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Research Paper

Thermal characterisation of compact heat exchangers for air heating and cooling in electric vehicles

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ABSTRACT

The use of air conditioning in all-electric cars reduces their driving range by 33% in average. With the purpose of reducing the energy consumption of the vehicle and optimising the performance of the batteries, the mobile air-conditioning can be integrated with the temperature control system of the powertrain by means of a coolant loop. In such layouts, the air-to-coolant heat exchangers must operate efficiently in both air heating and cooling modes. Dynamic simulation tools comprising the entire thermal system are essential to assess its performance. In this context, fast but accurate models of the system components are required.

This paper presents the thermal characterisation of a commercial compact louvered-fin flat-tube heat exchanger (heater core) for this novel application, based on an experimental campaign comprising 279 working points that reflect real air-conditioning (heating and cooling) working conditions. A general methodology to fit a single correlation of the global heat transfer coefficient for both dry and wet working conditions is explained. The semiempirical correlation developed is employed in a single-node model of the heat exchanger that requires minimal computation time. The present model predicts the heat transfer rate with an average deviation of 3.5% in the cases with dehumidification and 1.9% in the cases when the heat exchanger remains dry.

1. Introduction

The use of the air-conditioning (AC) in electric cars decreases the driving range by 33% considering an average use [1]. Compared to conventional cars, all-electric cars face an additional challenge: the waste heat from the powertrain of all-electric vehicles is not enough to provide a comfortable environment in winter. Electric heaters have been traditionally employed for warming the air inside the cabin, leading in winter to a reduction in the autonomy of the vehicle up to the 50% [2]. In order to shorten the energy consumption due to the AC and hence extend their autonomy, the most recent commercial all-electric cars already include reversible heat pumps (RHP).

A step further in this direction is to integrate the thermal management system of the powertrain with the cabin AC system. This concept enables not only to recover the waste heat from the electric components, namely the power electronics, the electric motor and the batteries, but also to control their temperature in order to achieve an optimum performance. Several architectures that integrate the electric vehicle thermal systems have been proposed and tested [3]. A convenient solution is to employ a coolant loop to communicate the different components with the cabin and the ambient air, as proposed for instance by Leighton [2], Kowsky et al. [4] or Zhou [5]. In such layouts, reducing the length of the lines and the number of heat exchangers is essential to minimise weight, volume and thermal losses. Therefore, the air-to-coolant heat exchangers must operate efficiently in both heating and cooling modes, under dry and wet conditions.

Compact louver-fin flat-tube heat exchangers (HEXs) are widely employed in automotive applications, consequently there are numerous studies about their performance especially under dry conditions, as reviewed by Park and Jacobi [6,7]. Finding general laws for compact HEXs is difficult given their complex fin geometries. Park and Jacobi [7] provided a comprehensive characterisation of the thermo-hydraulic performance of the air-side of compact HEXs under dry and fully wet conditions. They developed Colburn j- and friction factor correlations to predict the louver-fin flat-tube HEX performance as a function of its geometry, however their accuracy is limited by the complexity of the phenomena and the large number of parameters to be considered. Partially wet

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Nomenclature

A	surface [m^2]
A_c	cross-sectional surface [m^2]
c	specific heat capacity [$J\ kg^{-1}\ K^{-1}$]
d_h	hydraulic diameter [m]
e	thickness [m]
H	height [m]
h	convection coefficient [$W\ m^{-2}\ K^{-1}$]
i	specific enthalpy [$J\ kg^{-1}$]
k	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
L	tube length [m]
$\dot{m}$	mass flow rate [$kg\ s^{-1}$]
n_{pass}	number of passes per tube [–]
NTU	number of Transfer Units [–]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
Q	heat transfer rate [W]
R	heat capacity ratio [–]
Re	Reynolds number [–]
T	temperature [K]
U	global heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
W	width [W]
ε	effectiveness [–]
μ	viscosity [Pa s]
η	efficiency [–]
δ_l	louver angle [deg]

Subscripts

air	air side
dew	dew point
dry	dry conditions
fin	fin
in	inlet
m	mean
out	outlet
p	constant pressure
s	surface conditions
sat	saturation
tube	tube
w	coolant side
wall	tube wall
wet	wet conditions

conditions are avoided in that study, nevertheless they are usual in air cooling applications. More recently, Jokar et al. [8] presented a test facility consisting of an automotive RHP with secondary coolant loops in which five different air-to-coolant compact HEXs were tested. The discussion of the results focuses on the coolant side and the effect of condensation on the air side is not analysed. Vaisi et al. [9] studied two types of louvered fins configurations in an automotive radiator, but the temperature working conditions differ significantly from those of the air-conditioning applications. Xu et al. [10] compared the performance of compact HEXs with wavy and louvered fins under wet and frosting conditions working as evaporators. Automotive condensers and evaporators were also measured and compared by Liang et al. [11] under dry and wet conditions. In their study, Liang et al. [11] assessed about the suitability of the existing correlations for the prediction of the air-side heat transfer performance of these HEXs by means of a multi-node model.

In vehicle applications, simulation tools comprising the entire AC system are essential to assess its performance under a wide range of dynamic working conditions. All the loops and the electrical auxiliaries shall be included in the models in order to find the synergies among the components [12]. Grey box models offer a compromise between generalisation capabilities, accuracy and simulation time [13]. In this context, single-node or lumped parameter models of the HEXs are more convenient than multi-node or distributed parameter models due to its simplicity and speed. However, the traditional effectiveness approach is not accurate when the HEX works under dynamic dry and wet conditions, in which the boundary between the dry and wet surfaces moves. Several authors have developed simple dynamic HEX models for cooling coils with dehumidification [14–16]. Among them, the approach by Braun et al. [14] has demonstrated a good accuracy with minimal modelling effort and computation time.

In this paper, the thermal characterisation of a commercial compact louver-fin flat-tube HEX under dry and wet conditions is presented. The measured air-to-coolant HEX is intended for a novel application in both heating and cooling of an electric minibus cabin. With this purpose, a comprehensive experimental campaign has been carried out as a part of the European ICE Project FP7 [17]. Rather than analysing the performance of the selected geometry as previous studies did, the present work focuses on the operating conditions of the HEX. As a novelty, partially wet working conditions that are usual in air-conditioning applications are intentionally included and analysed. From these results, a methodology to fit a single everywhere correlation of the global heat transfer coefficient of the compact HEX for both working modes is explained. The developed correlation can be employed to build a semiempirical HEX model that considers dehumidification, based on the approach by Braun et al. [14]. The present model has provided excellent validation results and is useful for its integration a dynamic model of the entire mobile AC system [18].

2. Experimental method

In the European ICE Project FP7 [17], an innovative air-conditioning system for an electric minibus was developed. Specifically, the project addressed the design of a magnetocaloric heat pump that was intended for replacing the vapour-compression heat pump in a water-to-water layout. For compatibility reasons, the rest of the components of the air-conditioning system were kept the same regardless of the heat pumping technology employed [19]. Fig. 1 shows a scheme of the designed system, which included the water-to-water heat pump (HP), the power electronics of the vehicle (PE) and two intermediate coolant loops in which the air-to-coolant HEXs had to work in both cooling and heating modes. Three units of the commercial compact HEX A51-KS423 by the ICE Project partner MAHLE Behr (Figs. 2 and 3 and Table 1) were chosen for the coolant loop to the minibus cabin. This model is a louvered-fin flat-tube aluminium heat exchanger is used more commonly as heater core.

The thermal behaviour of a HEX depends on its geometrical characteristics and on the conditions of both flows. An experimental campaign was carried out by MAHLE with the purpose of characterising the thermal performance of this HEX for its novel use in air-conditioning applications, for both heating and cooling of a vehicle cabin. In order to obtain on-board performance data, the HEX was mounted inside one of the HVAC units of the minibus,