Aerodynamic Optimization of Cooling Airflow of a Production Vehicle

Xiaohui Liu, Tiantian Li, Jianxin Wang and Zhijun Zhu

ABSTRACT

As the demand for improved fuel economy and environmental protection increases, the vehicle development has to leave no means untried to beyond the past. Aerodynamic drag reduction has become more critical. One of the important factors is cooling airflow, its contribution accounts for up to 10% of total vehicle drag. Cooling airflow is affected by a large number of factors, such as engine cooling, engine room arrangement, inlet and outlet locations. As an advanced research, AOCA (aerodynamic optimization of cooling airflow) plan is engaged to improve the cooling air volume flow and efficiency from aerodynamics. It tries to optimize current design and manufacture, collect feasible and flexible solutions for cooling issues. In this paper, two aspect results are summarized with full of referential significance.

INTRODUCTION

Under the background of promoting energy conservation and emission reduction, the refined design of vehicle is respected. Modern vehicle’s development must get more attractive styling, better fuel economy, lower emissions, higher performance and safety. In order to achieve these goals, every system of vehicle has to be investigated, and the influence between each other also needs to be taken into account. As equation (1) shows, aerodynamic drag has a conspicuous contribution to fuel economy at high velocity.
$D = \frac{1}{2} \rho V^2 AC_d$  \hfill (1)

Generally, the aerodynamic drag can be divided into momentum loss around the body (external drag) and momentum loss through the body (internal drag)\textsuperscript{1}. External drag is directly coupled with styling while internal drag interacts with cooling airflow. The general function of cooling airflow is to provide sufficient heat sinks for all heat sources in a vehicle. The drag caused by cooling airflow is commonly referred to as cooling drag. In current vehicles, cooling drag accounts for up to 10\% of the overall aerodynamic drag\textsuperscript{2}, which is derived from the difference between the measured drag of a vehicle with cooling airflow minus the drag of the same model with Mock-up, shown in equation (2)\textsuperscript{3}:

\[ C_{DC} = C_{D \text{ with cooling air}} - C_{D \text{ Mock-up}} \]  \hfill (2)

A simple rule of thumb for a water-cooling engine in steady state is the so called one third rule: one-third of the fuel energy is converted into mechanical energy, one-third remains in the exhaust gas, and one-third of the heat is supplied to the cooling system\textsuperscript{4}. So the cooling air is crucial for a normal running vehicle. But too much cooling airflow will increase the cooling drag. To solve this contradiction, many solutions focus on the way to increase the efficiency of related parts, such as improvement of radiator, optimization of fan blade. In engineering respect, many strategies increase the cost. Even now, the application of AGS (Active Grille Shutter) is very popular, but due to the issues of flap angle and reverse flow, the AGS has a negative contribution on the airflow uniformity and efficiency of radiator\textsuperscript{5}.

Among these strategies, the cooling air flow field has not been improved, in other words, the momentum loss of internal flow has not been diminished. Reducing the separation and distortion of cooling airflow is the most economical and effective way. Based on the above, a plan called AOCA (aerodynamic optimization of cooling airflow) is launched by Tongji University and CSVW (SAIC Volkswagen automotive company limited). The whole plan covers the region of airflow from bumper to engine shield, these include: grille, front buffer beam, fan housing, deflector, apron, air dam and engine shield. In this paper, a new concept of fan housing and an optimized front buffer beam are introduced (see figure 1).
EXPERIMENT EQUIPMENT INTRODUCTION

The whole research is based on the resources of Tongji University Shanghai Automotive Wind Tunnel Center (SAWTC). There are two large facilities of full scale vehicle wind tunnel in SAWTC. The aerodynamic and acoustic wind tunnel (AAWT) is equipped with high precision six component balance, rolling road system and boundary layer remove system. The maximum wind speed is up to 250kph, and the background noise is lower than 61dBA at 160kph. The nozzle area is up to 27m$^2$, and the scope of test vehicle covers from mini car to van. The climate wind tunnel (CWT) can provide a repeatable environment simulation and driving resistance to validate the performance of test vehicle, such as engine cooling and air condition evaluation. The temperature ranges from -20\degree C to 55\degree C, and relative humidity ranges from 0\% to 95\%. The 4-wheel drive chassis dynamometer has high power of engine absorption. The wind speed can follow the vehicle speed up and down quickly, and the top speed is up to 200kph with the help of 7m$^2$ nozzle. With 14m$^2$ exchangeable nozzle, CWT can be fit for commercial vehicle test, and the maximum speed is up to 100kph. These two wind tunnels have enough capabilities to finish the AOCA. Figure 2 shows the test vehicle in AAWT and CWT.

Figure 2. Vehicle tested in AAWT&CWT.
MEASURE MATRIX AND PARAMETER CALCULATION

Considering the heat transfer is taken place between cooling air and coolant, the sensors should be layout both sides for evaluating the experiment accuracy. On the air side, we need to know the temperature and volume flow of inlet/outlet cooling air. On the other side, the coolant inlet and outlet temperature and the mass flow should be measured simultaneously. According to different physical characteristics, the sensors used in this test are listed at table I.

<table>
<thead>
<tr>
<th>TABLE I. CATEGORY OF SENSORS.</th>
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<tbody>
<tr>
<td>Air (sensor/ quantity/location)</td>
</tr>
<tr>
<td>--------------------------------</td>
</tr>
<tr>
<td>Velocity</td>
</tr>
<tr>
<td>Anemometer/16/inlet plane of radiator</td>
</tr>
<tr>
<td>Type Κ thermal coupler/16/inlet &amp; outlet plane of radiator</td>
</tr>
<tr>
<td>Rotating speed</td>
</tr>
<tr>
<td>Currency</td>
</tr>
<tr>
<td>Voltage</td>
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<tr>
<td>Open ratio</td>
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</table>

For the cooling air volume flow measurement, we take a different layout way. According to the flow field of fan system, the 16 anemometers distribute on the intercooler non-uniformly. With this method, each anemometer can represent corresponding area more accurately. Four mainly parameters will be calculated by the results of measurement throughout the study process. Table II shows their definition and formulation. Figure 3 shows the distribution of anemometers and the area dividing of cooling air volume flow calculation.

The test has been done on both single cooling module and vehicle. For evaluating the effect, the cooling air volume flow and uniformity have been compared. In order to verify the effect and influence of FHAGS, thermal equilibrium experiment in CWT and aerodynamic test in SAWTC have been done respectively.

Figure 3. The layout of anemometers.
TABLE II. PARAMETER DEFINITION AND FORMULATION.

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling air volume flow</td>
<td>$Q_v = \sum_{i=1}^{n} v_i \cdot A_i, \quad n = 16$</td>
<td>$m^3\text{.min}^{-1}$</td>
</tr>
<tr>
<td>Cooling air mass flow</td>
<td>$Q_{m} = \sum_{i=1}^{n} \rho \cdot v_i \cdot A_i, \quad n = 16$</td>
<td>$\text{Kg}\text{.min}^{-1}$</td>
</tr>
<tr>
<td>Uniformity of airflow</td>
<td>$ \lambda = \left(1 - \frac{</td>
<td>v_a - v_m</td>
</tr>
<tr>
<td></td>
<td>here</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$v_a = \frac{1}{A} \sum_{i=1}^{n} v_i \cdot</td>
<td>A</td>
</tr>
<tr>
<td>Fan power</td>
<td>$P = U \cdot I$</td>
<td>Watt</td>
</tr>
</tbody>
</table>

FHAGS APPLICATION BRIEF

Cooling air delivery system contains two aspects: grille opening and cooling fan. Grille opening provides ram airflow, which is the main cooling airflow of a vehicle at high speed. Cooling fan gives suction airflow, which is the necessary cooling airflow of a vehicle at idle and up-hill driving. Ram airflow is associated with the vehicle velocity (V), and suction airflow is related to the cooling fan speed (n). In fact, there is a conflict between ram and suction effect. The cooling fan produces a low pressure in front of the cooling module, and the air can be sucked in. In order to increase the low pressure area, enhance the efficiency of cooling fan, there is a fan housing behind the radiator. But for ram effect, the fan housing reduces the passage area, and increases the resistance of ram airflow, it’s a negative effect. To solve this conflict, a new type of AGS technology called FHAGS (Fan Housing Active Grille Shutter) is proposed in AOCA. By adjusting the flap angle (φ) of FHAG, we can control the cooling airflow passage area to find a balance between the ram and suction effect, and keep the cooling air volume flow to be adequate with lowest cooling fan speed. So the energy consumption and noise creased by cooling fan can be reduced. The fuel economy and NVH performance of the vehicle will be improved.

For realizing FHAGS, a shutter module is remodeled on the fan housing. A potentiometer is jointed with the control motor, so the flap angle (φ) can be known anytime. The shutter module can be adjusted from fully closed (0°) to totally opened (90°) automatically. When φ=90°, the cooling airflow passage area will be increased about 1.2%. Figure 4 shows the original fan housing and FHAGS fan housing.
FRONT BUFFER BEAM OPTIMIZATION BRIEF

The front buffer beam can protect the cooling module and passengers in case of a traffic crash. Most of the front buffer beam is a sheet metal part, and the shape is not friendly for aerodynamic. The front buffer beam is in front of the cooling module and pretty close, the cooling airflow behind the beam is turbulence flow. This will lead to less cooling air volume flow. One aspect of AOCA is to find a streamline form of front buffer beam, and reduce the influence on the cooling air volume flow. As illustrated in figure 5, three kinds of front buffer beams have been researched. They are original beam, beam with hole and NACA beam. The cross section of the original beam just likes a plank. The beam with hole seems to dig a hole on the plank. The NACA beam is molding by clay, and the outline of cross section comes from a part of NACA23016. Compared with original beam, the cooling air passage area of another two beams increased about 7%. Actually, the cooling module and vehicle without front buffer beam have already been studied.
RESULTS AND ANALYSIS OF FHAGS

For evaluating the effect of FHAGS, experiment has been done on both cooling module and vehicle with original front buffer beam. Figure 6 shows the cooling air volume flow of ram and suction effect of FHAGS. Under ram effect, the cooling air volume flow both increased for cooling module and vehicle when FHAGS was fully opened, the maximum increase is about 8%. Under suction effect, the cooling air volume flow reduced when FHAGS was opened, and the biggest drop is about 18%. Figure 7 illustrated that for ram effect, the uniformity of cooling airflow of opened FHAGS was better than closed, but the opposite result was achieved for suction effect. That is to say, FHAGS should be closed when suction effect is the main source of cooling airflow.

As shown in figure 8, the best way to verify FHAGS is vehicle thermal equilibrium experiment. When the coolant temperature did not reach the critical value, the fan speed reduced from 2800 rpm to 1000 rpm initiatively for fuel economy and fan noise reduction. A few minutes later, the coolant temperature rose up and the threshold was triggered. After calculation, FHAGS opened to the best angle (ϕ=20°). And if cooling airflow was still not enough the fan could speed up to increase the airflow. From this experiment, FHAGS has a very good effect.

For ram effect, the cooling airflow is generated by pressure difference between the cooling air inlet and outlet due to vehicle speed. Compared with suction effect,
vehicle can get “cheaper” cooling airflow. FHAGS inherits the advantages of traditional fan housing, and can provide a flexible, fast and practical way to solve the contradiction between ram effect and suction effect.

Figure 9 is aerodynamic drag coefficient deviation of the vehicle with FHAGS. The value is less than 2 count for different angle of flap. So the influence of FHAGS on aerodynamic drag can be neglected.

![Figure 8. Thermal equilibrium experiment with FHAGS.](image)

![Figure 9. FHAGS influence on aerodynamic.](image)

**RESULT AND ANALYSIS OF FRONT BUFFER BEAM**

For various reasons, the experiment of different front buffer beams was done by another vehicle, as showed in figure 10. It should be pointed out that the fan housing is the original one without FHAGS, and for getting the total contribution of front buffer beam, the tests on cooling module and vehicle without front buffer beam also have been done. From the point of aerodynamic, the optimization of front buffer beam is the same for each kind of vehicle.
As showed in figure 11, no matter with or without front buffer beam, the cooling air volume flow of cooling module and vehicle has no difference. In another words, for single suction effect, the cooling air volume flow just has relationship with the cooling fan. For ram effect of vehicle, the cooling air volume flow is almost the same between the vehicle without beam and NACA beam, and the maximal increasing is about 8%. For vehicle with hole beam, the cooling air volume nearly has no difference with the original one, it may be that the front buffer beam is just behind the front bumper, and no airflow goes through directly.

CONCLUSIONS

(1) Both FHAGS and NACA front buffer beam are aimed to do the aerodynamic optimization of cooling airflow. All of them focus on aerodynamic phenomenon, and the solutions come from basic aerodynamic mechanism;
(2) Vehicle with opened FHAGS, the passage area of cooling airflow increases about 1.2%, and makes 8% improved cooling air volume flow. By means of thermal equilibrium experiment, the advantage of FHAGS is verified;
(3) Under suction effect, the front buffer beam has no influence on the cooling air volume flow, and the cooling air volume flow only has relation with the cooling
fan. For ram effect, the cooling air volume flow of vehicle with NACA beam increases about 8%.

(4) In the next work, the AOCA plan will pay attention to other aspect, and hope to have more valuable achievement in the future.

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