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Research paper

# Experimental and simulation study on the air side thermal hydraulic performance of automotive heat exchangers

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## HIGHLIGHTS

- Automotive heat exchangers with different fin heights were examined experimentally.
- Distributed parameter models for automotive heat exchangers were developed.
- Models were validated by comparing the results to those derived from Coil Designer.
- Feasibility study was made on correlations for louvered surface.

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## ABSTRACT

Flat tube heat exchangers with louvered fins were applied in order to meet the performance requirements and compactness in automotive air conditioning systems. Experimental and simulation study focusing on the air side thermal hydraulic performance of automotive heat exchangers were performed in this article. Test results showed that the heat capacity of a condenser with 5.4 mm height louvered fins can be 3.0%–8.6% higher than the 8 mm fin height condenser of the same size. Automotive evaporator can have 9.3% volume reduction by using short louvered fins while retain the same cooling capacity. Distributed parameter models were developed for automotive heat exchangers and effectiveness NTU method was used to calculate the heat capacity. The models were validated by comparing the results to those calculated *via* Coil Designer 3.6. Verification has been done for several well-known correlations used for the calculation of thermal hydraulic performance of wet and dry louvered surfaces. The correlations were evaluated by comparing calculations with test data of 24 different specimens under typical automotive heat exchanger working conditions. It was concluded that the existing correlations can give satisfactory predictions for heat capacity of condensers and evaporators, and air side pressure loss of condenser. However, further study on the friction characteristic of wet louvered fins is still needed.

## 1. Introduction

There are high requirements on compactness and good performance of heat exchangers (HXs) for limited space applications, such as automotive air conditioning systems. In recent years, increasingly restrictive emission regulations and demand for energy saving has drawn intensive attention, as well as the passengers' requirements for thermal comfort. One effective solution is to use high performance HXs. The most commonly used methods for developing high performance HXs are increasing heat transfer area by increasing fin density and strengthening turbulence by using enhanced fins like louvered, wavy fins. Round tube-and-fin, laminated and serpentine HXs have also been used in automotive air conditionings. In the last century, parallel flow HXs consist of louvered fins brazed to multi-port flat tubes were developed, with merits including compactness, low refrigeration charge, light weight and low cost. They have replaced traditional HXs and were widely applied in the automotive industry.

Simulation model has been considered as an effective tool in design and optimization of HX for cutting experimental work and the manufacturing cost of samples, and has the ability to clarify some parameters that can't be measured directly during tests such as refrigerant quality and heat transfer coefficient. Models used to describe the HXs can be mainly divided into three types: lumped

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## Nomenclature

| | |
|---|---|
| $A$ | surface area (m$^2$) |
| $C$ | specific heat (J kg$^{-1}$ K$^{-1}$) |
| $c_p$ | specific heat at constant pressure (J kg$^{-1}$ K$^{-1}$) |
| $Dh$ | hydraulic diameter of air passage between fins (m) |
| $f$ | friction factor |
| $Fd$ | fin width (m) |
| $Fh$ | fin height (m) |
| $Fl$ | fin length (m) |
| $G$ | mass flux (kg m$^{-2}$ s$^{-1}$) |
| $h$ | heat exchange coefficient (W m$^{-2}$ K$^{-1}$) |
| $i$ | moist air enthalpy (J kg$^{-1}$) |
| $j$ | colburn factor |
| $k$ | thermal conductivity (W m$^{-1}$ K$^{-1}$) |
| $l$ | length (m) |
| $Ll$ | louver length (m) |
| $Lp$ | louver pitch (m) |
| $m$ | mass flow rate (kg s$^{-1}$) |
| $Nbl$ | number of louver banks |
| $Np$ | number of ports in every flat tube |
| $NTU$ | number of heat transfer units |
| $Ph$ | port height (m) |
| $Pw$ | port width (m) |
| $Q$ | heat capacity (W) |
| $Re$ | Reynolds number |
| $t$ | temperature (°C) |
| $Tl$ | tube length (m) |
| $Tp$ | tube pitch (m) |
| $Tw$ | tube width (m) |
| $U$ | overall heat transfer coefficient (W m$^{-2}$ K$^{-1}$) |
| $X_i$ | independent measurement |
| $y_w$ | thickness of water film (m) |

*Greek letters*

| | |
|---|---|
| $\delta$ | thickness (m) |
| $\rho$ | density (kg m$^{-3}$) |
| $\varepsilon$ | effectiveness |
| $\eta$ | fin efficiency (–) |
| $\theta$ | louver angle (°) |
| $\Delta P$ | pressure drop (Pa) |

*Subscripts*

| | |
|---|---|
| $a$ | air/air side |
| $f$ | fin |
| $i$ | inside |
| $in$ | inlet |
| $o$ | outside |
| $r$ | refrigerant/refrigerant side |
| $s$ | saturation |
| $t$ | tube |
| $w$ | water |
| $wet$ | wet condition |

parameter model, zone model and distributed parameter model [1]. The lumped model and zone model are simple and usually applied in cases where quick calculation speed are required. The distributed model divides the HX into several calculation cells, which has the ability to look into the geometric details (including manifolds, flow arrangement, fins and the tubes) and has higher accuracy. So it is commonly used for HX performance prediction.

There are several factors that affect the model's accuracy: (a) refrigerant distribution, (b) air distribution, and (c) air side and tube side heat transfer coefficients. The commonly used perforated baffles can effectively enhance the uniformity of flow distribution in headers, but neglecting the pressure drop in header will lead to unreasonable calculation of mass flow rate. Tuo and Bielskus [2] found model which reflects refrigeration distribution provides better prediction for cooling capacity and outlet superheat. Some more researchers have studied and proposed methods to calculate flow distribution for HXs [3–6]. And non-uniform air flow has been a necessary consideration in models for HXs [7,8]. In a HX model, the most important source of uncertainty comes from the correlations employed for the air and refrigerant side heat transfer coefficients [9]. Various correlations for condensing and evaporating have been proposed to predict the two phase heat transfer rate. Some widely used correlations were evaluated depending on their deviation to test data [9,10]. Actually, for HXs used in vapor compression refrigeration systems, the air side thermal resistance accounts for more than 80% of the overall thermal resistance, so the calculation of air side heat transfer coefficient is more critical to the model's accuracy.

The study on the thermal hydraulic performance of louvered surface has been a hot topic [11–22]. Davenport [11] studied 32 louvered surfaces and found fin performance is more relevant to Reynolds number based on louver pitch than that based on the hydraulic diameter of air passage between fins. Study from Achaichia and Cowell [12] showed the air flow turns from louver-directed to duct-directed as the Reynolds number reduces. Lots of correlations can perfectly predict performance based on their own test data, but they fail to offer accurate prediction for test data from other researchers. In light of this, Chang and Wang [13,14] collected data from 9 independent laboratories, and regression analysis was performed to obtain generalized correlations for louvered fins. Based on the most comprehensive experimental database in the literature, including 1030 heat transfer and 1270 pressure drop measurements, Park and Jacobi [17] tried to develop new form of formulas that can reflect all parametric effects found in database. Correlations under wet condition for louvered fins are limited. Kim and Bullard [18] performed an experimental study for 30 louvered fin HXs under wet conditions. They found that the sensitive heat transfer coefficient is smaller than that for the dry surface at low air velocity for large louver angle and fin pitch, while it is larger at high face velocity. Park and Jacobi [19] developed two forms of empirical correlations for wet condition, one uses wet-surface multipliers and the other are standalone j- and f-factors. Geometrical parameters of studied louvered fins from related researchers are listed in Table 1. Schematic diagrams of a typical automotive evaporator and constructions of louvered fin are shown in Fig. 1.

A typical louvered fin has nine or more geometrical parameters relevant to their air side performance, which means a large and diverse database is imperative to obtain accurate and reliable correlations for louvered fins. To guarantee the generality of correlations, generally, all test data are used to develop formulas, i.e., the same database is used for development and validation of new correlations, it is somewhat less convincing. Automotive HXs have their own geometrical features such as low fin height and small fin width. The fin height used in automotive HXs is usually less than