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Improved correlations of the thermal-hydraulic performance of large size multi-louvered fin arrays for condensers of high power electronic component cooling by numerical simulation

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A R T I C L E I N F O

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A B S T R A C T

In view of a good thermal performance of the multi-louvered fin arrays, it is intended to introduce the special fin structure into the design of condensers for high power electricity converter cooling on the CRH (China Railway High-speed) trains in order to improve the security of normal running for the high-speed trains. The geometrical size of the multi-louvered fin arrays needed for the high power condensers is relatively larger than that of the conventional louvered fin arrays and the flow state within the large size multi-louvered fin arrays is different as well, with the Reynolds numbers based on the louver pitch over the range of 2850–11,000 in the present study. Flow and heat transfer characteristics of the large size multi-louvered fin arrays with various structural parameters are numerically simulated using Large Eddy Simulation (LES). More reasonable parameters correlated with the thermal-hydraulic performance of the large size multi-louvered fin arrays are identified compared to the conventional characteristic parameters employed in the published work. Finally, improved correlations for the Fanning friction f factor and the Colburn-j factor representing the flow and heat transfer characteristics, respectively, are put forward in terms of the identified parameters with special interval bounds for the condenser design of high power electronic cooling.

1. Introduction

Compact heat exchangers with multi-louvered fin arrays (also called parallel flow heat exchangers) are widely used for automotive and air-conditioning cooling due to their good thermal performances [1–5]. Investigations show that the high performance of the multi-louvered fin arrays compared to smooth fins are attributed to the continuous interruption of flow boundary layer by the extended louvered fins [2,6]. In view of a good performance of the louvered fin arrays, it is intended to introduce the special fin structure into the design of condensers for high power electricity converter cooling on the CRH (China Railway High-speed) trains. The high power electricity converter as a power electronic component on the CRH trains, needs to be cooled down during operation in order to sustain normal running of the high-speed trains. Once the monitored core temperature in the converter achieves an upper limit temperature (usually 80–85 °C), the converter will be compulsorily stopped by an intelligent controller to protect the reliability and durability of the power electronic component. In this situation, a good design of the condenser for the high power electricity converter cooling is of significance to ensure the security of normal running of the high-speed trains.

Fig. 1 shows the photo of a power electronic converter and its condenser for the component cooling on a CRH train. The air-side terminal heat radiator of the prototype condenser made up of alloy aluminum is constructed by straight fin arrays for forced air cooling. As the air-side thermal resistance of the condenser usually accounts for 70–90% of the whole condenser thermal resistance [1–3], it does make sense to replace the original straight fins with multi-louvered fins to improve heat dissipation effect. However, the air-side geometrical size of the condenser for the power converter cooling shown in Fig. 1 is relatively larger than that of the compact heat exchangers with multi-louvered fin arrays for automotive and air-conditioning cooling. Usually, most structural parameters of the multi-louvered fin arrays for the compact heat exchangers are small, with fin pitch and louver pitch on the magnitude order of several millimeters, as well as flow length in the range of 16–42 mm [1–5]. While the fin pitch and the louver pitch for the high power condenser are around fivefold to tenfold as those for the small size multi-louvered fins. Thus, it is necessary to carry out a further investigation to ascertain the thermal-hydraulic performance of the large-size multi-louvered fin arrays used for high power electronic

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Nomenclature

A_o	air-side total heat transfer area of the fin arrays, m^2
A_c	minimum cross section area in the louver gap flow, m^2
A_{fr}	frontal surface area of the fin arrays, m^2
c_p	isobaric specific heat capacity, J/(kg K)
c_v	volumetric specific heat capacity, J/(kg K)
D_h	equivalent hydraulic diameter of pipe flow, mm
f	Fanning friction factor, –
F_d	flow length (or flow depth), mm
F_h	fin height, mm
F_p	fin pitch, mm
F_{th}	fin thickness, mm
h_o	air-side average heat transfer coefficient, W/(m^2 °C)
j	heat transfer Colburn factor, –
L_a	louver angle, °
L_{fl}	non-louvered flat-landing region width, mm
L_h	louver height, mm
L_p	louver pitch, mm
L_{tr}	louvered transitional region width, mm
LFA	a characteristic parameter correlating louver pitch, fin pitch and louver angle (Eq. (22)), –
p	pressure, Pa
Pr	Prandtl number, –
q	heat flux, W
Re_{Dh}	Reynolds number based on the equivalent hydraulic diameter, –
Re_{LP}	Reynolds number based on the louver pitch, –
$\bar{S}_{ij}$	resolved rate-of-strain tensor, –
T	temperature, K
T_p	flat tube pitch, mm
t	time, s
Nu	Nusselt number, –
u_{fr}	frontal velocity, m/s
$\bar{u}_i$	filtered velocity in LES, m/s
V_{max}	characteristic velocity in the louver gap flow, m/s
x_i	coordinate components, mm
x^+	dimensionless distance of inlet effect region, –

Greek symbols

ρ	density, kg/m^3
ν_o	kinematic viscosity of air, m^2/s
μ	dynamic or eddy viscosity, kg/(s m)
σ_{ij}	shear-stress tensor, –
λ	thermal conductivity, W/(m K)
δ	the effective spacing of the louver gap flow, mm
ΔT	temperature difference, K
Δp_{tot}	total pressure drop, Pa

Subscript

air	flowing air
in	inlet
out	outlet

cooling.

With regard to the state of the art of investigations on the multi-louvered fin arrays, the related subject matters mainly involve qualitative influence analysis of geometrical parameters [1,2,7–12], effect mechanism of flow and heat transfer [6,13–21], generalized correlations of thermal-hydraulic performance [22–32], frost behaviors [33–37] and so on. Several types of typical multi-louvered fin arrays are summarized in [29]. Specifically, the geometrical parameters comprise louver pitch (L_p), fin pitch (F_p), flow length (F_d), louver angle (L_a), fin thickness (F_{th}), fin height (F_h), louver height (L_h), non-louver region width (L_{fl}), louvered transitional region width (L_{tr}), etc. In the aspect of a single geometrical parameter, it is reckoned that the pressure drop and the average heat transfer coefficient of the louvered fin arrays decrease as the increase of louver pitch [1,2]. Tian [2] argued that an optimal louver pitch to fin pitch ratio existed with a ratio range of 0.9–1.6. As for the flow length, most of the sizes in the publications are in the range of 16–42 mm [1–5] and the heat transfer coefficient decreases meanwhile pressure drop increases as the flow length increases [9]. An optimal louver angle is also found in [1,9]. The optimal angle is 27° for the case of a flow length of 24 mm. Kim and Bullard [9] declared that the flow length is one of the main influence parameters of pressure drop and the effect of fin pitch on heat transfer is small. While Qi et al. [11] argued that the flow length, the ratio of fin pitch to fin thickness and the number of louvers are the primary influence parameters, using Taguchi method to evaluate the influence extent of five factors on different control levels.

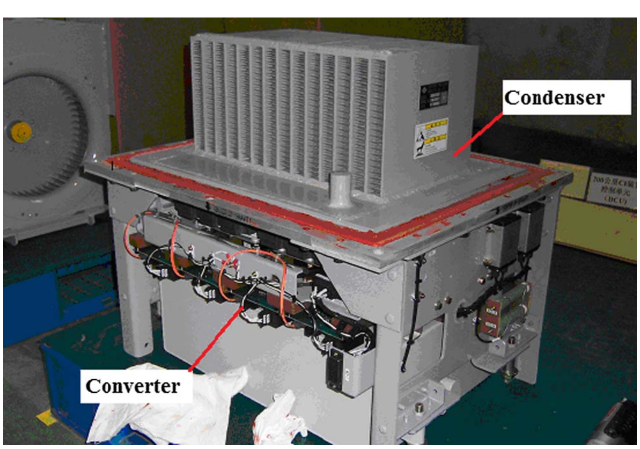

Fig. 1. Photo of a high power electronic converter and its condenser for cooling on a CRH train.

When it comes to the flow and heat transfer mechanism, it involves flow state, thermal wake effect, flow transition and unsteadiness, etc. The flow state represents the predominant flow direction, which can be delineated by flow efficiency [13,14]. The flow state is generally divided into two categories, duct flow and louver gap flow [15–18]. Zhang and Tafti [19] classified two types of thermal wake interferences that occurred in multi-louvered fins, inter-fin interference occurring between adjacent rows of louvers and intra-fin interference appearing on subsequent louvers of the same row or fin, respectively dominated by louver gap flow at a high flow efficiency and by duct flow at a lower flow efficiency. It was verified by them that the thermal wake effects could be expressed as functions of the flow efficiency and the fin pitch to louver pitch ratio. Besides, the flow transition analysis is aimed at disclosing the flow mechanism of multi-louvered fin arrays from steady flow to unsteady flow in terms of flow state [6,21]. It is argued in [6] that most of the louvers exhibit unsteadiness by a Reynolds number of 1300 except for the entrance louver and the first two louvers following it.

Apart from the qualitative analysis aforementioned, the correlations of thermal-hydraulic performance respectively for the flow and heat transfer characteristics are highly concerned as it can help to provide design rules for real engineering. Most of the generalized correlations are fitted in terms of the dimensionless Fanning friction f and Colburn-j factor, except that a few ones adopted Stanton or Nusselt number for heat transfer characterization [2,4,9,16,22–32]. Amongst all the