



# Heat transfer efficiency and capital cost evaluation of a three-phase direct contact heat exchanger for the utilisation of low-grade energy sources



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## ABSTRACT

Low-grade energy cycles for power generation require efficient heat transfer equipment. Using a three-phase direct contact heat exchanger instead of a surface type exchanger, such as a shell and tube heat exchanger, potentially makes the process more efficient and economic. This is because of its ability to work with a very low temperature driving force, as well as its low cost of construction. In this study, an experimental investigation of the heat transfer efficiency, and hence cost, of a three-phase direct contact condenser has been carried out utilising a short Perspex tube of 70 cm total height and 4 cm internal diameter. Only 48 cm was used for the direct contact condensation. Pentane vapour with three different initial temperatures (40 °C, 43.5 °C and 47.5 °C) was contacted with water with an inlet temperature of 19 °C. In line with previous studies, the ratio of the fluid flow rates was shown to have a controlling effect on the exchanger. Specifically, the heat transfer efficiency increased virtually linearly with this ratio, with higher efficiencies also being observed with higher flow rates of the continuous phase. The effect of the initial temperature of the dispersed phase was shown to have a lower order impact than flow rate ratio. The capital cost of the direct contact condenser was estimated and it was found to be less than the corresponding surface condenser (shell and tube condenser) by 30 times. An optimum value of the continuous phase flow rate was observed at which the cost of the condenser is at a minimum.

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## 1. Introduction

Energy usage is increasing around the world due to the development of technologies and population growth. Recent research revealed that the demand for energy could rise by up to 1.7% annually until 2030 [1]. However, fossil fuels remain the dominant energy source, producing about 80% of the gross energy required, while renewable energy contributes only 11%. Accordingly, many environmental problems such as global warming, ozone depletion and air pollution will increase. Furthermore, the fossil fuel prices will likely rise. Hence, industrial waste energy, especially from low-grade heat sources, for power production has recently received more attention [1]. This can be efficiently achieved by using a direct contact concept.

Most popular heat exchangers that are used in practice are surface type heat exchangers, in which hot and cold fluids are separated completely by metallic barriers. Shell-and-tube heat exchangers are a classic example of this type of exchanger. This, of course, results in a reduction in the rate of heat exchange between fluids and consequently reduces the process's efficiency, and increases the capital and operational costs. As a result, the implementation of such heat exchangers in heat recovery processes, or in low-grade thermal energy cycles for power generation (e.g. in solar energy systems such as solar ponds and solar collectors), is inefficient.

Thus, attempts to enhance the efficiency of conventional heat exchangers have recently received more attention. For example, Dizaji et al. [2] have demonstrated experimentally that the effectiveness of a shell-coiled type heat exchanger is significantly improved by the injection of small air bubbles into the exchanger shell. In the same context, Rashidi et al. [3] studied theoretically the effect of using a porous material inside a conventional heat

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### Nomenclature

$A$	area (m <sup>2</sup> )	$I$	cost index
$D$	diameter (m)	$K_c$	constant appearing in Eq. (7)
$C_A$	cost of equipment of size A (\$)	$M\&S$	Marshall and Swift cost index
$C_B$	cost of equipment of size B (\$)	$\dot{m}_c$	continuous phase mass flow rate (kg/min)
$F_c$	total correction factor	$\dot{m}_d$	dispersed phase mass flow rate (kg/min)
$F_m$	correction factor based on condenser operational pressure	$R$	mass flow rate ratio
$F_p$	correction factor based on the condenser material	$T$	temperature (°C)
$H$	total condenser height (m)	$\Delta T_{lm}$	log-mean temperature difference (°C)
$H_o$	active condenser height (water level) (m)	$U$	overall heat transfer coefficient (kJ/m <sup>2</sup> s K)

exchanger on its performance. Their exchanger was used for a solar energy application. They concluded that using a porous substrate with a high Darcy number can improve the thermal performance of the heat exchanger with an acceptable increase in pumping cost.

Alternatively, a direct contact heat exchanger allows working fluids to come into direct physical contact by eliminating the solid barriers. A high heat transfer rate, an absence of corrosion and fouling problems, a lower cost, a simple design and the potential to work at a very low temperature driving force are the main advantages of using direct contact heat exchangers. Accordingly, they can be found in many applications, for example water desalination, geothermal power generation, solar energy [4–6] and in low cost hydrogen generation from a direct mixing of water or gas hydrocarbons gas with Pb or Pb–Bi heavy liquid metal [7]. The three-phase direct contact heat exchanger (used as an evaporator or condenser) generally operates by injection of drops or bubbles as a dispersed phase into a flowing column of another immiscible liquid, which acts as a continuous phase. The temperature of the continuous phase must be above the boiling point of the drops for evaporation, or less than the saturation temperature of the bubbles in the case of condensation. An intimate mixing of the dispersed phase and the continuous phase can be achieved. The drops or bubbles therefore evaporate or condense directly when they touch the continuous phase, and two-phase bubbles are formed.

The main limitation of the direct contact heat exchanger is that a mutual mixing of fluids occurs due to their intimate direct contact. This necessitates an additional cost for separation. Practically, this problem can be all but eliminated by using two immiscible fluids, separation of which can be achieved using gravity. A second, more problematic, limitation is the difficulty in accurately predicting the direct contact heat exchanger's performance. Due to the mixing of the two fluids, a high, but difficult to predict, interfacial area for heat exchange is created, especially when the process involves bubbles or drops [8]. The difficulty in modelling the extent of this interfacial area means there is a general dearth of specialised mathematical theory and, indeed, experimental measurements or correlations, which can be used for design purposes. This is especially true for condensers. Furthermore, a detailed understanding of the hydrodynamic phenomena is also required if a functional, plant-scale exchanger is to be designed. Such direct contact devices can, potentially, suffer from problems due to flooding and back mixing. Such problems can only be understood, and ultimately overcome, through detailed experimental and theoretical study.

In spite of the great potential of the direct contact heat exchanger for use in fields such as energy recovery and renewable energy it is, somewhat surprisingly [8,9], not widely mentioned in the heat transfer handbooks. Much attention has focussed on the simpler problem of the heat transfer and the hydrodynamics in the direct contact condensation of single bubbles [5,6,10–18] and trains of multiple bubbles [19–22]. Only Sideman and Moalem [23] studied,

theoretically, the parameters that control the performance of a direct contact three-phase condenser. They exploited previous models of the condensation of a single two-phase bubble in an immiscible liquid. Recently, Mahood et al. investigated the three-phase direct contact condenser theoretically [21] and experimentally [24–29]. These studies investigated various characteristics of the thermal performance of a lab.-scale direct contact condenser during both transient and steady state operation. Specifically, the overall volumetric heat transfer coefficient during transient operation [24] was measured. A model was proposed for the steady state temperature distribution, which compared favourably with the experimental measurements [25]. Furthermore, a model predicting the transient temperature profile along the length of the direct contact column was also developed [26]. The effects of various parameters, such as the ratio of the mass flow rates of the continuous and dispersed phases, on the outlet temperatures was also investigated [27]. In addition, the variation of the volumetric heat transfer along the column [28], and the suitability of direct contact condensation for use in desalination were also investigated [29].

These studies produced promising results, which showed the effect of key process parameters on the thermal outputs of the condenser. The specifics of these thermal effects must, however, be considered in totality by investigating the condenser's efficiency and capital cost; it is these parameters that will ultimately determine the industrial relevance of this technology. These two critical measures of exchanger performance have not been investigated previously. Therefore, this work reports these important properties of the three-phase direct contact condenser for the first time.

Specifically, an experimental investigation of the heat transfer efficiency in a three-phase direct contact is described in Section 2. The effects of the operational parameters, such as the dispersed phase mass flow rate, the continuous phase mass flow rate and the initial dispersed phase temperature on the heat transfer efficiency are examined in Section 3. Subsequently, these results are used to estimate the capital cost of the direct contact condenser, which is then compared to the cost of a traditional shell and tube condenser.

## 2. Experimental setup and procedure

A general view and a schematic layout of the experimental test rig are shown in Fig. 1a. The test section is a Perspex cylindrical column with a total height of 70 cm and 4 cm internal diameter. The volume is thus 0.00352 m<sup>3</sup>. Only 48 cm (0.00241 m<sup>3</sup>) was used as the active height (i.e. the height containing the continuous phase) during the experiments. The pentane, in the vapour phase, was introduced into the bottom of the column via a tube of 6 mm internal diameter. Similarly, the continuous phase was removed from the bottom of the column via a tube with 6 mm internal diameter. At the top of the column, a 6 mm tube introduced the

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