Energy 67 (2014) 538–547

Contents lists available at ScienceDirect

Energy

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

Analytical solution and experimental measurements for temperature distribution prediction of three-phase direct-contact condenser

Hameed B. Mahood [a,b,*], A.O. Sharif [a,c], S. Al-Aibi [a], D. Hawkins [a], R. Thorpe [a]

[a] Centre for Osmosis Research and Applications (CORA), Chemical and Process Engineering Department, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, UK
[b] University of Misan, Misan, Iraq
[c] The Qatar Foundation, Qatar Energy and Environment Research Institute, Qatar

ARTICLE INFO

Article history:
Received 16 September 2013
Received in revised form
11 November 2013
Accepted 13 December 2013
Available online 14 January 2014

Keywords:
Direct-contact heat transfer
Three-phase condenser
Analytical modelling
Experimental measurements
Temperature distributions

ABSTRACT

An experimental and analytical investigation for the temperature distribution prediction of a three-phase bubble-type direct-contact condenser conducted, using a short Perspex column with 4 cm internal diameter and 70 cm height as a direct contact condenser. Vapour pentane and water were exploited as dispersed phase and continuous phase respectively. The effect of mass flow rate ratio (43.69%, 22.97%, 12.23%, 8.61% and 6.46%) and initial dispersed phase temperature (37.6 °C, 38.4 °C and 41.7 °C) on the direct contact condenser output were studied. Linear temperature distributions along direct contact condensers were found experimentally, except at mass flow rate ratio 43.69% and with less magnitude at 22.97%, for different initial vapour temperatures, while theoretically this behaviour is purely linear. The results showed that the mass flow rate ratio and the hold up have a dominant effect on the direct contact condenser output. On the other hand, the initial vapour temperature had a slight effect on the direct contact condenser output temperature which indicates that the latent heat is controlled in the exchange process. The analytical model is based on the one-dimensional mass and energy equations. New expressions for average heat transfer coefficient and two-phase bubbles relative velocity are derived implicitly. Furthermore, the model correlated very well against experimental data obtained.

1. Introduction

DCC (Direct contact condensers) have been known for a long time and have been utilised in different applications, for example open feed water heaters, petroleum refinery processes, geothermal power production, water desalination and solar energy applications. Direct contact condensers as a type of direct contact heat transfer equipment have many advantages over the surface type condenser. For instance lower cost, closer temperature approach (in some cases less than 1 °C), easier and economical separation of contacting fluids, a high heat transfer rate, absence or very few problems with fouling and corrosion. They are efficient in extracting non-condensable gases, smaller in size and less cooling water is required (60% less than that needed in surface type condensers) which makes them a preferred option in geothermal power production plants. In this context, Mercado and Heard [1] have pointed out, as an example that for a total power production of about 5827.55 MWe, in an organic Rankine cycle plant using 174.826 MWe, about 1400 MWe is a steam cycle plant with surface condenser and the reminder, about 4252.723 MWe, is a steam cycle plant with a direct contact condenser. Furthermore, another existing geothermal power plant in Mexico at Cerro Prieto with capacity of 620 MWe entirely uses a direct contact condenser [1].

Nevertheless, few publications are available regarding their scientific bases and design procedures [2,3] and most of these publications have concentrated on the thin film or the packed column type, which widely exploit the humidification – dehumidification water desalination technique.

Only the work of Sideman and Moalem [4] has been found to be relevant with the direct contact condensation of multi-vapour bubbles in an immiscible liquid. A simple model based on the previous single bubble model given by Sideman and co-workers [5–7] has been developed by solving a quasi – steady state, energy equation along the bubble column to find the collapsing history of multi-bubble system. The effect of bubble frequency,

* Corresponding author. Centre for Osmosis Research and Applications (CORA), Chemical and Process Engineering Department, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, UK.
E-mail addresses: hbmahood@yahoo.com, h.al-muhammedawi@surrey.ac.uk (H.B. Mahood), asharif@qf.org.qa (A.O. Sharif).

0360-5442/$ – see front matter
http://dx.doi.org/10.1016/j.energy.2013.12.026

relative velocity, horizontal spacing and inert contents in both single and two − component systems, in either concurrent or counter current flow were evaluated. According to their results, the relative velocity was found to decrease with increased bubble frequency, while it was slightly affected by the non-condensable gas content within the bubbles. On the other hand, no effect was shown by the temperature driving force on the relative velocity at a given bubble frequency and the number of injection nozzles, except at very small temperature differences of up to 0.5 °C. In addition, they found that the effect of horizontal bubble spacing is much clearer than vertical, the counter current flow configuration is more efficient than the concurrent operation mode and the complete condensation of bubbles can be achieved by using a counter current flow exchanger.

The insufficient experimental data or lack of a theoretical model, as shown from the literature review, inhibits industrial applications of the three-phase direct contact condenser. This is because of the difficulty in understanding of overall complex heat transfer and hydrodynamics phenomena involved. However, the present research increases the knowledge about the heat transfer characteristics of the three-phase direct contact condenser which is capable of the enhancement of energy recovery from the low-grade heat sources. To do so, the improvement of energy recovery from low-grade heat sources, which deem as promising alternative energy sources, could be accomplished.

In this investigation, an experimental technique and an analytical model are developed to study the heat transfer characteristics of a bubble-type direct contact condenser. The temperature distribution along the column height was found for different light hydrocarbon (pentane) vapour mass flow rate to water (continuous phase) mass flow rate ratios and different initial vapour temperatures.

2. Experimental set-up and procedure

A schematic layout of the experimental test rig is illustrated in Fig. 1. It consists of three main parts; the test column (DCC), the vaporising vessel and the water storage tank with auxiliary equipment. The test section, as a direct contact condenser column, is a Perspex cylindrical column of 70 cm height and 4 cm internal diameter. The heating (vaporising) vessel is a Perspex cylinder of large diameter with ID about 22 cm and height about 13 cm, with two covers fixed tightly on both ends and set on a digital scale to take the initial and the final vessel weights. The vessel contains a copper coil with an internal diameter of about 6 mm and a length of about 7 m, used for heating purposes by carrying hot water as a heating medium from a constant temperature water bath. In addition, the heating vessel is half filled with water. The liquid pentane (C_5H_{12}), its properties are given in Table 1, as a dispersed phase is injected inside the heating vessel using a small feeding tube. This water has two main functions; it helps to make the heat distribution uniform inside the heating vessel and it can be used as a heating medium to maintain an almost constant temperature during dispersed phase vapour injection. The volume and weight of liquid pentane are measured before injection into the heating vessel. A K-type calibrated thermocouple is fixed to the upper part of the heating vessel to measure the dispersed phase (vapour) temperature. In addition, a venting pipe and pressure gauge are fixed on the upper vessel cover. At the same time, about 160 L of water is pumped at a constant temperature from its storage tank as a continuous cooling phase. A calibrated rota meter is used for measuring the continuous phase (water) mass flow rate.

A short isolated pipe, about 3 cm length, is used for connecting the heating vessel with the test section (direct contact column).

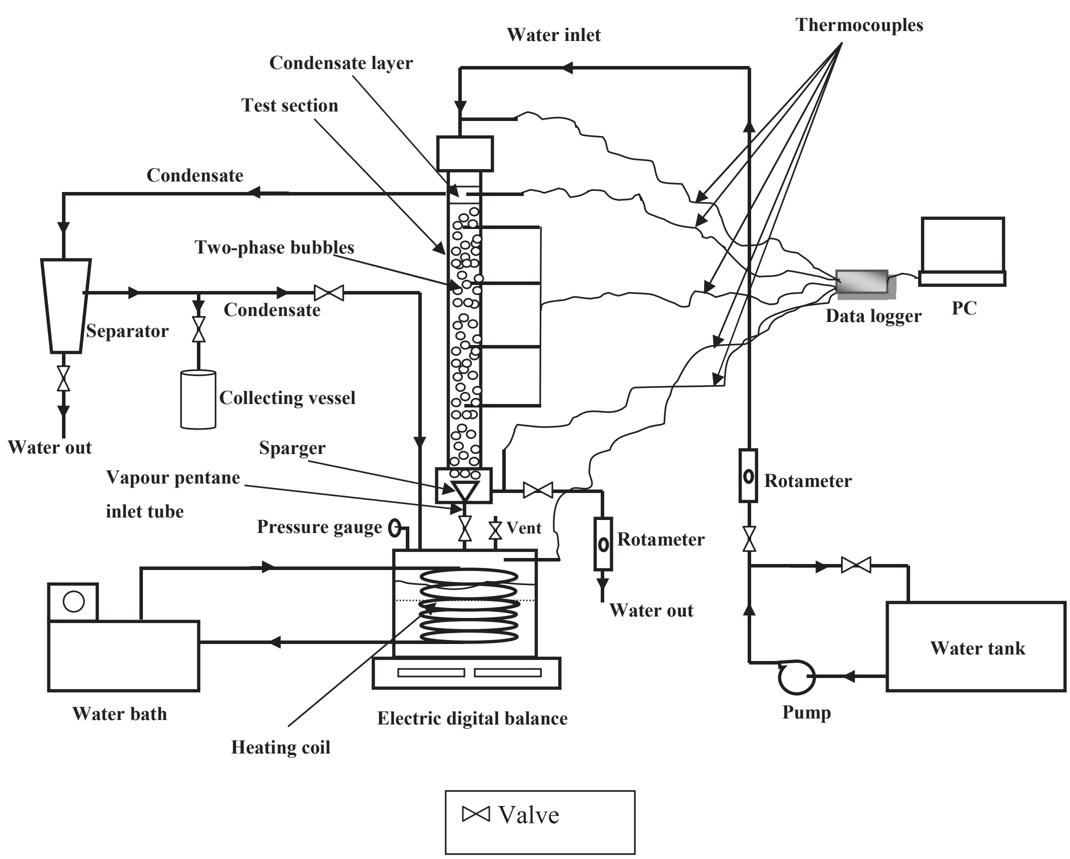

Fig. 1. Schematic diagram of the experimental rig.