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Effect of air temperature non-uniformity on water–air heat exchanger thermal performance – Toward innovative control approach for energy consumption reduction

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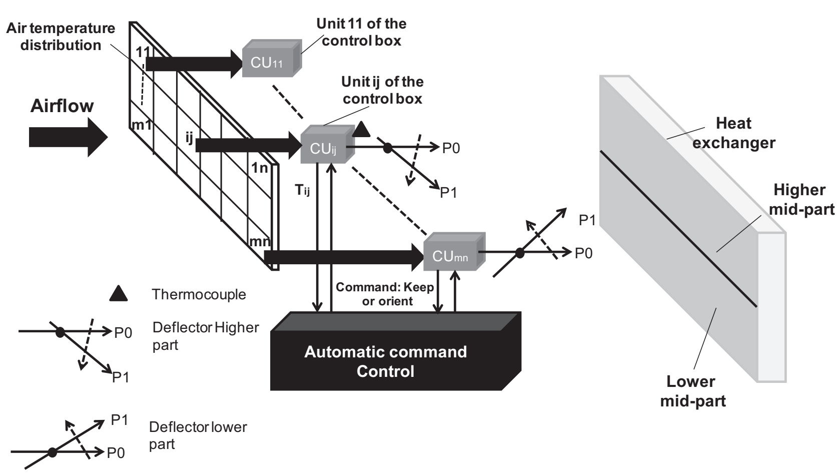
HIGHLIGHTS

- Air temperature distribution affects air–water heat exchanger thermal performance.
- This effect is modeled using an in-house computational code.
- Non-uniformity in air temperature can increase or decrease the thermal performance by up to 5%.
- A new control approach is proposed to optimize the thermal performance.
- For a vehicle running 3 h, the new control approach reduces the fuel consumption by up to 1.34 L.

GRAPHICAL ABSTRACT



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ABSTRACT

Parametric numerical analysis that explores the relation between the non-uniformity of air temperature distribution upstream of a heat exchanger and its thermal performance is performed. The obtained numerical results are employed toward the optimization of water–air heat exchanger thermal performance. Furthermore, the numerical results lay out the foundation to develop an innovative control approach for monitoring the airflow upstream of a cross-flow water–air heat exchanger that lead to the optimization of its thermal performance and energy consumption. Consequently, an in-house computational code is established to evaluate the aforementioned thermal performance based on known parameters; namely, distribution of upstream velocity and temperature of an air–liquid heat exchanger, the flow rate of heat exchanger liquid, in addition to the inlet liquid temperature. It was observed that non-uniformities in air temperature can, depending on the configuration, increase or decrease the thermal performance of a heat exchanger up to 5%. Additionally, controlling air temperature non-uniformities, the fuel consumption and carbon dioxide emission can be reduced by up to 0.97 kg (1.34 L) and 3.17 kg respectively for a vehicle running three hours per day.

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1. Introduction

Heat exchangers HXs are mainly categorized according to the mode of interaction between the cold and hot streams [1–3] or depending on the considered application. Heat recovery is one of the domains where the heat exchanger is the main component [4–6]. Another domain of application for heat exchanger is geothermal energy [7–9]. Heat exchangers are also studied in cooling processes [10–12]. Performance of heat exchangers is analyzed either numerically [13–15] or experimentally [16–18].

Some of the familiar types of heat exchangers are the tubes-and-fins heat exchangers, shell-and-tube heat exchangers, counter-flow channels and micro-channels, reactors, and multi-functional heat exchangers. Heat exchangers of tubes-and-fins types are commonly used in many widespread industrial applications, particularly the automotive industry, heating, ventilating, and air conditioning. This is mainly because of their light weight, high thermal efficiency, and compactness. As depicted in Fig. 1, the tubes-and-fins heat exchangers are cross-flow heat exchangers composed of numerous tubes of elliptical geometry over which several continuous parallel fins are positioned. These exchangers are the most commonly used water–air heat exchangers where water flows through the elliptical-section tube and air through the exchanger fins. The thermal performance of these types of heat exchangers is tremendously dependent on the topology of the upstream airflow, the liquid flow in the exchanger, and the air temperature distribution upstream of the exchanger. Indeed, when integrated into a space of complex geometry, such as an engine compartment of an actual vehicle, water–air heat exchangers are continually subjected to non-uniform air velocity and temperature distributions. Furthermore, all heat exchangers are usually assembled with the fan to form what is called "Cooling module", as shown in Fig. 2. This causes some of the heat exchangers to be in contact with hot air flow at its upstream. However, non-uniformities in velocity and temperature, in addition to operational method implemented in each of the aforementioned heat exchangers makes the thermal performance of heat exchangers strongly dependent on several parameters. The most weighing among them are the air flow, water flow, the air and water temperatures, as well as the geometry of the heat exchanger and its position.

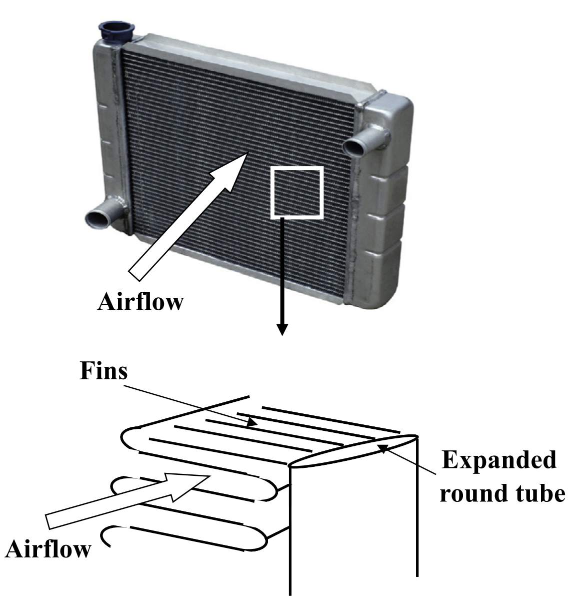

Fig. 1. Tubes-and-fins heat exchanger.

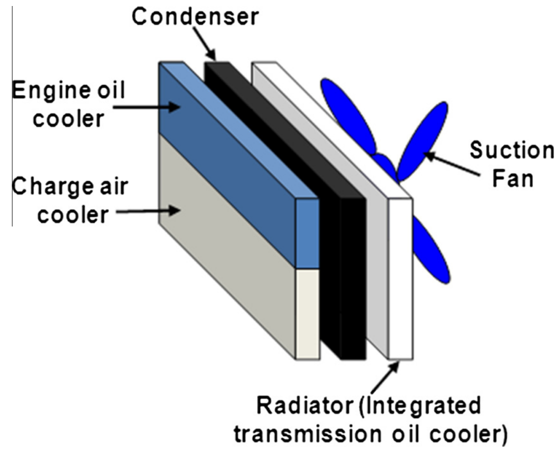

Fig. 2. Illustrative schematic of a vehicle cooling module.

In 1997, Kou and Yuan [19] investigated the effect of temperature distribution on the heat performance of a direct transfer type heat exchanger with two hot fluids and one cold fluid. They declared that the inlet temperature non-uniformities increase the heat performance of the heat exchanger.

In 1998, Kou and Yuan [20] revealed that the thermal performance of heat exchangers is decreased by longitudinal wall conduction and non-uniform inlet temperatures.

In 1999, Ranganayakulu and Seetharamu [21] employed finite element analysis to investigate the effectiveness of a cross-flow plate-fin compact heat exchanger and its deterioration due to the combined effects of longitudinal heat conduction, flow non-uniformity and temperature non-uniformity for various design and operating conditions of the exchanger. It was found that the thermal performance variations are quite significant in some typical applications.

In 2002, Guo et al. [22] studied theoretically and experimentally the effectiveness of different types of heat exchangers in relation with the uniformity of the temperature difference field and showed that the more uniform the temperature difference field is, the higher the thermal performance effectiveness of the heat exchanger. Heat exchanger effectiveness for the best flow distribution was found to be 11.2% greater than that of the conventional flow distribution without associated increase in pressure drop.

In 2008, Mishra et al. [23] utilized finite difference method to observe transient temperature response of a cross-flow heat exchanger as a function of temperature and flow non-uniformity at different input conditions. Transient temperature responses are found to be dependent on the relative position of the individual temperature streams and the position of the fluid moving device for the temperature and the flow non-uniformity as well.

In 2011, Chin and Raghavan [24] showed that the thermal performance of a tubes-and-fins heat exchanger is found to be noticeably affected by mean, standard deviation and skew but not the kurtosis of an air flow mal-distribution profile.

Kærn et al. [25] studied numerically the effect of mal-distributions in inlet liquid/vapor phase, feeder tube bending and airflow distributions on the evaporator performance. They showed that mal-distribution reduced the cooling capacity and the coefficient of performance of the system.

In 2013, Huang and Wang [26] suggested optimum designs for yielding the uniform tube flow rates of a three-dimensional U-type compact parallel flow heat exchanger. Mao et al. [27] conducted CFD analysis of the performance of multi-louvered fin and flat tube heat exchanger under airflow mal-distribution. The results indicate that airflow mal-distribution affects the condensation capacity,