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Thermohydraulic characteristics of a multi-string direct-contact heat exchanger

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ABSTRACT

Direct-contact heat exchangers that involve energy exchange between gas and liquid streams have a variety of applications, including waste heat recovery, thermoelectric power plant cooling, and thermal desalination. Direct-contact heat exchangers are appealing as they may help mitigate potential corrosion, fouling, and scaling of solid surfaces and enhance heat transfer effectiveness. In this study, we experimentally investigate the thermohydraulic characteristics of an economic light-weight direct-contact heat exchanger that incorporates an array of strings of diameter of the order of 0.1–1 mm to sustain flows of thin liquid films. We constructed a 1.6 m-tall prototype heat exchanger with an array of as many as 112 vertically aligned strings. Thin films of a non-evaporating liquid are flown down the strings by gravity and exchange thermal energy with a counterflowing gas stream. We obtained axial liquid temperature profiles and frictional loss in the gas stream for different combinations of liquid and gas flow rates and two different string pitches. Numerical simulation is also performed to help interpret and indirectly validate our experimental results. The overall, gas-side, and liquid-side heat transfer coefficients extracted from the experimentally measured temperature profiles are examined to evaluate the impact of instability in liquid film flows and inter-bead spacing. The applicability of the Reynolds analogy is also assessed using the measured gas-stream pressure drops and air-side heat transfer coefficients. The present study helps improve our understanding of heat transfer and gas-stream pressure drop in string-based direct-contact heat exchangers and provides an experimental database to help systematically optimize their design.

1. Introduction

The low thermal conductivity and low volumetric heat capacity of gases makes it difficult to design effective heat exchangers involving gas streams. Direct-contact heat exchangers are good candidates in certain applications, such as indirect dry cooling of thermoelectric power plants; waste heat capture; and heating or cooling of gaseous feed stocks or products in chemical processing. Packed beds are widely used in various direct-contact heat transfer applications [1–3] because their tortuous flow paths help achieve high heat transfer effectiveness. However, relatively high pressure drops experienced by the gas streams and low limits on gas loadings due to liquid flooding remain major challenges [4,5]. Spray columns achieve heat transfer by dispensing small droplets into gas streams [6] but they can experience practical challenges: excess liquid pumping power required for spray generation; potential environmental issues associated with small droplets carried away with gas streams; and degraded heat transfer performance due to short residence time of large droplets [7]. New concepts and designs for direct-contact heat exchangers that can deliver high heat exchanger effectiveness while circumventing these challenges are desirable.

One promising alternative design of direct-contact heat exchangers is a multi-string column schematically illustrated in Fig. 1. Each unit consists of a dense array of vertically aligned polymer strings of radii of the order of 0.1 mm. A heated non-volatile coolant is fed into each unit through top liquid distributors. As it travels along the strings, the coolant is cooled by the counterflowing air stream. The straight and contiguous flow paths in-between the strings are expected to reduce pressure drops experienced by the gas streams than packed beds. At the same time, large gas/liquid interface-to-volume ratios and long residence times enable effective interfacial heat transfer process. The string arrays also limit radial liquid transport, facilitating more uniform liquid distributions. The use of polymer strings also reduces the cost and weight of the heat exchanger.

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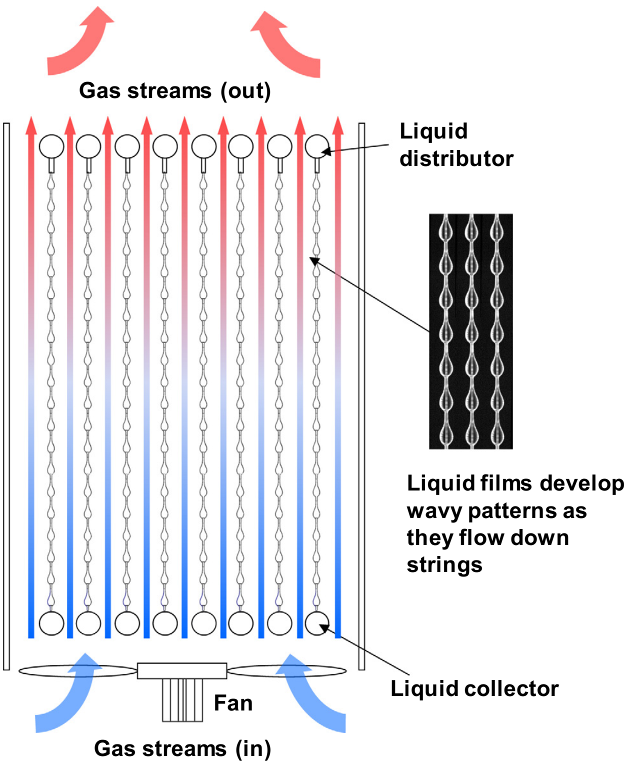

Fig. 1. Schematic of a multi-string heat exchanger unit.

To enable systematic design of the multi-string heat exchanger, we need a rigorous understanding of the fluid dynamics and heat transfer characteristics of liquid films flowing down vertical strings. Most early studies of heat transfer involving liquid films focus on planar surfaces or large diameter tubes [8–19]. Liquid films flowing on highly curved surfaces show wavy profiles due to intrinsic flow instability arising from interplay among surface tension, viscous, inertia, and gravitational force [7,20,21]. Two main flow regimes have been observed. In the Rayleigh-Plateau (RP) regime [22], liquid films develop liquid beads that travel along the string at the same speed with uniform inter-bead spacing. In the Kapitza instability regime [23], liquid films develop beads that travel at different velocities and two successive liquid beads may coalesce [24–26].

Several previous studies investigated liquid films flowing down strings in the Rayleigh Plateau regime for mass transfer applications with counterflowing air velocities below 1 m/s. One such study [27] experimentally investigated the CO_2 absorption by water films. It reported that multi-string mass exchangers achieved higher CO_2 absorption effectiveness than spray columns and packed beds under nominally the same operating conditions. A later study [5] reported the development and validation of an analytical model for the CO_2 absorption performance [27]. Another study [28] developed a numerical model for CO_2 absorption by water/monoethanolamine liquid films along a single string and performed a parametric study on absorption efficiency. More recent studies reported numerical fluid dynamics simulation of liquid films in the Kapitza instability regime under high counterflowing gas loads [29]. These studies also found the CO_2 absorption effectiveness to be higher for liquid films flowing on strings than liquid films on planar surfaces [20].

Migita et al. [30,31] constructed a prototype multi-string mass exchanger containing an array of 109 strings to study CO_2 absorption and gas-stream pressure drop. They demonstrated that multi-string mass exchanger has higher absorption effectiveness and lower pressure drop than conventional packed beds. A more recent study [32] investigated hydrazine absorption by a multistring column, and confirmed the advantage of low air side pressure drop.

Relatively few previous studies focused on heat transfer in multi-string exchangers. Hattori et al. [33] presented an approximate analytical model for temperature distribution along a liquid film flowing down a string in the presence of cross-flows of a cooling gas. A modified version of the model in the counterflow configuration was validated in our previous study using a single-string [34]. A later study [7] constructed an experimental setup consisting of a single string and determined the liquid-to-gas overall heat transfer coefficient. The study reported enhanced heat transfer in wavy films in the Rayleigh-Plateau regime, which was ascribed to enhanced internal mixing. However, the study was limited in that it reported the experiments at one fixed gas velocity and that it did not separate the gas-side and air-side thermal resistance. It also did not explore how convective instability, also referred to as the Kapitza instability, in liquid films flows affects heat transfer.

In the present article, we report our experimental study of a direct-contact multi-string heat exchanger. Although multi-string exchangers can generally be used in applications involving gas-liquid phase changes, such as evaporators and condensers, we will limit ourselves to non-evaporating liquids and non-condensing gases (air) in the present manuscript. We measure axial liquid temperature profiles and gas-stream pressure drop to examine the impact on the thermohydraulic performance of the liquid and air flow rates, instability modes, and string pitch. The applicability of the Reynolds analogy is also examined.

2. Experimental setup and numerical simulation

2.1. Experimental

A schematic of the experimental setup used in the present study is shown in Fig. 2. The setup consists of a vertical acrylic cylinder of diameter 10 cm; a top liquid reservoir; a bottom chamber with flow conditioners to ensure a uniform inlet air stream; and a square array of either 112 polymer strings (7 mm pitch) or 56 strings (10 mm pitch). The polymer strings (R_w = 0.1 mm) are fixed to a metal rod to keep them under tension. The liquid is pumped to the top reservoir, where a cartridge heater with a maximum rating of 2000 W is used to heat the liquid before it exits from the liquid nozzles. After exiting the nozzles, the liquid flows along the strings and is then collected at the bottom. The collected liquid is later recirculated to the top reservoir through a gear pump. Compressed air (inlet pressure ~1.3 bar, temperature ~20.8 °C) is fed into the bottom chamber through four plastic tubes with an inner diameter of 3.8 cm. A variable-area flow meter with a range of 6–60 SCFM is used to measure the volumetric air flow rate. The superficial air velocity is calculated by dividing the measured volumetric air flow rate by the cross-sectional area of the acrylic cylinder.

The liquid nozzles have a diameter of 1 mm and are made of stainless steel. The silicone oil is a well-wetting liquid and tends to rise along the nozzle outer surface, especially during a flow start-up phase where the liquid flow rate is negligible (Fig. 3a). For our nozzles and working fluid, nozzle lengths greater than 2.5 mm are necessary to prevent the liquid from merging with the top plate and forming an undesired liquid puddle that can impede the liquid flow (Fig. 3b). The minimum necessary nozzle lengths are generally smaller for liquids with higher viscosities.

Four groups of 3 micro-thermocouples with tip diameter of 250 μm are placed at three radial locations (i.e. next to 3 different strings) and several axial locations (0.4 m, 0.7 m, 1.0 m, and 1.3 m from the liquid nozzle as indicated in Fig. 2) to measure the liquid temperatures. We position the micro-thermocouples nomi-