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Absorption of steam bubbles in lithium bromide solution

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HIGHLIGHTS

- An experimental bubble absorption column is constructed and operated.
- The absorption of steam bubbles in a hotter lithium bromide solution is tracked.
- A simple ordinary differential equation model is developed to describe the collapse.
- The model is demonstrated to explain 96% of the observed experimental variance.
- Parametric studies are conducted examining factors influencing the rate of absorption.

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ABSTRACT

Absorption heat transformers are thermodynamic cycles that are capable of recycling waste heat energy by increasing its temperature. One of the most important unit operations in a heat transformer is the exothermic absorption of water vapour into a solution of choice at a higher temperature. Bubble columns are potentially an efficient means of achieving this. An experimental analysis is conducted which examines the absorption of single steam bubbles into a concentrated aqueous lithium bromide solution. The bubbles are tracked using a high speed camera, and their rate of absorption is modelled using a simple ordinary differential equation model. Accurate model predictions are obtained when oscillating bubble Nusselt and the Sherwood number correlations are utilised. The proposed model is capable of describing 96% of the observed experimental variability. Very large mass transfer coefficients of approximately 0.0012 m/s are obtained, which is higher than any previously reported values used in heat transformer absorber design.

1. Introduction

Due to rising energy prices and the increasing regulation of industrial emissions, chemical and processing sectors are under ever increasing pressure to increase energy efficiency and to reduce thermal waste. Heat energy is one of the largest sources of industrial energy wastage, with up to 50% of the energy input to this sector leaving in the form of exhaust gases, cooling water, heated products and from surfaces of hot equipment (Johnson and Choate, 2008). Heat transformers are systems which can recover such low grade heat energy. These are closed cycle thermodynamic units, which are capable of increasing the temperature of waste heat streams so that they may be recycled within a plant (Donnellan et al., 2013). Such systems are generally capable of upgrading up to 50% of the energy supplied to them (Ma et al., 2003). In a heat transformer, it is vital to minimise equipment scale, in order to enhance economic feasibility. To do this the efficiency of all units within the cycle should ideally be examined and optimised. It has been demonstrated that the absorber can contribute up to 50% of the irreversibility within a heat transformer (Rivera, 2000), and therefore it is of primary interest in terms of design optimisation. This unit is also one of the most critical ones to the process. In a heat transformer, the absorption of saturated water vapour into concentrated salt solutions at higher temperatures (solutions may be $>50\,^{\circ}C$ hotter than entering steam/water vapour) in the absorber enables the system to increase the temperature of the waste heat energy (Donnellan et al., 2014).

The conventional method of vapour absorption is the falling film method where a lithium bromide solution ($LiBr–H_2O$) flows down either in vertical or horizontal tubes as a thin film while absorbing water vapour from the surrounding environment (Guo et al., 2012). The heat of absorption is removed by a cooling fluid flowing on the inside of the tubes. Several studies have been

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conducted on such falling film absorbers. The Nusselt and Sherwood numbers are correlated experimentally for a vertical falling film absorber by Miller and Keyhani (2001), based upon inlet conditions to the absorber. Heat and mass transfer coefficients of approximately 570 W/(m^2K) and 3.15×10^{-5} m/s respectively are obtained. Alternative designs in which the solution flows on the inside of vertical tubes are shown to not achieve any appreciable improvement in performance (Medrano et al., 2002).

One possible method of increasing the performance of an absorber is to increase the vapour–liquid interfacial surface area. Spray absorbers aim to achieve this by atomizing the LiBr–H_2O solution prior to contacting it with the water vapour. The liquid is sprayed into the top of the absorption vessel through a nozzle, while the water vapour enters from the bottom or side. This arrangement is often found in machines actuated by solar energy. An experimental spray absorber was built by Warnakulasuriya and Worek (2008) and was shown to increase the Sherwood number of horizontal tube absorbers by roughly fourfold while mass transfer coefficients of 6×10^{-5} m/s were reported. Different designs of gravity driven adiabatic absorbers have also been tested and compared (Arzoz et al., 2005). The film flow method (a film of LiBr–H_2O solution falling freely through a vessel containing water vapour) tested achieved the best results in this study, with mass transfer coefficients of $1.5\text{–}2 \times 10^{-4}$ m/s reported. Generating such freely expanding liquid sheets using a conical nozzle has been demonstrated to achieve mass transfer coefficients of up to 7×10^{-4} m/s due to increased mixing in the liquid phase prior to disintegration into droplets (Palacios et al., 2009). A possible disadvantage of such absorbers is however that they require a separate heat exchanger to cool the solution following absorption. This is in contrast to other absorber designs which achieve both cooling and absorption in one single step.

Bubble absorbers aim to achieve a high liquid vapour interfacial area by means of bubbling the vapour stream into the continuous liquid phase. A detailed numerical analysis has been conducted upon the absorption and eventual collapse of a single ammonia bubble in a NH_3–H_2O solution (Merrill and Perez-Blanco, 1997). Very high mass transfer coefficients of 1.15×10^{-3} m/s are reported in that study. The paper demonstrates how the bubble's diameter remains almost constant for the first approximately 0.06 s due to two way mass transfer, but then begins to decrease steadily until finally collapsing. A direct comparison between the performance of a vertical falling film absorber (with NH_3–H_2O solution and water vapour contacting on the inside of the tubes) and the performance of a bubble absorber using the same working fluids has been conducted (Castro et al., 2009). The results show that for the same solution mass flowrate, the bubble absorber always has a higher absorber load and is therefore more efficient. It has been demonstrated in a combined numerical and experimental analysis that in order to minimise its required height, the bubble absorber should be operated in counter-current mode while keeping solution temperature and concentration as well as the entering vapour mass flow rate to a minimum (Lee et al., 2003). A study which aims to examine factors which influence bubble properties during the absorption of ammonia into a NH_3–H_2O solution has found that the residence time of bubbles in the absorber increases with an increase in the initial bubble diameter and the liquid concentration (Kang et al., 2002).

From the above review, it is observed that bubble absorbers have significant advantages over conventional falling film units. However, no bubble absorber operating with LiBr–H_2O solution has yet been tested to the authors' best knowledge, even though this is the most commonly utilised working fluid in absorption heat transformers (Abrahamsson et al., 1997). Much work has been

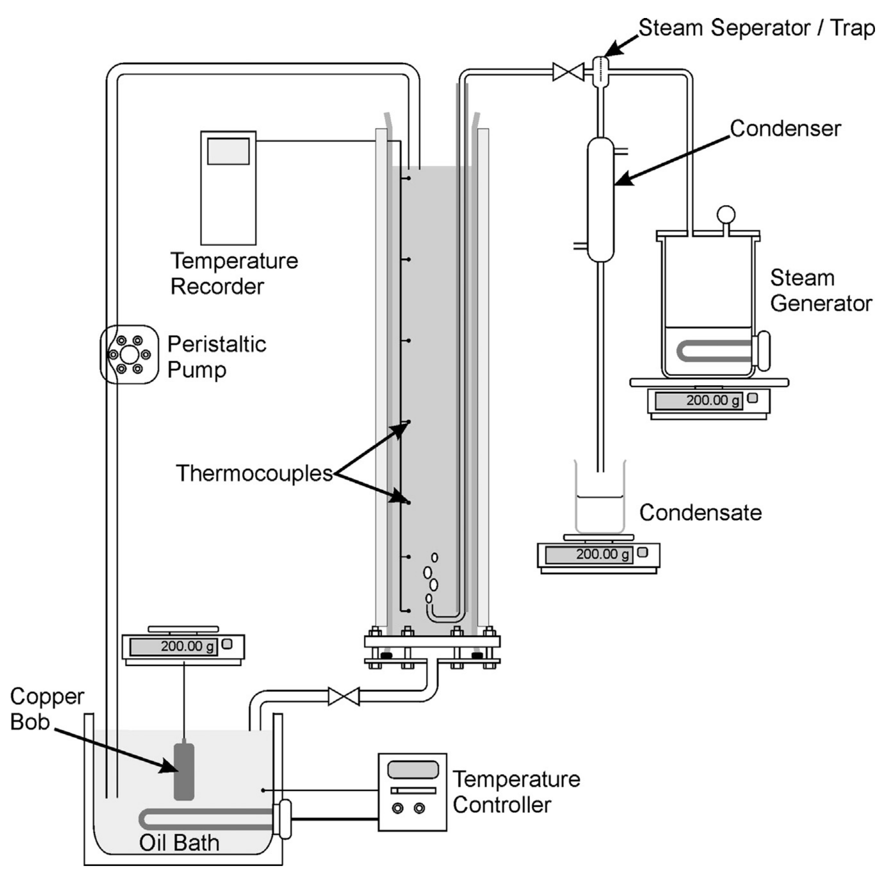

Fig. 1. Schematic of the experimental bubble column developed for study.