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Review Article

Airflow Management in Automotive Engine Cooling System - Overview

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Abstract

Engine cooling system plays a vital role in improving the vehicle fuel economy and meeting the stringent emission norms apart from maintaining the operating temperature of engine. The airflow through vehicle subsystems like the grille, bumper, hood-latch baffles, the heat exchangers, the fan and shroud is called as front-end flow. Front end flow (Underhood air flow) is crucial factor in engine cooling system as well as in determining the aerodynamic drag of vehicle. This paper discusses the front end flow rate prediction, factors influencing the front end flow and its influence on vehicle drag. Further the trends in the aerothermal management in order to improve the front end flow and vehicle performance also discussed.

Keywords: *Engine cooling system, Front End Flow, Cooling drag, Airflow circuit, Fan, Radiator*

1. Introduction

The airflow through vehicle subsystems like the grille, bumper, hood-latch baffles, the heat exchangers such as condenser and radiator, the fan and shroud is called as front-end or underhood or cooling air flow (Fig.1). The amount of airflow through the engine compartment is determined by the front end vehicle geometry, the cooling system package and the engine compartment geometry including the inlet and outlet sections. The airflow in the underhood is driven by fan/ram air. During idling condition fan is the main source and in vehicle running condition ram air is the main source for driving air. However this will change with respect to vehicle speed.

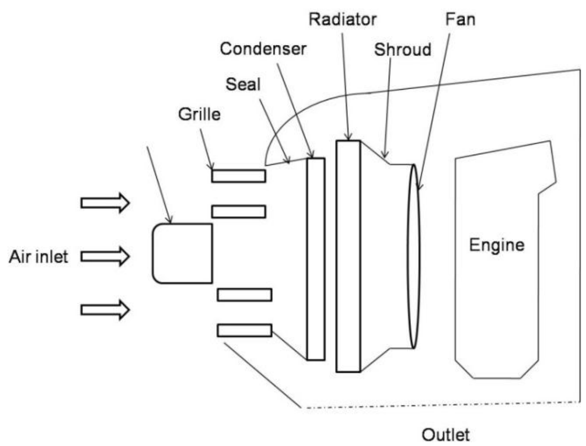

Fig.1 Front End Flow

The knowledge of airflow through underhood with respect to the engine cooling system becomes more important recently. The necessity of this kind of study from various researchers' aspect as follows

- The objective of cooling airflow subsystem is to achieve the required heat exchanger air mass flow rate, with minimum power consumption while maintaining aerodynamic drag and noise within vehicle NVH target (Peter Kanefsky *et al* 1999, Hu *et al* 2011)
- No link established between the airflow uniformity through the heat exchanger and cooling drag (D Hondt *et al* 2011)
- The interaction between underhood airflow and external aerodynamics is not yet fully understood (D Bader *et al* 2011)
- The influence and impact of cooling flow rates are not studied and configurations favorable to engine cooling are undetermined. (Marion D Hondt *et al*, 2011)
- Increase in air velocity has much impact on the overall heat transfer coefficient than the effect due to increase in mass flow rate of coolant (Naraki *et al* 2013, Karthick *et al* 2012)
- Thus for optimum design of cooling system, subjects to be studied to ensure satisfactory performance are Heat exchanger and airflow (Masatoshi *et al* 1993). Much detailed review available on Heat exchanger development (R. K. Shah 2003, Josef kern and JochenEit el 1993, L.P. Saunders 1936).

The above facts delineates a clear path towards the development of airflow management in engine cooling system is essential in the automotive systems.

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There are reviews available on engine cooling system (S C Pang *et al* 2012, H H Pang *et al* 2004). Khaled *et al* 2014 reviewed the influences of components architectural arrangement on aerothermal behavior in the underhood compartment. In automotive systems energy consumption, management and recovery has been reviewed by fabiochiara *et al* 2013 focusing on conventional powertrain. Still it lags a clear picture on front end flow rate prediction, factors influencing front end flow and aerothermal management in automotive systems.

Objective of this work is to develop an understanding of airflow management with respect to the engine cooling system as well as opportunities and potential challenges in improving the front end flow and vehicle performance. Recently Wamei Lin and Bengt Sunden 2010 reviewed the importance of vehicle engine cooling system(ECS) for reducing fuel consumption and Carbon dioxide. Impact of ECS on vehicle cost reduction was discussed by Neal A. cook 1972, Michael sortor 1993.

This paper has been arranged in the following way. First it discusses the current status on airflow management in the engine cooling system focusing on –front end flow rate prediction, factors influencing the front end flow and its influence on vehicle drag. Then current, past and future trends in the aerothermal management of underhood components in order to improve the front end flow and vehicle performance followed by conclusion.

2. Front End Flow rate prediction

This section discusses about finding out the front end flow rate in automotive using CFD tools and experimental methods. The various modeling techniques and measurement methods are discussed here.

2.1 CFD analysis

For a vehicle the required amount of front end flow rate can be predicted with the help of operating point. Operating point is defined as Intersection of the system resistance curve and the fan performance curve (Fig.2). System resistance curve represents the total pressure drop in airflow from the grille entrance area to exit region of vehicle. Fan performance curve represents pressure rise vs flow rate of a particular fan. CFD modeling, can be used to predict system and fan resistance curve. (Damodaran *et al* 2003, Shigarakanthi *et al* 2011, Dube *et al* 2007, SadekRahman *et al* 2010, Regin *et al* 2014)

Mostly CFD tools used to predict the front end airflow rate. In CFD modeling, the obstructions in the airflow path from grille entrance area to exit area needs to be captured as it's in real vehicle.

The vehicle domain and the flow domain size plays a major role in front end flow rate prediction. (K D Huang *et al* 2004). The recommended guideline for flow domain as follows

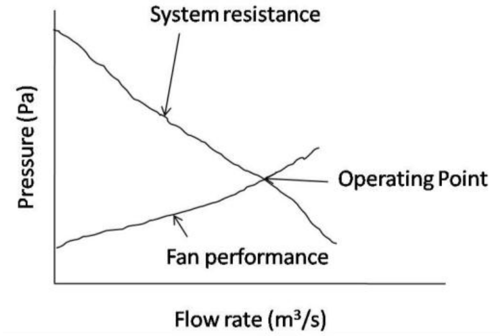

Fig.2 Predicting operating point using system resistance and fan performance curve

From the sides and above vehicle model: five characteristic length.
In front of the bumper: Eight characteristic length.
Behind vehicle domain: four characteristic length.
(Characteristic length is the distance between the bottom of the vehicle to the top of vehicle domain)

The various flow resistances in engine compartment and modeling techniques of the various underhood components as follows

2.1.1 Perforated inlets: Sudden expansion and contraction leads to losses at perforated inlets. Momentum sinks are calculated and included in the momentum equations (sami *et al* 1994). Rosberry 1990 studied on the grille coefficient. They defined the grille coefficient as a fraction of free stream total pressure which is delivered through grille.

2.1.2 Radiator core: The radiator was modeled using lumped blockage approach and average porosity factor used throughout the radiator (sami *et al* 1994).
Hur *et al* 2009 proposed Semimicroscopic heat exchange (SHE) method. SHE method was employed to do conjugate heat transfer analysis in the regions of coolant water in a tube, tube wall, louver fin and ambient air. The louver fin region has been separated into air and solid porous media. The temperature difference in between these two porous media determines the local heat flux. The obtained results are in good agreement with experimental results. Sang Hyuk Lee *et al* 2014 proposed further modification in SHE method.

2.1.3 Fan modeling

The various methods available for fan modeling as follows
a) Body Force Model
This model also known as Lumped Fan model. In this model fan characteristics represented rather than modeling the geometry of the fan blades. The experimental results of fan blade characteristics curve are represented as Pressure Jump boundary condition in CFD analysis. The accuracy of this model depends upon the fan blade characteristic curve. (Wang *et al* 2005, Sami *et al* 1994)

Table 1 Overview of various flow measurement methods (Ng *et al* 2004) E-excellent, M-moderate, P-poor

Technique	Time effectiveness	Cost effectiveness	Simplicity of use	Accuracy, volume flow rate	Accuracy, airflow distribution	Suitable for on road testing
Propeller anemometer array	E	M	M	M	P	E
Propeller anemometer rake	E	P	P	E	E	P
HWA	P	M	P	E	E	P
HFA	P	M	P	E	E	P
LDA	P	P	P	E	E	P
PIV	P	P	P	E	E	P
Pitot-static tube	M	E	E	P	P	P
Multi-hole pressure probe	M	P	P	E	E	P
Thermistor	E	E	E	P	P	P

(HWA - Hot Wire Anemometry, HFA - Hot Film Anemometry, LDA - Laser Doppler Anemometry, PIV - Particle Image Velocimetry)

b) Multiple Reference Frame (MRF) Model
In this model the geometry of fan blades are represented. No need to depend on the experimental results of fan blade characteristic curve. The fluid zone of fan region is modeled as rotating frame and the surrounding zones are modeled as stationary frame. (Wang *et al* 2005). MRF model is a steady state approximation.

c) Sliding Mesh Model
As the rotor stator interactions are time-periodic the fan modeling requires the flow to be solved in transient method. This method very time consuming which makes it impractical for industrial application. (Wang *et al* 2005)

A brief discussion on the fan modeling methods discussed by sami *et al* 1994, H. Knaus *et al* 2005. More fan modeling research is needed in the area of fan resistance and radial flow to make the model more suitable. Mostly MRF model is used in underhood flow simulation.

The front end flow rate can be predicted with two-dimensional computation domain. (Jongsoo *et al* 1993, kazuo kawashima *et al* 1988)

2.2 Experimental Measurement

The measurement of airflow through radiator/underhood system is a challenging task. But the knowledge of airflow distribution and determination is a key factor in determining the more suitable front-end configuration for the cooling capacity as well as aerodynamics.

The various methods available for airflow measurement and its merits and demerits are shown in Table-1. The various available literature are (Rick Ruijsink *et al* 1993, Helmut *et al* 1993, E Y Ng *et al* 2004).

3. Factors influencing the front end flow

This section discusses the factor which influences the front end flow and the required operating condition of front end flow. Different people categorized in different way.

The engine compartment is fully occupied with the lot of components which acts as obstruction in the airflow passage. Refki EI-Bourini 1993 studied on the influence of front end components on vehicle engine compartment air flow.

Olson 1976 studied the aerodynamic effects of front end design on automobile engine cooling systems. The influences of the bumper, grille, air dam, fan and shroud were clearly noticed. The various factors which influences the front end flow rate from the different researchers aspect as follows.

There are four major contributions to the air side system resistance in automotive cooling system. They are front end resistance, engine blockage, engine bay exit path loss and engine bay back pressure due to vehicle motion. Detailed list as shown Fig-3 (U N Schaub and H N Charles 1980)

The parametric diagram for cooling airflow subsystem as per Peter Kanefsky *et al* 1999
Unwanted Engine heat → Airflow subsystem → Air mass flow rate

The control factors are system resistance, fan geometry, fan speed, fan tip clearance, protrusion of fan shroud, fan shroud geometry.The side effects are fan power consumption, fan noise, and aerodynamic drag.

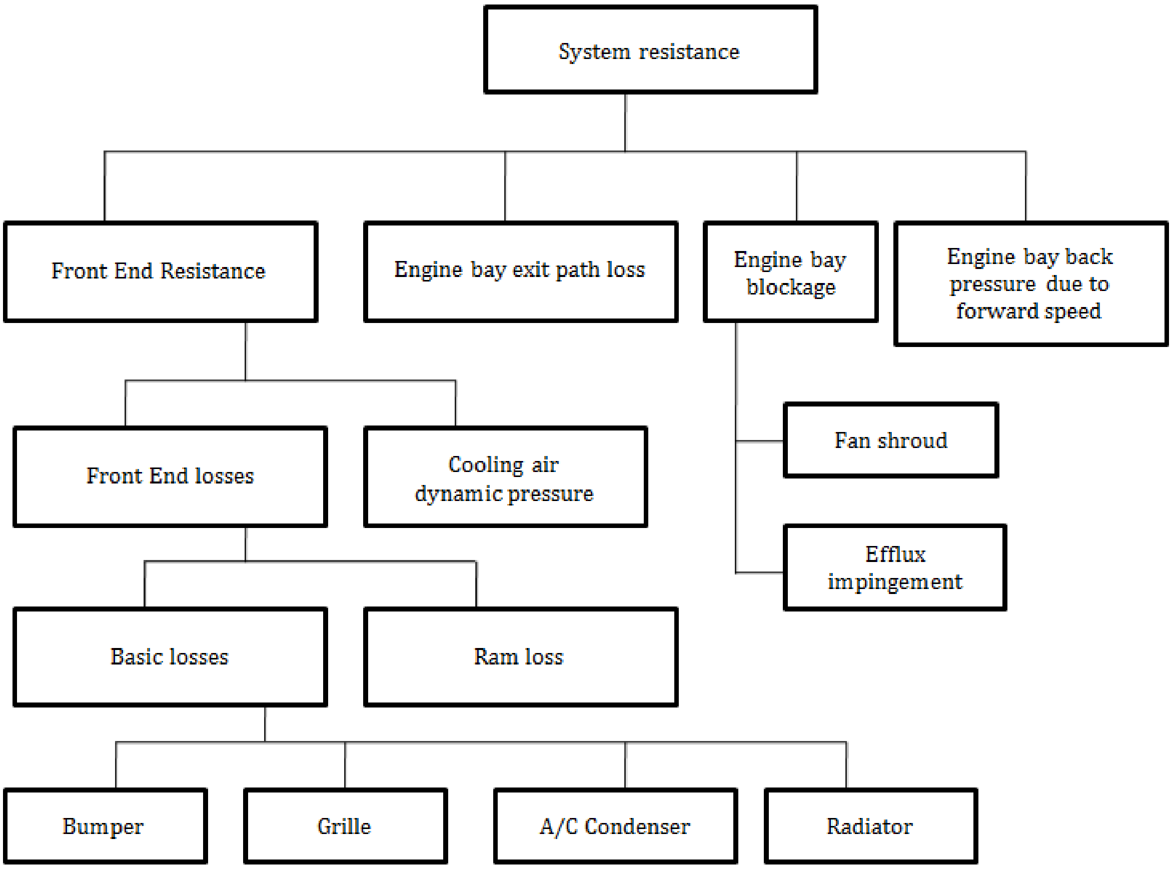

Fig.3 system resistance chart(U N Schaub and H N Charles 1980)

The parameters that characterize the air circuit of an engine cooling systems as per A Costelli *et al* 1980,

- System resistance
- actual fan performance and its coupling with system
- aerodynamic efficiency of air intake (ratio of average air velocity through radiator and vehicle speed)

Significance of the parameters which affects underhood air flow with respect to engine cooling system are classified as follows. (Taylor *et al* 1976).

Fan characteristics, Projection of fan into shroud - Highly significant parameter.

Fan to radiator distance, radiator characteristics, and fan tip to shroud clearance - Significant parameters.

Fan to engine block distance and type of shroud - Not significant parameter.

It is to be noted that type of shroud is not important, but shroud to be used to maintain a reasonable tip clearance. It has been shown that shape of the fan shroud can be of great importance for some cases and not in some other. But the depth of shroud is most critical parameter. Increasing the depth influences both mass flow and uniformity. Fan projection into the shroud influences the performance of fan. (Thomas Hallqvist 2008, X Hu *et al* 2011)

The recommended operating conditions of front end air flow as follows (Hoshino *et al* 1981)

a. Cooling airflow rate: As high as possible. But to be optimized in such a way to reduce the drag.

b. The turbulence of cooling airflow: As low as possible.

c. The cooling airflow distribution on the radiator front: Uniform. Influence of flow distribution on radiator has been addressed by other researchers also.(Esmeili *et al* 2010, Tomasz Bury 2012,Ng *et al* 2005, WaiMeng Chin 2013, M Khaled *et al* 2011, Oliet *et al* 2007)

d. The cooling airflow leakage at radiator front: To be minimized.

The influence of air flow leakage in the engine compartment discussed separately by M Khaled*et al* 2014.

Still the influence of blade thickness on the fan performance is a open question. (C Sarraf *et al* 2011)

4. Front end flow and drag

This section discusses on cooling drag and factors which influences cooling drag mainly front end flow.

The cooling drag coefficient in wind tunnel is evaluated by measuring the aerodynamic drag of vehicle with opened and then closed air inlets. In old cars (1970 - 1980 era) the cooling drag contribution is around 0.04 counts (Hucho 1998). The contribution of cooling drag into the total drag generally varies from 5% to 10%.

(Barnard 2000). The area and resistances offered by cooling air inlet, outlet and heat exchanger are the main drag contributors.

Increasing the cooling air inlet area beyond a certain value does not change the cooling mass flow whereas increases the cooling drag. (D Baeder 2011, 2013)

It was found that the location of air outl*et al*so influences the cooling drag. Cooling airflow outlet located at the base of geometry favors low cooling drag value compared to an outlet located in the underbody. (Hondt and Gillerion 2011). Air exiting the wheel house has much contribution to the cooling drag. (D Baeder *et al* 2013). The relation between aerodynamic drag of radiator with cooling air flow was reported as nonlinear. (Petrov 2008)

5. Current, Past and Future trends in Front End Flow management

The Grille opening area, Heat exchanger and fan are the key players for better air flow management. This section outline the existing, past and future technologies on these things.

5.1 Grille Opening Area

Openings in front of the radiator through which air enters into the vehicle front end is called as Grille Open area (GOA) or front end opening area. This area determines the amount of air entry into the engine compartment. GOA also plays a role in temperature stabilization of underhood components. However TanjuSofu *et al* 2004 observed that underhood temperatures are stabilized near an air flow ratio of 2. The ventilation air flow rate was normalized with respect to engine combustion flow rate.

It was shown that upto 13.5% reduction in drag value of vehicle could be attained by closing the GOA (MIRA report). The GOA should be in such a way that it allows the optimal ram air only which meets the functional requirement of respective system. Reduction in the unnecessary ram air entry into the engine compartment can be done by the optimizing the size and location of GOA.

The various criteria which has been used to fix the GOA as follows

- Basically the GOA is based on the rule of thumb or projected radiator area design standards.
- Front end opening ratio (open area of front end divided by radiator area) of approximately 30% is desirable to meet the styling requirements (Kazuo kawashima and Fugi 1988).
- The recommended area ratio between inlet section of grille and frontal surface of radiator is 0.4 (Ngy *et al* 2002)
- Jack Williams 1985 proposed a performance based approach to fix the GOA. It is expected that large GOA provides huge air flow. But in reality it was observed that GOA is not a very good predictor of cooling air flow, specifically at 30 mph grade condition. They established a statistical relation between grille open areas, drag and ram airflow.
- Smaller front grille opening and large engine cooling fan will favor the fuel economy. It's mentioned that this is not a general guideline for vehicle development. (Bing Xu *et al* 2013)
- Vehicle system resistance curve and coolant inlet temperature are used to optimize the front grille opening area (Regin *et al* 2014)

Various configurations of grille and front end intake geometries of a passenger car were investigated with respect to mass flow and mass flow distribution on engine cooling components (Knaus *et al* 2005, Myung-SeokLyu *et al* 1996)

Four different shielding methods were employed to determine best among them. The shielding methods were vertical, horizontal, side-to-side and side-to-center. It was observed that the best method of shielding would be horizontal method followed by vertical method. More uniform airflow distribution obtained in horizontal method compared to others. (Jama *et al* 2004)

S. D. Oduro 2012 assessed the effect of blockage of front end air flow with respect to the coolant inlet and outlet temperature. It was observed that percentage area covered resulted in the increase of coolant inlet and outlet temperature.

As the GOA to be based on the performance oriented rather than based on thumb rule. And it needs a lot of study on engine compartment components to meet the airflow requirement. With the advanced technology there is a concept called Active Grille shutter system, which opens and close the grille automatically.

5.1.1 Active grille shutter system (AGS)

The shutters open and close automatically to control airflow, reduce aerodynamic drag and by the way improves the fuel efficiency. The car manufacturers using active grille shutters include General Motors, Chrysler, BMW, and Honda.

Shigarkanthi *et al* 2011 studied the application of design of experiments and physics based approach in the development of aero shutter control algorithm. Active aero shutters are devices that control the airflow through heat exchanger module to optimize the balance between aerodynamic drag and engine cooling. The predictive algorithm of aero shutter predicts the cooling need of the system and actuates the engine cooling fan and shutter to different position to meet the real time cooling requirement.

There is a reduction in the fuel economy up to 2.6% (Rashad Mustafa *et al* 2012). AGS provides reduced air resistance as well as reduction in engine loss (El-Sharkawy *et al* 2011)

5.2 Heat Exchanger

The heat exchanger (Radiator) position, performance and its material plays a crucial role in offering resistance to the airflow path.

With improved heat exchanger performance there is a scope to minimize the requirement of the airflow. The distance between the radiator and engine block will be adjusted automatically to increase heat exchangers evacuation capacity in situations during engine over heat condition. It was observed that increase in heat transfer performance of radiator about 18% at fan low speed and 7% at high speed (Khaled *et al* 2012). This helps in reduction of compressor and pump work which ultimately reflects in vehicle fuel consumption.

The heat exchangers like condenser, Radiator and Charge Air Cooler are located behind the grille offers resistance to the airflow. Especially the arrangement one behind the other increases the resistance. It was found that by placing them in parallel the overall thermal performance improved by 4.4% and 0.9% of pressure losses were eliminated (Khaled *et al*, 2011)

It was proposed that placing a heat exchanger at the roof of the heavy vehicle driver compartment (countercurrent flow) could be a good option. (Wamei Lin *et al* 2012) With increased power requirement and underhood space requirement in vehicle, a countercurrent heat exchanger was proposed on the roof of vehicle.

Recently enormous study available on the performance of radiator using nano materials as coolant. And it resulted in considerable enhancement in thermal performance and reduction in frontal area of radiator (Leong *et al* 2010). Shanti *et al* 2012 conducted a detailed review on the application of nano material and its limitation. Kim *et al* 2010 has done a study on radiator performance using Phase change material as a coolant.

Another efficient method to increase the thermal performance of heat exchanger is the utilization of foam materials. The graphite foam fin has higher heat transfer coefficient than aluminum. It is to be noted that this method is preferable in application where reduced heat exchanger volume is favored over reduced mass or COP (Wamei Lin *et al* 2014). But the pressure drop through graphite foam is huge. And it was concluded that there are still several problems in developing the application of graphite foam heat exchanger in vehicle. (Patrick *et al* 2010)

R. J. Gaeta 2004 evaluated aerodynamic heat exchanger. A 2D wing was fabricated and radiator core was integrated into it. Three different materials were investigated: Aluminum finned, dense carbon-graphite foam material, smaller carbon-graphite foam fins. This device has low drag and Carbon-graphite foam shows optimal performance. However Pneumatic system and coolant pump size are the concerns for commercialization.

5.3 Fan

Fan could consume 4.5 kW of engine power at a vehicle speed of 112 km/h in the older design medium sized car (White). It was observed that cooling air moved by fan alone was less power consuming than when the cooling air was moved jointly by the fan and ram pressure. SP Haws 1976 reported that, compared to a fan, the use of ram air would require over 30% more power from an engine with same radiator air circuit and cooling requirement. It was recognized that electric fan performance is better than viscous fan. (Terrace *et al* 1979, J H Kim *et al* 2011, David Martin *et al* 1991). The potential benefits are:

Improved passenger comfort; reduced interior noise; improved engine compartment packaging; improved fuel economy; reduced aerodynamic drag.

Conclusions

This study is a comprehensive outlook on the research progress made in airflow management of automotive front end underhood flow with respect to engine cooling system. The objective is to maximize cooling airflow with minimal cooling drag and packaging constraints. More research is required to optimize the cooling flow entry into the engine compartment, especially in the area of active grille shutter system. The strategy on fan modeling to be explored more like with minimum fan power consumption and optimal airflow delivery. Advanced research on countercurrent flow, Nano materials as coolant and fin materials would help to minimize the heat exchanger contribution on vehicle drag. Still integration of optimal front end flow with minimum cooling drag, aesthetic front end styling with minimal cost continues to be herculean challenge.

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