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The optimization design of Off-Highway machinery radiator based on genetic algorithm and ε-NTU[1]

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Abstract. The advantages and disadvantages of the construction machinery cooling system are closely related to the machine performance. However, it is difficult to design a high efficient radiator to manage the high heat emittance of the high-powered diesel engine. In this study, we put forward an mechanical optimization design that uses the effectiveness-number of transfer units (ε-NTU) method as the mathematical mode of the radiator performances estimation to build a radiator parameters design model, which puts the heat transfer rate and pressure drop of airside as the objective function, and also solves the alternative advantage solution set through genetic annealing algorithms (GAA). Moreover, designers could achieve the expected performance indicator or optimize the original radiators from revising radiator geometrical parameters at the beginning of the design through verifying the model effectiveness by comparing the experimental data.

Key words. Wavy fin, heat transfer, numerical simulation, genetic annealing algorithms, Off-Highway machinery.

1. Introduction

The compact heat exchanger has a broad applications in many fields due to its efficient heat transfer rate and compact volume. The research and development of current radiators are inspired by Kays et al. [1], who firstly invented various kinds of radiators in 1984, and they also obtained the original correlations between the heat transfer and resistant features of the general fins by experiences [2]. Between 2000 to 2010, Wang et al. [3] matched the laboratory correlations of the variations between the Colburn factor and fanning factor in different Reynolds numbers. Based on the previous study, in 2007 Dong [4] utilized the wind tunnel test bench to test 67 different structure parameters of five general fins and matched the laboratory correlations between their heat transfer and resistant features, which highly increased

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the fitting precision; and the deviations of correlations are only 12 %. Caputo et al. [5] applied the simulated algorithm to the solutions of industrial radiator optimized problems. Copiello et al. [6] studied the influences of cross-cut flow control on fluid resistance and heat transfer rate of radiators by improving genetic algorithm. Mostly, the traditional radiators were designed by using the method of logarithm mean temperature difference (LMTD), which used the specified parameter (inlet and outlet temperatures of hot and cold fluids) to calculate the heat transfer rate and the correction factor to decrease deviations. This method is less computed, which can fast estimate heat transfer rate, but lower accuracy. In this study, we directly applied the fins' parameters into the calculation of heat transfer rate and pressure drop by the laboratory correlations, which can accurate estimation of heat transfer rate and pressure loss of the radiator. And also we could change the appropriate heat transfer rate and pressure drop by regulating geometrical parameters of fin.

2. Mathematical model of radiator performance estimation

The design of radiators is for heat transfer rate and pressure drop of airside. This study uses the ε-NTU as the theoretical basis, the wheel loader radiator from LONKING as the vector to construct the mathematical model of radiator performance estimation. This radiator is the wavy finned tube heat exchanger. Figure 1, top and bottom parts, show its structure and geometric parameters of fin and Table 1 shows the structural parameters of the radiator.

Table 1. Structural parameters of the radiator

Parameter	Data	Parameter	Data
Core size	880 mm×858 mm×92 mm	Fin thickness δ	0.06 mm
Cooling area A	44 m^2	Wavy angle β	150 rad
Fin height $F_{\rm h}$	1.5 mm	Fin space $P_{\rm f}$	3.3 mm
Wavy pitch $\lambda_{\rm w}$	12 mm	Fin number	262

Frontal area, hydraulic diameter and Reynolds number could be obtained by calculating the geometrical parameter of the wavy fins, which do not need to be mentioned more. For other kinds of fins, the design parameter is got only by changing the specified geometrical parameter. And also, the specified parameter could be obtained by operating the fin unit simulation with CFD program when there are no experimental data. In addition, the NTU of radiator could be got by computing the fin and fin facial efficiency resulted from the formula (1). The efficiency of radiator is calculated by formula (2) and Colburn factor and friction factor are calculated according to the method presented in [1]. At last, formulae (4) and (5) provide the pressure drop and heat transfer rate [7]

$$R = \frac{(q_{\rm m}C_{\rm p})_{\rm min}}{(q_{\rm m}C_{\rm p})_{\rm max}}\,, \tag{1}$$

$$\varepsilon = 1 - \exp\left\{\frac{\mathrm{NTU}^{0.22}}{R}\left[\exp\left(-R \cdot \mathrm{NTU}^{0.78}\right) - 1\right]\right\} \tag{2}$$

$$\begin{cases} C_{\min} = \min\left[(\dot{m} \cdot C_{\mathrm{p}})_{\mathrm{hot}}, (\dot{m} \cdot C_{\mathrm{p}})_{\mathrm{cold}}\right], \\ C_{\max} = \max\left[(\dot{m} \cdot C_{\mathrm{p}})_{\mathrm{hot}}, (\dot{m} \cdot C_{\mathrm{p}})_{\mathrm{cold}}\right]. \end{cases} \tag{3}$$

Pressure drop:

$$\Delta P = \frac{\dot{m}}{2A_{\mathrm{c}}\rho}\left[\left(K_{\mathrm{c}} + 1 - \sigma^2\right) - \left(1 - \sigma^2 - K_{\mathrm{e}}\right)\frac{\rho_{\mathrm{in}}}{\rho_{\mathrm{out}}} + f\frac{4L}{D_{\mathrm{e}}}\rho_{\mathrm{in}}\left(\frac{1}{\rho}\right)_{\mathrm{m}}\right]. \tag{4}$$

Heat transfer rate:

$$h = j\dot{m}C_{\mathrm{p}}\left(A_{\mathrm{c}}\,\mathrm{Pr}^{\frac{2}{3}}\right)^{-1}, \tag{5}$$

$$Q = \varepsilon \cdot C_{\min}\left(T_{\mathrm{hotin}} - T_{\mathrm{coldin}}\right). \tag{6}$$

In the above equations (1)–(6), C_{p} is the specific heat of the coolant, Q denotes the heat transfer rate, ε represents the effectiveness of the heat exchanger, $\dot{m}$ stands for the mass flow, NTU is the number of the transfer units, T_{m} is log mean temperature difference, K_{c} is the entrance loss coefficient, K_{e} is the exit loss coefficient, δ is the minimum flow to face area ratio, A_{c} is the minimum cross-sectional flow area, Pr is the Prandtl number, D_{e} is the hydraulic diameter and A is the heat transfer surface area.

This predicted mathematical model is commonly used to some extent. Besides the tube-fin type shown in this study, it also can be used in plate-fin radiator and ribbon-tubular radiator, which are general in Off-Highway machinery. The only way that needs to be done is changing the specified formula of geometrical parameter and empirical formula such as the heat transfer surface area, colburn factor and friction factor [8].

3. Designed model of optimized radiator parameter

3.1. Design parameter and objective function

The objective to optimize the radiator design is to adjust the heat transfer rate and pressure drop to the range of designers' request by regulating the main structural parameter of radiators. This procedure includes the selection of designed variable, the extraction of constraint conditions, the construction of design objective and the choice of algorithm. This study gets rid of some variables that slightly affect the objective function and choose 8 parameters of radiators as the independent variables [9]. The design variables should be constrained subjected to the limited volume of production technology and power cabin. The range of design variables is shown in Table 2. The objective function 1 is heat transfer rate as shown in (5), and the objective function 4 is pressure drop as shown in equation (10), the volume of new radiator, which is less than original radiator, as the constraint conditions.

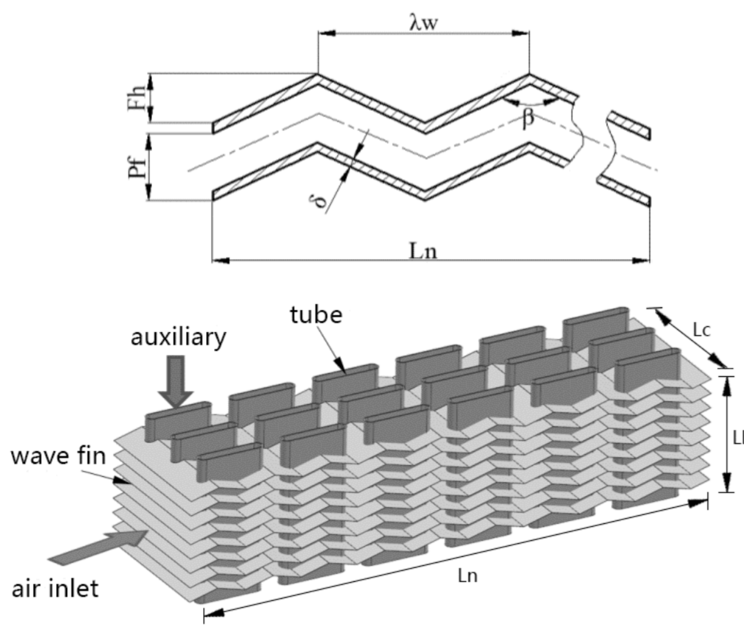

Fig. 1. Wavy fin: top–geometric parameter, bottom–structure of the fin and tube radiator

The friction factor shown in (8) and Colburn factor shown in (7) make use of the empirical formula from the wavy fin unit wind tunnel test data and the way of the next section to get the heat transfer coefficient figured in (9) and pressure drop correlation displayed in equation (10). The correction factors f_{fix1} and f_{fix2} are obtained based on the data from different fins in different radiators. This paper is in the confirmed process. So the correction factor f_{fix1} and f_{fix2} are valued 1.

Table 2. The value range of design parameter

Design parameter	Range	Design parameter	Range
L_{n}	800∼880 mm	β	130∼170 rad
L_{h}	800∼858 mm	δ	0.05∼0.07 mm
L_{c}	80∼92 mm	P_{f}	3∼3.6 mm
λ_{w}	10∼14 mm	F_{h}	9∼13 mm

$$j=\left(\frac{P_{\mathrm{f}}}{2F_{\mathrm{h}}}\right)^{0.1284}\cdot\left(\frac{P_{\mathrm{f}}}{4F_{\mathrm{h}}+\lambda_{\mathrm{w}}}\right)^{-0.153}\cdot\left(\frac{L_{\mathrm{n}}}{\lambda_{\mathrm{w}}}\right)^{-0.326}\cdot 0.0836\mathrm{Re}^{-0.2309}\,, \qquad (7)$$

$$f=\left(\frac{P_{\mathrm{f}}}{2F_{\mathrm{h}}}\right)^{0.3703}\cdot\left(\frac{P_{\mathrm{f}}}{4F_{\mathrm{h}}+\lambda_{\mathrm{w}}}\right)^{-0.25}\cdot\left(\frac{L_{\mathrm{n}}}{\lambda_{\mathrm{w}}}\right)^{-0.1152}\cdot 1.16\mathrm{Re}^{-0.309}\,, \qquad (8)$$

$$h = 100\eta^{-0.283} \cdot 9.2394 \cdot C_{\mathrm{p}}^{0.33} \cdot \lambda^{0.67} \cdot (\rho \cdot V)^{0.731} \cdot \sigma \cdot D_{\mathrm{e}} \cdot P_{\mathrm{f}} \cdot f_{\mathrm{fix1}}\,, \tag{9}$$

$$\Delta p = \rho^{-1} \cdot \sigma_{\mathrm{d}}^{-3} \cdot 1.07673 \cdot \left(\frac{A}{A_{\mathrm{c}}}\right)^{0.468} \cdot (\rho \cdot V)^{1.68} \cdot \left(\frac{\eta}{D_{\mathrm{e}}}\right)^{0.32} \cdot f_{\mathrm{fix2}}\,. \tag{10}$$

In the above equations, f is the friction factor, h is the heat transfer coefficient, j is the Colburn factor, Δp represents the pressure loss, ρ denotes the density of air, β is the wave angle, λ stands for the heat conductivity of air, λ_{w} is the wave pitch, σ denotes the fin thickness, η represents the dynamic viscosity of air, f_{fix1} and f_{fix2} are correction factors, F_{h} is the fin height, K denotes the heat conductivity of the radiator, P_{f} stands for the fin pitch, Re is the Reynolds number and $sigma_{\mathrm{d}}$ is the porosity of airside.

3.2. The selection of algorithm

Engineering problems always comes down to the complex multi-objective optimization problems. These functions possess the features of nonlinear, multivariable and hard redescender. Genetic algorithm (GA), as an easy computed and high efficient method, is widely used in engineering problems. However, it is limited by premature convergence and lower partial searching ability, so it cannot usually get the most optimized solution in global situation. The heuristic algorithms, such as the steepest descent, hill-climbing, simulated annealing (SA) and the list of optimization method have the strong global searching capability, and also some heuristic algorithms, which contain some information that are related to the problems, are highly effective. As hypothesized, merging the basic idea of SA in the search process of GA to construct a hybrid genetic algorithm, which contains both advantage, so as to improve efficiency of the GA operation and the quality of solution, which could help to adapt to the complex engineering problems in mechanical optimized design. GAA, used in this study, overcomes the traditional genetic algorithms and improves the search efficiency as well. The introduction of elitist preservation (the individual, which has highest fitness, will directly copy to the next generation instead of the recombination mutation) and disaster-modification (when it cannot get the optimized state after algorithms' several iterations, using probability 1 to mutate and interlace operation, at the same time, keep the optimal individuals). Do not recover to the normal cycle until a better individual is produced. The first one-the phrase has been modified to "If there is no better solution in the iteration step, the convergence of the calculation result is considered. The algorithm in this paper reduces the possibility that the algorithm falls into the local optimal solution, and improves the efficiency of calculation and the quality of solution."

The brief steps of GAA in this study are:

1) Select the original populations randomly, and compute the original fitness.

2) Repeat step 3) and 7), until satisfy the convergent roles.

3) Stochastic tournament and select the optimal father generation, then reproduce.

4) Simple mutation to the selected father generation and accept new individual by the method of probability.

5) Arithmetic crossover to the father generation and mutated sub-generation.

6) Simulate annealing operation to the father generation and produced sub-generation, then cool them down based on index.

7) Elitist preservation and judge if it need do disaster-modification. Output the global optimal results. "

4. Experimental comparative analysis

4.1. Optimal solution analysis

This study describes the optimized problem as the style of equation 10 with the objective functions and constraint conditions that are derived from previous section, and the simulation conditions are shown in Tables 3. Set the genetic algorithm as follow: population size 100, crossover fraction 0.7, migration fraction 0.01, function tolerance 1e-6, and max generation 100. The result are shown in Fig. 2, top and bottom parts. Using NSGA-II algorithm (as shown in Figure 3) to verify the validity of the Pareto optimal solution. It can be seen that the regions of the optimal solutions are matched. However, the rate of convergence, equilibrium of distribution and the capacity of global searching of GAA are better than NGSA-II.

$$\begin{cases} \min F(x) = [f_1(x), f_2(x)], \\ f_1(x) = -Q, \\ f_2(x) = \Delta p, \\ g(x) = \Delta V = V_1 - V_2 \geq 0. \end{cases} \tag{11}$$

Here, $g(x)$ is the volume change, while $f_1(x)$ and $f_2(x)$ are the objective functions.

Table 3. Simulation boundary conditions

Parameter	Data	Parameter	Data
Ambient temperature	30 °C	Coolant flow rate	120 l/min
Airside inlet	30 °C	Coolant inlet temperature	100 °C
Ambient pressure	101325 Pa	Velocity of the airflow	12 m/s

Multi-objective optimization function does not exist a set of solutions for all constraints, replaced by an optimal solution set. The contradiction among many objective functions in real engineering problems is always met. Designers should make their choices and select the solutions that are fit to the whole designs through their own request. In this study, the design goal of radiator is to pursue the high heat transfer rate and lower pressure drop, which are obviously contradictory. However, some compromised solutions with the optimized algorithm can be obtained. Table 4. shows the result that comparing three typical preponderant solutions of GAA and the experiment data of original radiator from wind tunnel test: Type solution 1 heat

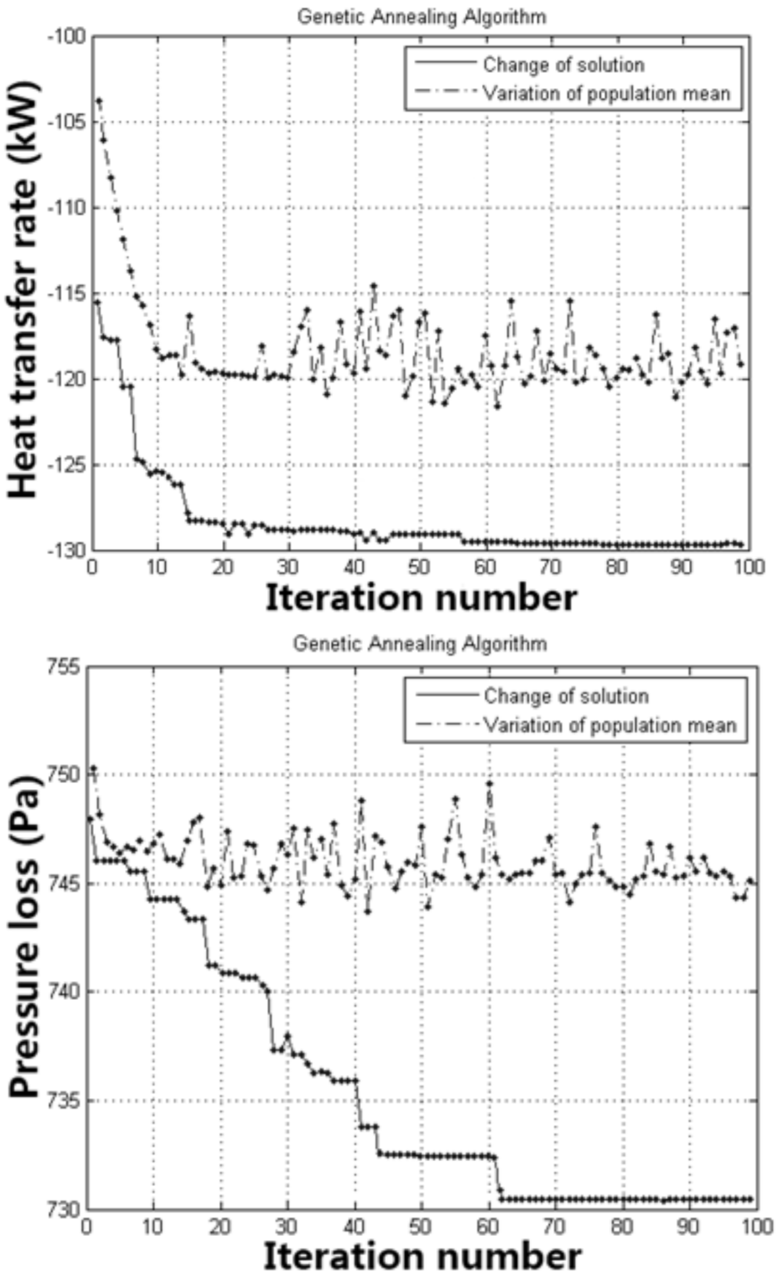

Fig. 2. Results: top–heat transfer rate of GAA, bottom–pressure drop of GAA

transfer rate increases slightly and pressure drop decreases slightly. Type solution 2 heat transfer rate and pressure drop grows significantly. Type solution 3 pressure

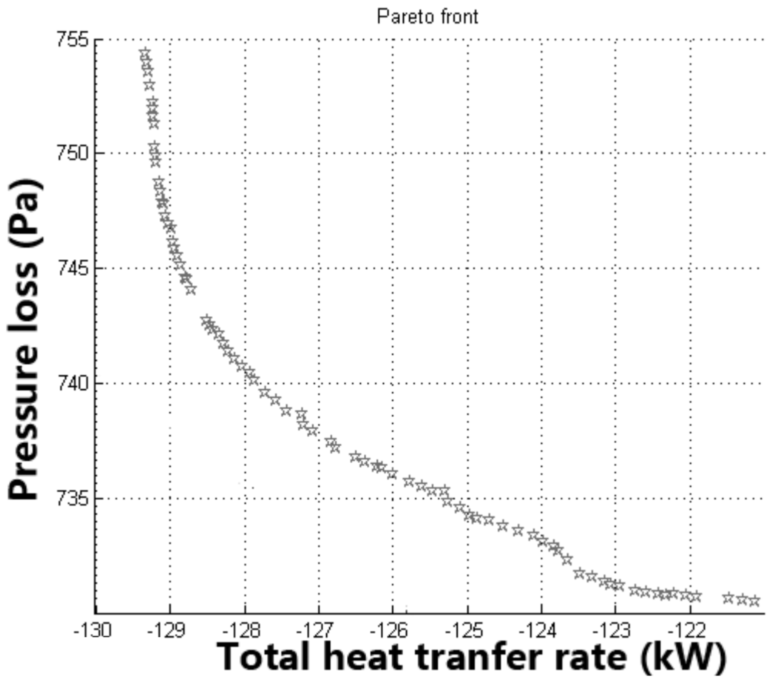

Fig. 3. Optimization results of NGSA-II

drop falls highly and the loss of heat transfer rate is higher as well. According to the actual needs, designer can choose the solution with small pressure loss or large heat transfer rate.

Table 4. Comparison of calculation results

Parameter	Experiment data	Solution 1	Solution 2	Solution 3
Q (kW)	124.55	126.65	129.74	121.41
ΔP (Pa)	140.11	137.77	148.81	131.72
L_{n} (mm)	880	872.5	870.1	869.2
L_{h}	858	849.9	846.9	846.1
L_{c}	92	91.1	91.1	90.4
ΔV (%)	N/A	–2.75	–3.36	–4.29
λ_{w} (mm)	12	11.4	11.6	11.1
β (rad)	150	135.5	153.2	147.2
δ (mm)	0.06	0.05	0.05	0.05
P_{f} (mm)	3.3	3.3	3.2	3.2
F_{h} (mm)	10	11.9	12.1	12

4.2. Analysis of radiator performance

Radiator bench test was carried out according to Fig. 4.

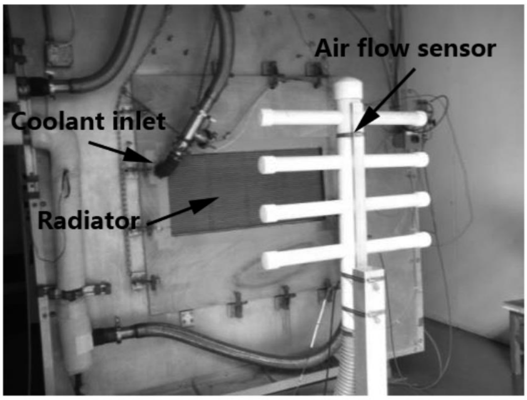

Fig. 4. Radiator bench test

Establishing the radiator model with UG, we did the stimulation by putting the viscous resistance coefficients and inertial resistance coefficients obtained from the results of fins parameters in the three groups (as shown in Table 4) into the porous media model. As shown in Fig. 5, through bench test the pressure drop curves and heat transfer curves at different inlet velocities are compared with the original radiator.

The heat transfer rate and pressure drop increase with the increase of the inlet velocity; the growth rate of pressure drop increases with the increase of inlet velocity, which is consistent with formula (4). The growing rate of heat transfer rate decreases gradually with the increasing of inlet speed. To start from the Macro-view, the increasing speed of inlet flow led to the decreasing of heat exchange time. Although the amount of air intake is increasing, the heat exchange time is reduced which causes the loss of the heat exchange efficiency. Theoretically, the heat transfer rate of radiator is mainly related to the effectiveness of radiator and $C_{\min}$. In terms of the experimental data, the effectiveness of radiator is in a convex function relationship with the NTU. The value of NTU and effectiveness of radiator varies inversely with the inlet velocity. According to the principle of heat transfer, while the inlet velocity increased to a certain size $C_{\min}$ and efficiency will be changed to a certain value, continuously increasing the inlet velocity will no longer increase the heat transfer rate.

In order to verify the accuracy of the simulation, a new radiator is made according to the fin parameters of the typical solution 1 and the bench test is carried out. The bench test experimental results are compared with the simulation results as shown in Table 5. We can figure out that the new radiator made by typical solution1 basically matches the simulation result, and the average error is about 6 %, which confirms the accuracy of the GAA calculation model.

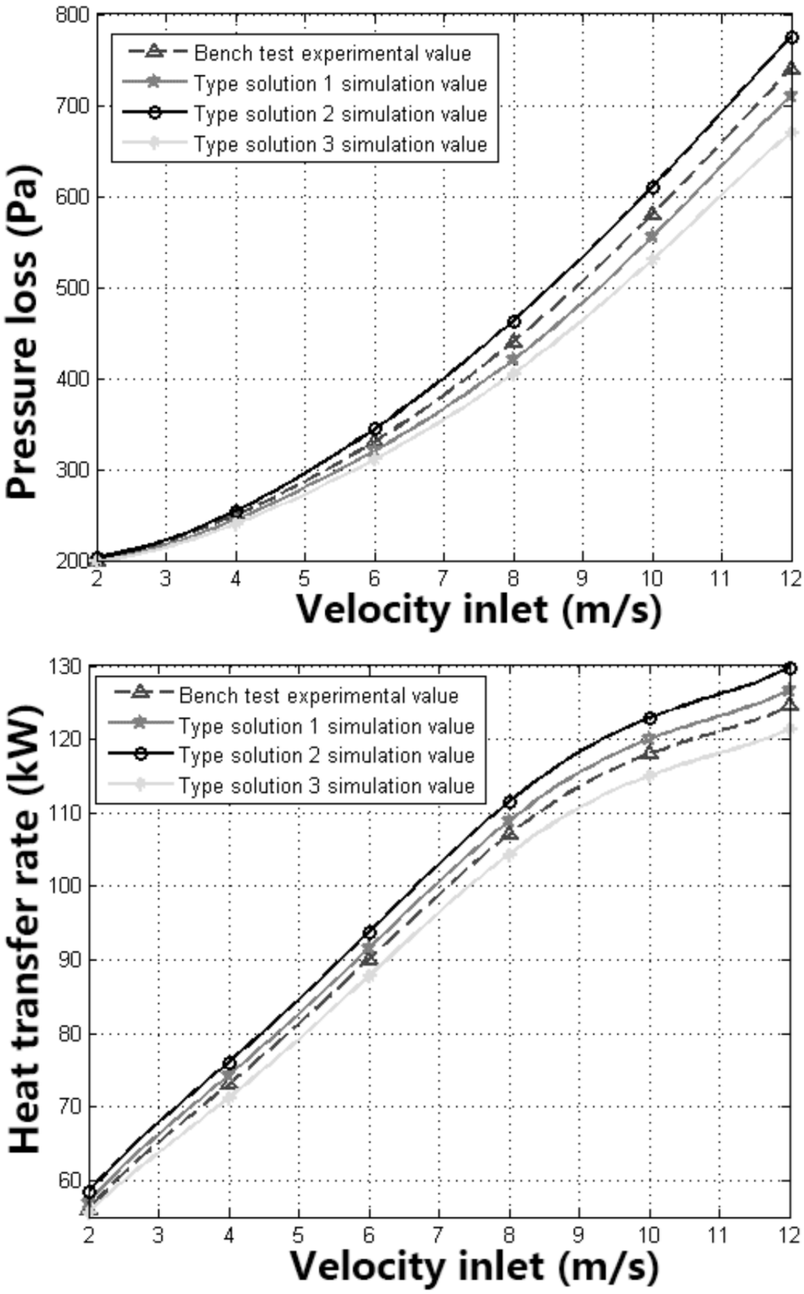

Fig. 5. Important characteristics of radiator at different inlet velocity: top-pressure loss, bottom–heat transfer rate

Table 5. Comparison of CFD simulation and experimental results

Inlet velocity	6 m/s	8 m/s	10 m/s	12 m/s
Pressure loss of type solution 1	320 Pa	420 Pa	555 Pa	710 Pa
Pressure loss of the new radiator	322 Pa	422 Pa	559 Pa	714 Pa
Heat transfer rate of type solution 1	85.43 kW	102.72 kW	116.96 kW	126.65 kW
Heat transfer rate of the new radiator	85.26 kW	102.52 kW	116.73 kW	126.42 kW

5. Conclusion

Using the ε-NTU as the theoretical basis, and the engine coolant radiator of wheel loader (wavy fin-and-tube radiator) as the research object, the mathematical model of radiator performance estimation was constructed. This model is powerful generalization, and it could be adapted to Plate-fin radiator and can be used for plate fin or Ribbon-tubular radiator when several geometrical parameters and empirical formula changed. It can also focus on the performance study in different fins of the same kind of radiators. When MATLAB to routinize mathematical model of radiator performance estimation with the mix genetic algorithm was used, the introduction of annealing algorithm complements the disadvantages of genetic algorithm in searching process. Analyzing one group of the dominant results, we find that the volume could decrease 2.7 %, and the heat transfer rate grows 1.7 %, when the pressure drop falls 1.7 % by modifying the design of the original radiator. In addition, the optimal dependability is verified by Wind tunnel test of the new radiator. The heat transfer rate and pressure drop of the radiator are greatly influenced by the fin parameters. They are increasing with the growth of inlet velocity of cold side. The increased heat transfer rate stops when the inlet velocity reaches to a certain extent. In this paper, with ε-NTU theory as the basis for the establishment of the radiator performance prediction model, combining with the genetic algorithm to optimize the size of core and fin parameters, and the optimal solution is performed by CFD simulation and wind tunnel tests to verify the effectiveness of the calculation model. This paper provides a new idea for the design and optimization of the radiator, which is conducive to shorten the development cycle and reduce the design cost.

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