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Experiment study of multi-fans cooling module using different shroud structures for advanced vehicle thermal management system

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Abstract

As one of the most important components of the vehicle thermal management system, multi-fans cooling module can potentially be used to optimal the system performance in order to save the energy consumption and reduce the vehicle fuel consumption. In this study, a test rig has been designed, constructed and used to test the heat transfer performance of the multi-fans cooling module using four different fan shroud structures. Results indicate the separated plates, which have limited or worse effect on the performance of the system, are not recommended to be used in the multi-fans cooling module. The optimal shroud structure for multi-fans cooling module has been identified and experimentally tested. By adding shutters at the ventilation part of the fans (Shroud C) can significantly improve the overall performance of the module (Shroud A) by 13.25 % to 69.08 % under various operation conditions.

Keywords: Multi-fans module ; Fan shroud structure, Vehicle thermal management system, Heat transfer performance

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1. Introduction

As the energy consumption of vehicle continues to increase, its energy saving research becomes very important and urgent. As an important subsystem of vehicle, the Vehicle Thermal Management System (VTMS) is one of the most promising energy saving technologies for not only in traditional internal combustion engine vehicles, but also in hybrid electric vehicles, electric vehicles and fuel cell electric vehicles (FCEVs) [1]. The comprehensive VTMS consist of the vehicle cooling system, climate control system, and waste energy recovery system such as Organic Rankine cycle (ORC) technology [2, 3]. The development trend of VTMS is to adopt electric devices [4], such as the electric thermostat, the electric coolant pump [5], and the electric fans [6]. The cooling module consisted of electric fans was called multi-fans cooling module, can operate to the thermal requirement of vehicle controlled by using advanced control strategies [7] for the purpose to reduce energy consumption and therefore improve the overall energy efficiency.

The multi-fans cooling modules have been applied in different vehicles including in army vehicle [8], light duty truck [9] and bus [10]. However, the study of heat transfer performance using different structures is quite limited. Stephens et al. [11] reports a study on the interaction between the multi-fans and radiator, and the interaction between the fans, they announce that adding the separated plates inside the heat exchanger shroud can eliminate the secondary flows induced by the fans to improve the performance of the cooling module, which requires more detailed experimental verifications. On the other hand, the researches of the traditional mechanical fan cooling module suggest shroud structure can influence greatly the heat transfer performance of the cooling module [12].

This paper aims to study the influence of using different shroud structure on the heat transfer performance of the multi-fans cooling module and identify the optimal structure. The shutters added at the ventilation holes of the fans have been designed as controllable version based on the working condition of the fan, which provides a new insights to guide the fluid flow in other similar areas that several fluid machineries are used and operate partially sometimes, such as the array of axial flow fans for air-cooled condensers in a power plant [13].

2. Methodologies

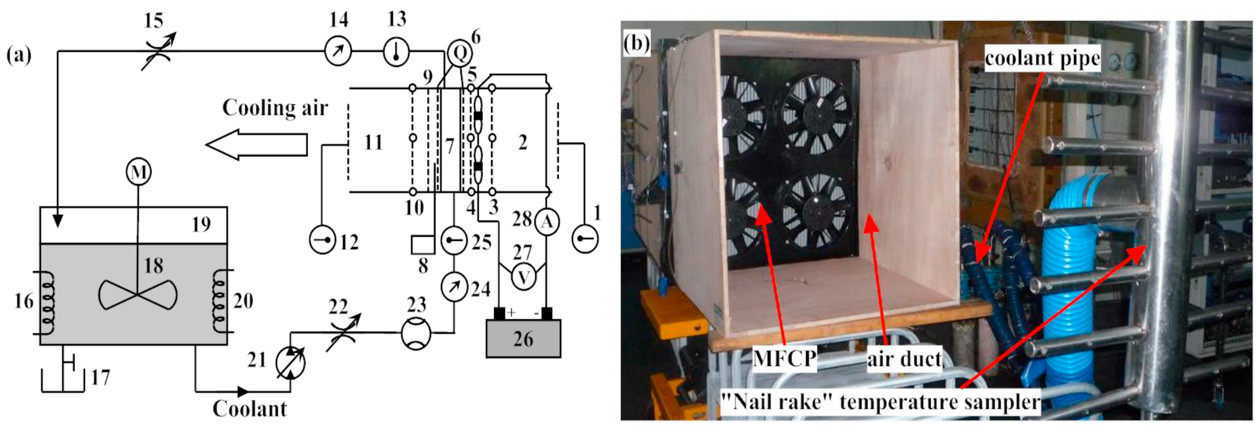

Fig. 1 Experimental rig (a) Schematic diagram; (b) Photo of the rig.

1, 12- "Nail rake" temperature sampler；2-air inlet section；3, 5, 10-pressure measurement；4-electric fans；6-diagonal pipe flow meter；7-radiator；8-hot wire anemometer；9-outlet temperature sensor net；11-air outlet section；13, 25-temperature sensor；14, 24-pressure sensor；15, 22-flow valve；16, 20-electric heaters；17-drainpipe；18-agitation system；19-cooltant tank；21-pumps；23-Coriolis mass flow meter；26-DC power；27- voltmeter；28- ammeter

2.1. Description of the test rig

Wind tunnel experiments were carried out to complete the tests. The experimental setup included hot coolant system, the cold air system, the measuring and control system, as presented in Fig.1. To simulate the heat generated during the combustion process of the engine, the electric heaters were adopted in the hot coolant system. It mainly consists of a coolant tank, electric heaters, agitation system, an electric pump, a flow valve and control module. The entry and exit of the air duct were free to the air environment, so there is no extra interference with the test multi-fans. All the coolant pipes and the air duct were used of insulation materials or wrapped by the insulation materials to prevent the heat losses.

2.2. Test object and scheme

The test object in this study is a typical multi-fans cooling module, consisted of four electric fans and a radiator. The radiator is a tube-fin aluminium radiator from an electric vehicle. The width of the core of the radiator is 810 mm, the height is 802 mm and the thickness is 70 mm. The electric fan's diameter is 312 mm, with 7 blades, its performance has been tested in the standard wind tunnel and the results are presented in Fig.2. The curve signed by "P" is static pressure curve and the curve signed by η is static pressure efficiency curve. The digital subscript means the speed of the fan, for example, the curve signed by P_{1025} is the static pressure performance when the fan runs at 1025 r/min. As show in Fig.2, the lower the fan speed, the lower the fan static pressure efficiency will achieve. The minimum speed of the electric fan used in this paper is 1025 r/min.

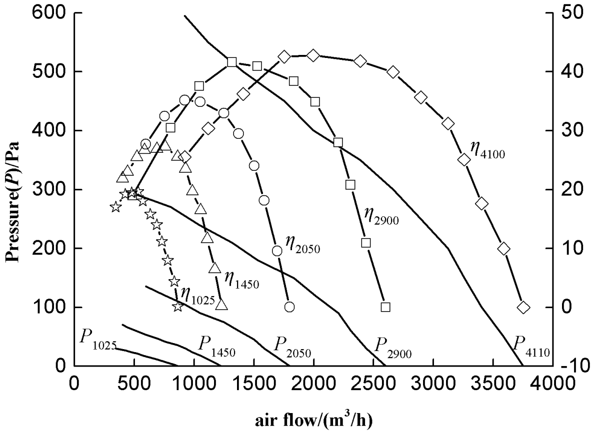

Fig. 2 Performance curve of electronic fan

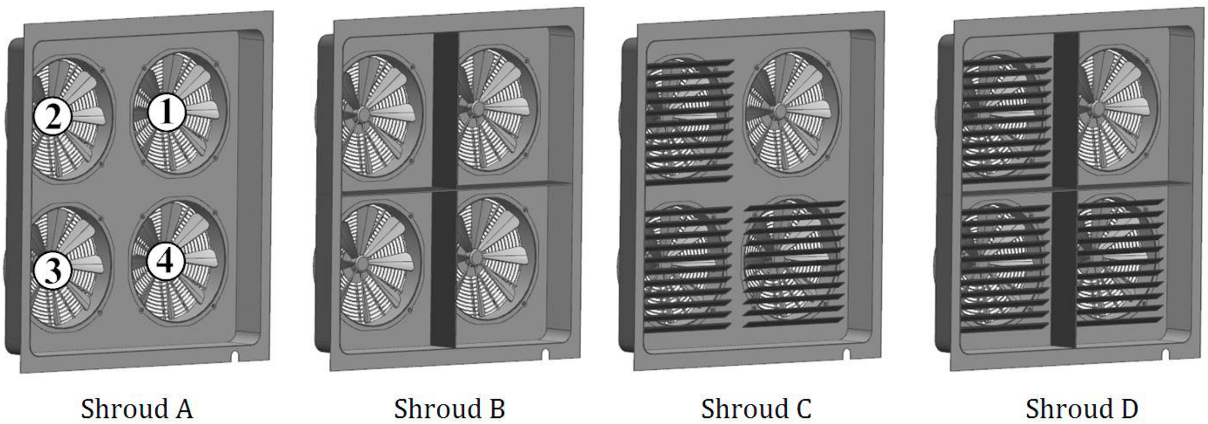

Fig. 3 Diagram of four shroud structures

The shroud is used to link the electric fans and the radiator. Four kinds of shroud structures have been used as shown in Fig.3. Shroud A is the basic structure and used widely now, evolved from the shroud structure of the traditional mechanical fan cooling modules. Adding the separated plates between the fans to the shroud A, the shroud B is formed. The shroud C and D have been formed respectively by adding the adjustable shutters at the ventilation holes of fans of the shroud A and B, in order to simulate the partial fans working conditions proposed by Wang et al. [6].

According to the 'Rule of Thumb' proposed by Wang et al. [6] only part of the four fans operates when the heat dissipation is low, then all fans operates when the heat dissipation is high enough. The test scheme can therefore be designed as shown in Table 1.

Table 1. Test scheme

Test set No.	Operating fans	Fan speed (r/min)	Coolant mass flow rate (kg/s)	Liquid-Air temp. Difference(℃)	Ambient temp. (℃)	DC voltage (V)
Case 1	1	1025/1450/2050/2900/4100	3.0	60	24±1.5	26.5
Case 2	12					
Case 3	123					
Case 4	1234					

2.3. Measuring procedure and data processing

The data were recorded while the system reached thermal equilibrium. The criteria of the thermal equilibrium are as follows:1) the coolant flow rate reached the set value and kept stable; 2) the inlet and outlet temperature of the coolant side and air side remained stable and last 10 minutes. The calculation model of the thermal equilibrium is as follows:

$$\phi_c = q_{m,c} Cp_c \left(t_{c,in} - t_{c,out} \right) \tag{1}$$

$$\phi_a = q_{m,a} Cp_a (t_{a,in} - t_{a,out}) \tag{2}$$

$$\phi = \phi_c = \phi_a \tag{3}$$

$$\Delta = \left| \frac{\phi_c - \phi_a}{\phi_a} \right| \times 100\% \tag{4}$$

$$\phi_c' = \frac{60}{\Delta t_{c-a}} \phi_c \tag{5}$$

Where ϕ is heat flux, q_m is mass flow, Cp is specific heat, t is temperature. The subscript c represents coolant side, a represents air side, in represents inlet, out represents outlet.

However, the thermal equilibrium required in Eq. (3) is impossible because of the unavoidable heat dissipation across the coolant pipe and air duct, despite the insulation step had been taken. So, there are difference between ϕ_c and ϕ_a. The difference, Δ, was defined as Eq. (4), and was required below 5%. In order to uniform the comparing standard, the rate of heat rejection from the radiator was adopted the value of ϕ_c. In addition, because of the control precision, the difference between the coolant inlet temperature and the air inlet temperature, called Liquid-air temperature difference, is impossible to keep the required value of 60 °C constant during the test. The actual rate of heat rejection ϕ_c should be converted into the computational rate of heat rejection ϕ_c', as shown in Eq. (5), where Δt_{c-a} is the measured Liquid –air temperature difference.

3. Results and discussions

Fig.4 displays the plot of the rate of heat rejection of the multi-fans cooling modules with shroud A~D, for different case, with the fan(s) motor speed. As shown in Fig.4, the rate of heat rejection of the module with shroud B is not better than the module with shroud A, except the fan speed is below 2050 r/min in case 1 and the fan speed is 4100 r/min in case 4. The rate of heat rejection of the module with shroud D is worse than the module with shroud C, the rate of deterioration is between 6.56 % and 24.12 %. It can be concluded that adding the separated plates between the fans is not helpful to improve the heat transfer performance of the multi-fans cooling modules, which is different from the conclusion of Stephens et al. [11]. Because Stephen et al. adopted a fan plate model without considering the real working condition of the fan. The electric fans adopted in this study had the stators at the outlet face. These stators not only can improve the static pressure of the fan, but also can weaken the rotation effect of the fan. Therefore the interference between the fans are not stronger than the study of Stephen et al. [11], adding the separated plates cannot weaken further the interference between the fans and will not improve the heat transfer performance of the multi-fans cooling module.

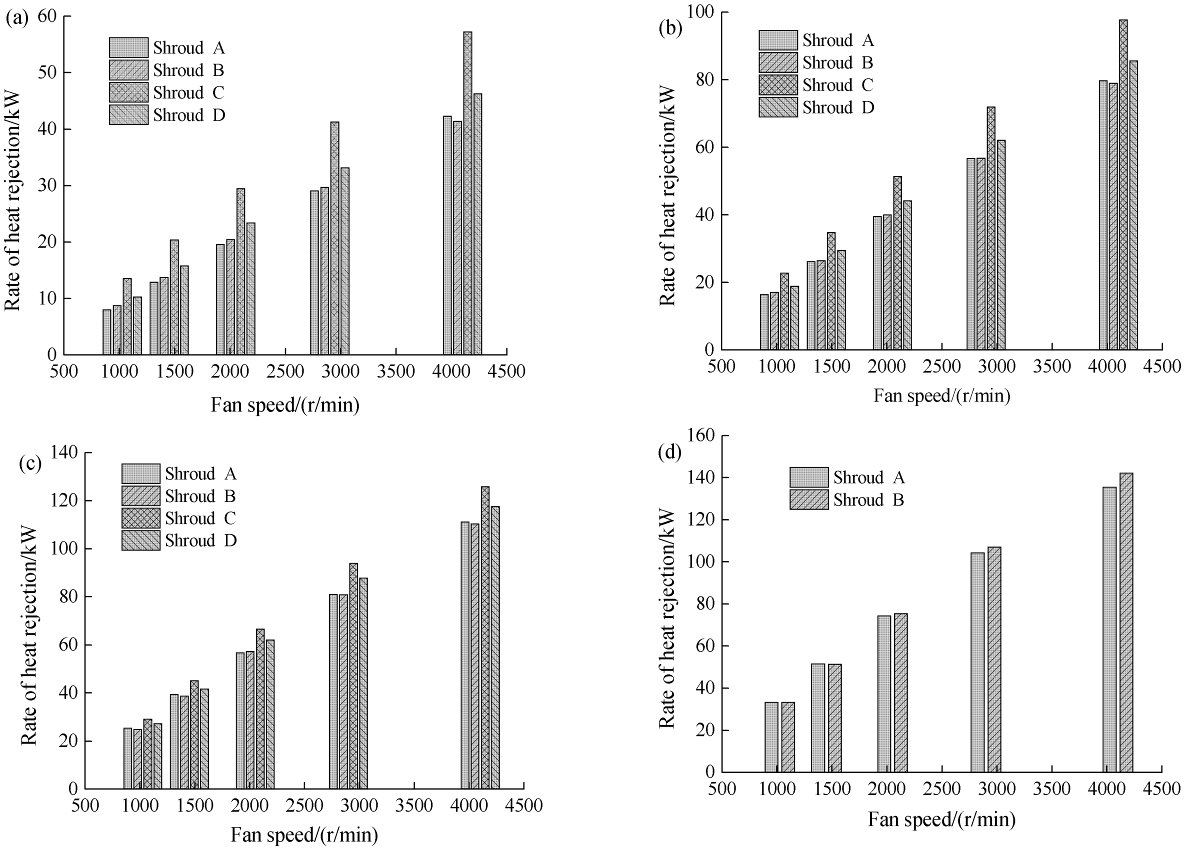

Fig. 4 the rate of heat rejection VS fan speed at different case (a) case1; (b) case 2; (c) case 3; (d) case 4

Meanwhile, it is clear shown in Fig.4 that the rate of heat rejection of the module with shroud C can be increased greatly, comparing with the module with shroud A. The rate of the increase is between 13.25 to 69.08 %. It is similar to compare the module with shroud D with the module with shroud B, although the rate of the increase becomes less, only between 6.51 to 17.72 %. Results suggest by adding adjustable shutters at the ventilation holes of fans can significantly enhance the heat transfer performance of the multi-fans cooling module.

In order to explain deeply this phenomenon, the outlet speed contour of the cooling module, in case 2, the fan speed is 2050 r/min has been represented in Fig.5 by interpolation based on the measured 10×10 air speed points. As shown in the figure, the outlet speed distribution of the module with shroud A is very inhomogeneous. On the other hand, the outlet speed distribution of the module with shroud C is more uniform. The speed uniformity of cooling air can affect greatly the heat transfer performance of cooling modules, more uniform, better the performance [14].

Therefore the rate of heat rejection of the module of shroud C is higher than that of shroud A under the same operational conditions.

The reason of the improved uniformity of the outlet speed as the results presented in Fig 5 can be explained as follows. When partial fans are operating, the air can reflow from the ventilation holes of the idle fan, this is similar to the hot air recirculation in the other areas of the vehicle. Closing the shutters amounted on the ventilation holes of the idle fans, the backflow disappear, and then form a complete static pressure chamber between the shroud and radiator. The uniformity of the outlet speed contour can therefore be improved.

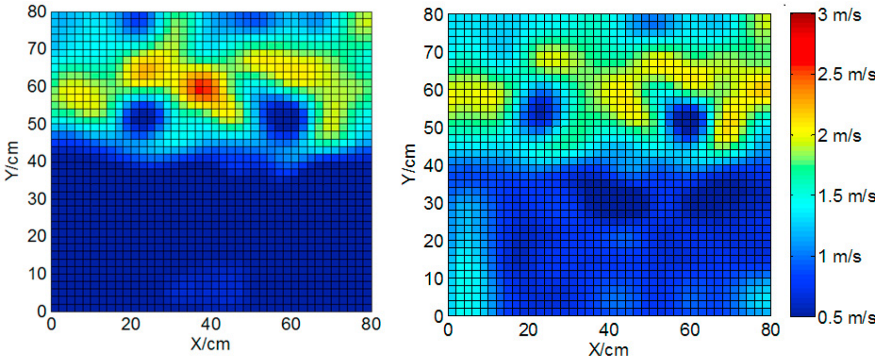

Fig. 5 Speed contours at outlet of cooling module

Comparing the rate of heat rejection of the multi-fans cooling modules with four kinds of shroud, shroud C is recommended to be used as the optimal structure for multi-fans cooling module, which has the best heat transfer performance under all tested conditions.

4. Conclusions

This paper reports the experimental study of multi-fans cooling module using different shroud structure for vehicle cooling application. Four kinds of shroud structure were selected to be used in the multi-fans cooling module and tested the heat transfer performance in a standard wind tunnel. The experimental results show that:

(i) Adding separated plates between the fans can hardly improve the performance of the module, even weaken the performance of the module with the shroud added shutters. The separated plates between the fans are not recommended to be used in multi-fans cooling module.

(ii) When the shroud has been added with shutters at the ventilation holes of the fans, the performance of module can significantly be improved by 13.25 to 69.08 % under various operational conditions.

(iii) The optimal shroud structure to achieve the best heat transfer performance under different fan operational conditions has been identified. The shroud C, which has added shutters without using separated plates is recommended to be used.

This work is important because the new shroud designed in this paper can improve the module performance greatly, if it can be widely applied in practice, it can potentially reduce the overall energy consumption in vehicle. However, the limitation of the present study resides in the fact that the working principle how this kind shroud improves the cooling module performance should be explained more deeply. Further investigation by computational fluid dynamics method will be conducted in the future.

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