward by the continuous phase.

Few studies can be found in literature regarding the three-phase direct contact condenser, although efforts have been reported on the condensation of single vapour bubbles (K. Higeta *et al*, 1983; J. Isenberg & S. Sideman, 1970; K. Higeta *et al*, 1979; H. Kalman & Y. H.,Mori, 2002; H. Kalman , 2003; Lerner, Y. *et al*, 1987, D. Moalem & S. Sideman, 1973; Raina G. *et al*, 1984; R. K. Wanchoo, 1993) and train bubbles (D. Moalem, *et al*, 1973; H. Kalman, 2006; H. B. Mahood, 2014a) in an immiscible liquid, which is deemed as the basis on which the real condenser has been built upon. Only the theoretical work of Sideman and Moalem (1974) has dealt with the three-phase direct contact condenser. Their model was based on the previous single-bubble model given by Sideman and co-workers (J. Isenberg & S. Sideman, 1970; D. Moalem & S. Sideman, 1973, D. Moalem, *et al*, 1973). A quasi-steady state energy

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equation along the bubble column is solved to find the condensing history of a multi-bubble system. The effect of bubble frequency, relative velocity, horizontal spacing, and inert gas content in both single and two-component systems, and in both co-current and counter current flow were evaluated. According to their results, the relative velocity was found to decrease with increased bubble frequency, while it was affected only slightly by the non-condensable gas content within the bubbles. On the other hand, there was no effect resulting from the temperature driving force on the relative velocity at a given bubble frequency or from the number of injection nozzles, except at very small temperature differences (up to 0.5°C).

Recently, the authors H.B. Mahood *et al*. (2014b) have investigated the steady-state temperature distribution along a three-phase direct contact condenser both experimentally and theoretically. An increase in the continuous phase temperature with the condenser height was observed and analytically predicted. The mass flow rate of the dispersed phase was found to have a considerable effect on condenser output (continuous phase outlet temperature). Furthermore, Mahood *et al*. (2015) have observed that the instantaneous volumetric heat-transfer coefficient of the three-phase direct contact condenser decreases with time. A high volumetric heat-transfer coefficient at the first few centimetres from the dispersed phase bubble inlet is noticeable.

In this paper, an experimental study of temperature of the continuous phase of the three-phase direct contact condenser is carried out. The effect of the mass flow ratio and continuous phase mass flow rate on the output of a three-phase direct contact condenser was researched. In addition, the continuous phase temperature distribution along the direct contact condenser at three different dispersed phase initial temperatures was obtained.

2. Experimental Setup and Procedure

Figure 1 shows the setup of the experiment used in this study. Briefly, it comprises three main parts in addition to the auxiliary equipment: the direct contact test section, which is a 75 cm total height, and 4 cm diameter Perspex column. Only 48 cm is used as an active height.

The heating vessel is a cubical, stainless steel pool boiler with a height of 100 cm and a width of 50 cm. The vessel contains a copper coil with an internal diameter of 6 mm and a length of 6 m used for vaporising and carrying the dispersed phase. This coil is immersed completely in the water pool, which is heated by two electric heaters with a total power of 6 kW. These heaters are controlled by a thermostat.

Finally, we have the continuous phase and the dispersed phase supply systems. Water at a constant inlet temperature (19°C) is used as a cooling or a continuous phase. It is pumped from a large storage tank (about 160 l) via a centrifuge low-pressure pump and a calibrated rotameter. The large storage tank helps maintain the temperature of the continuous phase at a constant level during experiments. The continuous phase (water) enters the test section at the top and leaves from the bottom. On the other hand, liquid pentane (its properties are given in Table 1) is used as a dispersed phase. It is heated through the heating vessel after it is pumped from a small storage vessel via a low-pressure pump and enters the test section as vapour bubbles from the bottom, condensates, and leaves from the test section top. A short tube is used to connect the inlet of the dispersed phase with the direct contact column (test section). This tube is heated by a variable temperature trace heater with a controller to maintain the dispersed phase vapour at a constant inlet temperature.

The temperature along the test section is measured using five calibrated K-type thermocouples fixed at the following different positions from the bottom of the column (see Figure 1b): TC1 at 0 cm (for continuous phase outlet), TC2 at 12 cm, TC3 at 24 cm, TC4 at 36 cm and TC5 at 48 cm (for continuous phase inlet). The following three additional thermocouples were used: one for measuring the condensate temperature at a height of 52 cm and the other two for the injected vapour temperature and the dispersed phase temperature in the heating vessel. All these thermocouples were connected to an eight-channel data logger to display the measured temperature directly on a computer.

The experiment starts by preparing the cooling phase (water) at a constant temperature in its storage tank and pumping the water through the direct contact column (condenser) to maintain a uniform temperature throughout the column. Simultaneously, liquid pentane is pumped to the heating vessel and heated to the desired temperature.

The experimental run begins when the pentane vapour reaches the desired temperature and the ball valve is opened. The extent of opening determines the flow rate. The desired flow is achieved using a calibration curve. The calibrated size of the open injection ball valve is determined before the beginning of the real test by completing calibration runs. Hence, the real test begins when the pentane vapour reaches its desired temperature. Then, the ball valve is opened at the calibrated limit. The cooling water flow rate is controlled by adjusting both the inlet and the outlet rotameters, and the water is recycled throughout the direct contact column before pentane vapour is injected into the column. This ensures that the temperature is uniform within the column before the pentane vapour is injected. The temperature along the column is recorded on the computer via the digital data logger from the moment of vapour injection into the column when the condensation process starts. The injected vapour temperature and pressure are controlled carefully using a thermocouple and a pressure gauge. The dispersed phase (vapour) mass

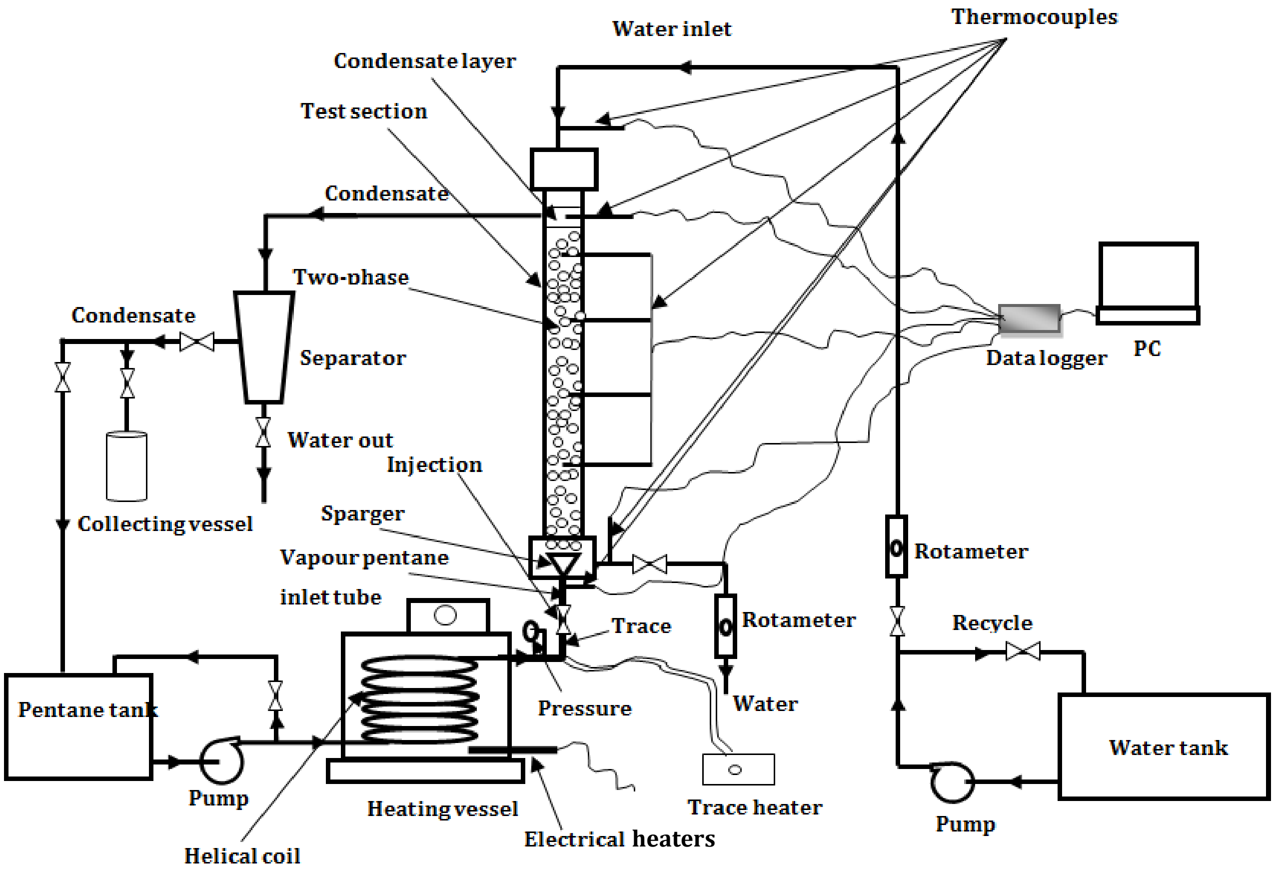

Fig 1: Schematic diagram of the experimental rig

flow rate is determined by a mass balance, where the condensate layer formed in the column top is collected, weighted, and divided by the experimental time. A conical separator flask is used to completely recover the condensate. Finally, all the condensate is sent back to the heating vessel or collected and used in another run.

Table 1 The physical properties of n-pentane at 1 bar

Properties	Values
Saturation temperature $(°C)$	36.0
Molar mass $(kg/kmol)$	72.15
Thermal diffusivity (m^2/s)	7.953×10^{-8}
Specific heat of liquid $(kJ/kg.K)$	2.363
Specific heat of vapour $(kJ/kg.K)$	1.66
Thermal conductivity of liquid $(W/m.K)$	0.1136
Thermal conductivity of vapour $(W/m.K)$	0.015
Kinematic viscosity (m^2/s)	2.87×10^{-7}
Viscosity $(kg/m.s)$	1.735×10^{-4}
Latent heat of vaporization (kJ/kg)	359.1
Density of liquid (kg/m^3)	621
Density of vapour (kg/m^3)	2.89
Surface tension (N/m)	0.01432

3. Results and Discussion

The experimental study was conducted on a three-phase direct contact condenser utilising pentane vapour and tap water as a dispersed phase and a continuous phase, respectively. The experiments involve the measurements of the continuous phase temperatures at five different locations along the direct contact condenser, including its inlet and outlet points. Figures 2 and 3 show the variation of the continuous phase outlet temperature with the mass flow rate ratio (variable dispersed phase mass flow rate per constant continuous mass flow rate), for two different continuous mass flows rates and three different dispersed phases initial temperatures.

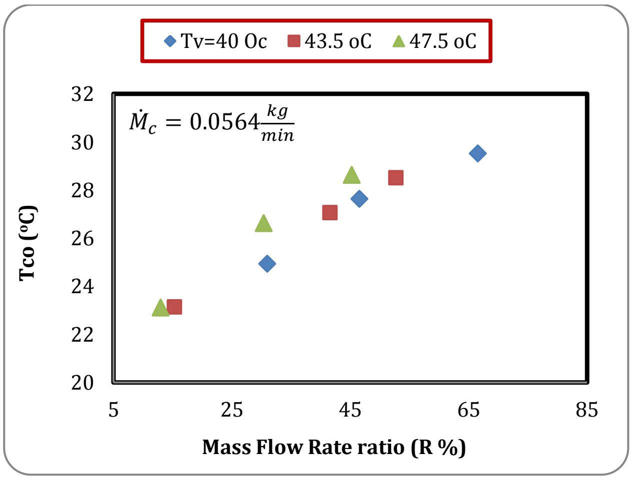

Fig 2: The outlet temperature of the continuous phase versus the mass flow rate ratio.

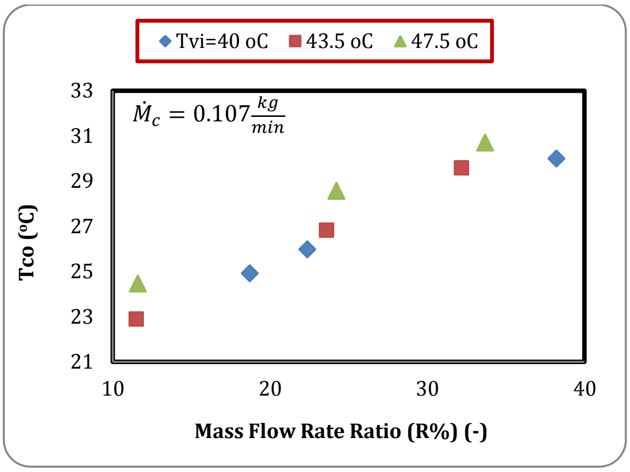

Fig 3: The outlet temperature of the continuous phase versus the mass flow rate ratio.

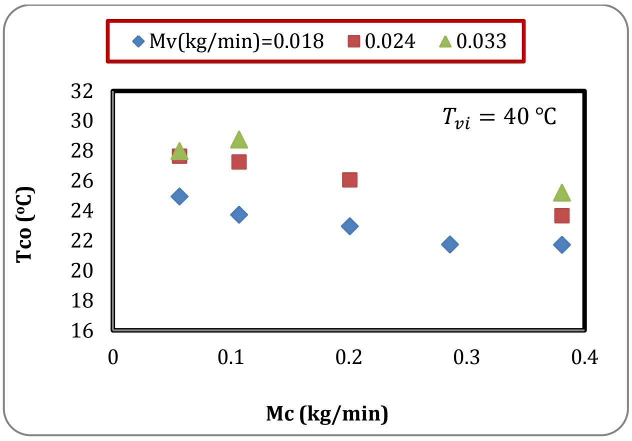

Fig 4: The outlet temperature of the continuous phase versus the continuous mass flow rate

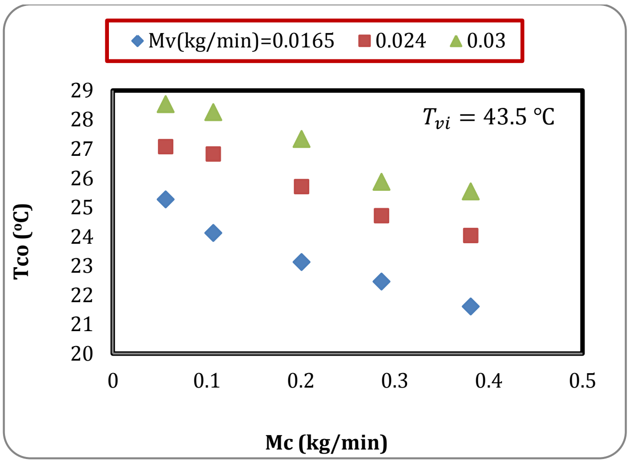

Fig 5: The outlet temperature of the continuous phase versus the continuous mass flow rate.

It is obvious that the continuous phase outlet temperature (condenser output) increases with an increased mass flow rate ratio and slightly increases with an increased initial dispersed phase temperature. The relationship is almost linear. This may be contributed to by the fact that the increase in the mass flow rate ratio means an increase in the heating medium (hot vapour) in the condenser. Subsequently, and according to the energy balance principle of an isolated system, the energy loss of a heating phase (dispersed phase) is completely absorbed by a cooling phase (continuous phase).

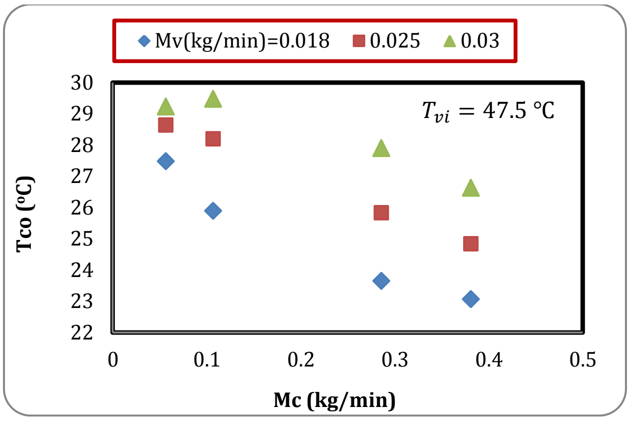

Fig 6: The outlet temperature of the continuous phase versus the continuous mass flow rate

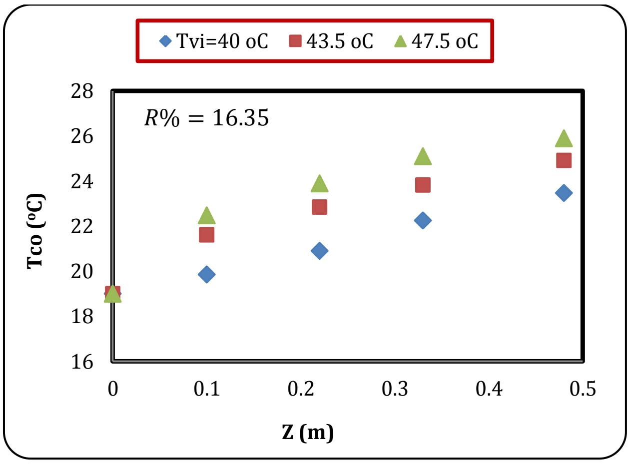

Fig 7: The continuous phase temperature distribution along direct contact condenser height.

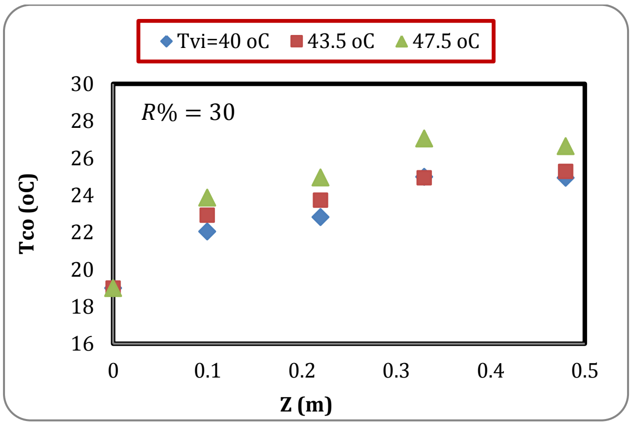

Fig. 8: The continuous phase temperature distribution along direct contact condenser height.

The slight effect of the dispersed phase initial temperature on the condenser output indicates that the latent heat of condensation is dominant throughout the direct contact condensation process. In addition, the direct contact column height may be insufficient to extract sensible heat (degree of superheating) from the dispersed phase.

An inverse effect of the continuous phase mass flow rate on the direct contact condenser outlet temperature is obtained and shown by Figures 4 through 6. However, at very low continuous phase mass flow rates, such as 0.0564 kg/min, incomplete direct contact condensation of vapour bubbles (dispersed phase) is expected, especially at a high (or a relatively high) dispersed phase mass flow rate. Therefore, this could reduce the direct contact condenser output.

Dispersed phase vapour injection pressure was found to be another effective parameter (results not detailed here). The increase of vapour injection pressure results in a decrease in the continuous phase outlet temperature (condenser output). High injection pressure makes the vapour bubble move with a high velocity, which reduces the resident time (contact time) of the hot bubbles during the cooling phase. Subsequently, incomplete bubble condensation takes place.

Finally, the temperature distribution of the continuous phase along the direct contact condenser at a constant mass flow rate ratio and a different dispersed phase initial temperature is shown in Figures 7 and 8. It is clear that the continuous phase temperature increases with an increase in column height from its inlet towards its outlet. A higher mass flow rate ratio results in a higher continuous phase outlet temperature. The initial dispersed phase temperature, again, seems to be slightly affected by the continuous phase outlet temperature, which confirms the latent heat has a dominant effect during the direct contact condensation process.

Conclusions

An experimental study has been carried out regarding the heat transfer characteristics of a three-phase direct contact condenser. According to the results, the following conclusions can be made:

- The mass flow rate ratio is positively affected by the direct contact condenser output.
- The continuous phase mass flow rate is inversely affected by the direct contact condenser output.
- The temperature distribution along the direct contact column increases when increasing the column height.
- A slight effect of the dispersed phase initial temperature on the direct contact condenser output was obtained (continuous phase outlet temperature), which confirms that latent heat is dominant in the process.

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Nomenclature

$\dot{M}$	mass flow rate (kg/min)
R	mass flow rate ratio
T	temperature (°C)
Z	direct contact condenser height (m)

Subscripts

c	continuous phase
i	initial
o	outlet