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Experimental and analytical performance investigation of air to air two phase closed thermosyphon based heat exchangers

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ABSTRACT

In recent years, the use of wickless heat pipes (thermosyphons) in heat exchangers has been on the rise, particularly in gas to gas heat recovery applications due to their reliability and the level of contingency they offer compared to conventional heat exchangers. Recent technological advances in the manufacturing processes and production of gravity assisted heat pipes (thermosyphons) have resulted in significant improvements in both quality and cost of industrial heat pipe heat exchangers. This in turn has broadened the potential for their usage in industrial waste heat recovery applications. In this paper, a tool to predict the performance of an air to air thermosyphon based heat exchanger using the ε-NTU method is explored. This tool allows the predetermination of variables such as the overall heat transfer coefficient, effectiveness, pressure drop and heat exchanger duty according to the flow characteristics and the thermosyphons configuration within the heat exchanger. The new tool's predictions were validated experimentally and a good correlation between the theoretical predictions and the experimental data, was observed.

1. Introduction

Over the past 20 years, climate change has established itself as the greatest driving force for innovation in the industry for the first time in over two centuries [1–5]. This fact has forced engineers and designers to go for more sustainable and efficient energy systems designs in built environment [6] and process industries [7,8]. In the 21st century, every corporation must be aware of the environmental damage it may cause through its actions; actions, which may come in many interchangeable forms, namely waste [9,10], radiation [11], greenhouse gases [1] and/or heat [12–15]. With regards to heat energy, when released from a hot exhaust, it can be reutilised and/or recycled by heat exchangers [16–18] for re-use within industrial processes or for district heating of neighbouring communities.

Heat exchangers are devices that, as the name states, are able to extract heat from where it is unwanted and transfer it to where it may be usefully applied [19–21]. They can be found essentially everywhere in modern industry due to current environmental policies [22], adopting different shapes depending on their application including the thermosyphon based designs [15,23], which is the topic of this paper.

Heat transfer within a thermosyphon heat exchanger, instead of being done through a solid boundary, is facilitated through the use of two phase closed thermosyphons. A thermosyphon consists of a hermetically sealed evacuated tube partially filled with a working fluid. The working fluid enters a permanent state of evaporation-condensation the moment there is a temperature difference between the top and the bottom sections of the pipe. A high amount of heat can be transferred through the phase change processes that are constantly taking place within the thermosyphon during the working fluid evaporation/condensation cycles. This characteristic is the key to these devices' high effective thermal conductivity, allowing them to have an equivalent thermal conductivity of one to two orders of magnitude higher than that of copper [15].

The working cycle of a thermosyphon (Fig. 1) starts when heat is added to the evaporator section (bottom). The working fluid readily absorbs the heat and evaporates, travelling to the condenser section (top) in a gaseous form. By making contact with the cold wall of the tube in the condenser section, the working fluid condenses, transferring all the energy it had absorbed to the wall and flowing back down to the evaporator section, thus repeating the cycle. In

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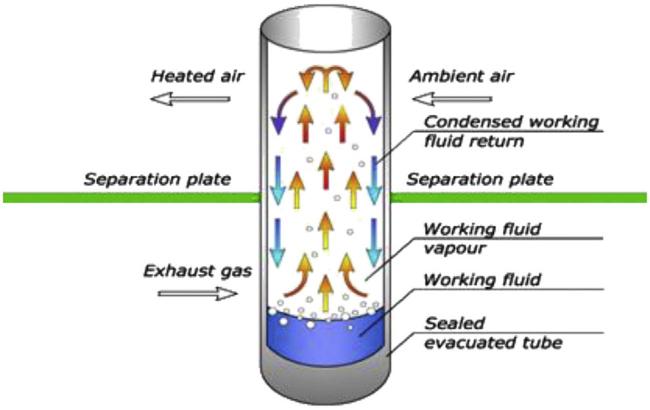

Fig. 1. The thermosyphon's working cycle.

wickless heat pipes, it is essential for the condenser section to be located above the evaporator section, hence the alternative name "gravity-assisted heat pipes". Heat pipes can also be equipped with a wick structure, having the advantage of being able to transfer heat even when turned upside-down, as the condensate is returned to the evaporator via capillary action forces [15]. Heat pipes have been tested and proven in the thermal management of electronics and in the space industry [24,25], in heat storage systems [23,26,27], in renewable energy [28,29] and in waste heat recovery [30–32].

When equipping heat exchangers, thermosyphons are often preferred to heat pipes especially due to the reduction in costs coming from the absence of a wick structure [32]. The advantages of thermosyphon heat exchangers over conventional heat exchangers include a good flow separation, no additional power input to the system, high reliability [12,17,33,34], lower initial investment and operating costs [16,35], the ability to work at lower temperature differences [35] and a contingency plan – if a pipe or number of pipes were to fail, the heat exchanger would remain operational [16,20]. Their application is not limited to waste heat recovery in the industrial domain; in fact, heat pipe technology utilisation has spread to ventilation and air conditioning [13,16,21,33,36–38], solar collectors [39] and even water desalination systems [20].

Air to air cross-flow thermosyphon based heat exchangers have been of interest to many researchers. It can be seen from the literature that there are many methods available to gauge the performance of these devices [12,13,16,18,40]. In this paper, the ε-NTU (Effectiveness-Number of Transfer Units) method is used to develop a prediction tool of the thermal performance of a thermosyphon based air to air heat exchanger. Using this method, Jouhara and Merchant [16] have investigated a thermosyphon heat exchanger with respect to its inclination and it was found that this type of heat exchanger performed better as it became closer to the vertical inclination. Noie [18] also used the ε-NTU method and arrived at the same conclusion; but he also found that the minimum effectiveness for a heat exchanger with this specific geometry is encountered when the heat capacity is the same for both hot and cold flows; if the flows consist of the same gas, the minimum effectiveness will be found when the mass flow rates are equal. It was also found that the accuracy of prediction methods increased with increasing the inlet velocity. In other studies, different working fluids [40] and different filling ratios [41] have been experimentally studied in similar heat exchangers as well as different sets of variables, such as EHD (electrohydrodynamics) [42]. In addition, similar investigations for such systems were also reported for solar collectors' applications [39].

In this paper, the ε-NTU method is used to measure the performance of the heat exchanger and to predict the temperatures and flow conditions between the rows of thermosyphons within the heat exchanger. A computational model is then created, based on the experimental work, with the purpose of predicting the performance of the cross-flow thermosyphon-equipped gas-to-gas heat exchanger with reliable accuracy. It is believed that the reported modelling approach of thermosyphon based air to air heat exchangers will provide a straightforward and useful tool to engineers and researchers working in this area to help them designing such systems.

2. Test facility design

Fig. 2 shows a photo and a schematic of the tested heat exchanger. The characteristics of the heat exchanger were studied experimentally in order to validate the heat transfer ε-NTU based model that will, besides allowing the determination of the overall heat transfer coefficient and effectiveness, enable the prediction of the air stream temperature between any two thermosyphon rows. In order to gather the necessary data, different test parameters were experimented upon where the hot and cold air streams velocities varied from 0.3 m/s to 0.5 m/s with mass flow rates of up to 1 kg/s. The hot air temperature varied up to 120 °C while the cold air stream temperature varied up to 30 °C.

As can be seen in Fig. 3, the inlet air flows were driven by fans, which were connected in series and powered by electric motors. The fan's speed was adjusted in order to control the hot and cold inlet air mass flow rates. The air blown across the fan would then be forced through the air filter and cooled to the required temperature by travelling through the water temperature control framework. After passing through the flow straightening fitting, the cold air was directed to a nozzle and then to the condenser section of the thermosyphon heat exchanger.

After being heated in the condenser, the air would then flow through the water heater in order to help preheat the incoming air to the evaporator to the desired inlet temperature. The heated air would then flow through the straightening fitting and through the nozzle, and then would be allowed to pass through the evaporator section of the heat exchanger. An additional measuring outlet was provided, which served to further measure the mass flow rate of the air after passing through the heat exchanger, allowing an estimation of the potential air leakage from one stream to another within the tested parameters.

The static and dynamic pressures were measured at specific points before and after the heat exchanger using micro

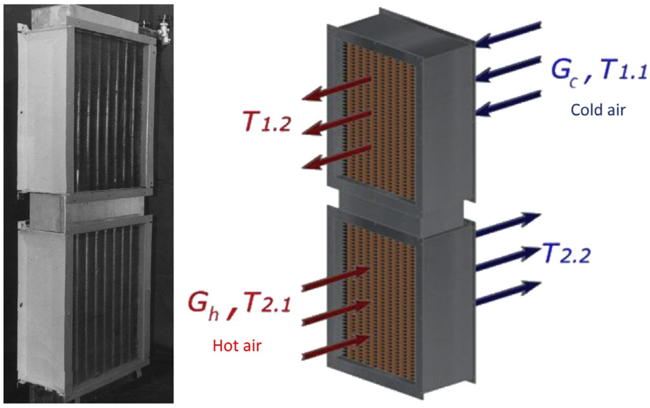

Fig. 2. A photo and an illustration of the thermosyphon heat exchanger from an isometric perspective.

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