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AutomotiveCooling Systems for Reducing Fuel Consumption and Emissions

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Abstract

The vehicles in use are increasing from year to year. It leads to more fuel/energy consumption, and more carbon dioxide or other exhaust gases are released to the environment. The emissions norms have become stricter than before. To adhere with such a stringent requirements, some advanced technological solutions need to be developed to reduce fuel consumption and emissions from vehicles. More than half of the energy in vehicles is lost to different cooling systems and exhaust gas. Fuel efficiency of the vehicles can be enhanced by reducing the amount of energy lost in vehicle. This paper presents a literature survey of automotive cooling systems. The flow field and thermal management are important factors for designing the engine cooling system. Whereas the exhaust gas can be re-circulated to the engine to reduce emissions. This literature survey is offering a starting point for future research in the Automotive cooling systems.

Keywords:*Fuel consumption, exhaust gas, cooling system, emissions*

1. Introduction

In last couple of years the number of vehicles being used has constantly increased. Table 1 shows the number of registered trucks and buses in selected countries has increased from 179,498 to 266,236 in the years from 1998 to 2007. Increasing number of vehicles causes more energy/fuel to be consumedandmoreexhaustgases tobereleasedtotheenvironment.Table2shows the highway transportationpetroleumconsumption.Figures in Table3shows the emission of carbon monoxide. In order to keep the sustainable development of vehicles, different alternative fuels are used, as shown in Table 4. In addition, more stringent emissions are introduced. These forces the vehicle manufacturers to develop advanced technological solutions to meettheemissionnorms.Accordingtothelegislations in Europe, average emission of new passenger car registered in the European Union must not exceed 130g CO_2/km from 2012 onwards [1].

A lot of technical developments has been introduced in order to meet the low fuel consumption and low emission requirements of vehicles. In [3] few advanced engine technologies were discussed in view of reducing emissions. They included improving the combustion process, using a flexible fuel injection system, high rates of exhaust gas recirculation (EGR), improving the engine control systems, charge air and coolant temperature control, low friction, Advanced exhaust after treatment system recuperationofenergycontainedintheexhaustgasstream and so on. More investigation about technique of reducing vehicle emissions can be found in [4,5,6,7].

Year	China	India	Japan	France	UK	Germany	Canada	USA	World total
1998	8313	2610	20919	5500	3169	4357	3694	79062	179498
1999	9400	3000	20559	5609	3392	3370	722	86640	188367
2000	9650	2390	20211	5753	3361	3534	739	85579	203273
2001	10212	2663	19985	5897	3412	3592	729	87969	207033
2002	10500	3535	17714	5984	3487	3568	724	91120	210776
2003	17222	4025	17312	6068	3569	3541	740	95262	223729
2004	19800	4190	17012	6139	3696	3540	745	98576	233537
2005	21750	4415	16734	6198	3943	3133	786	104788	245798
2006	24000	4850	16731	6230	4041	2766	841	109596	256222
2007	26336	5327	16505	6297	4164	2837	872	113477	266236
				Average annual percentage change					
1998-2007	**13.2%**	**7.1%**	**-2.6%**	**1.7%**	**1.3%**	**-0.9%**	**-11.9%**	**3.6%**	**3.3%**

Table 1 Truck and bus registrations for selected countries

Year	Cars	Light trucks	Light vehicles subtotal	Motor-cycles	Buses	Heavy trucks	Highway subtotal	Total transportation
1997	4559	3222	7781	13	91	1949	9834	11777
1998	4677	3292	7969	13	93	2012	10086	12061
1999	4780	3448	8228	14	96	2212	10550	12639
2000	4766	3453	8219	14	98	2298	10630	12792
2001	4798	3491	8290	13	93	2295	10690	12672
2002	4923	3602	8525	12	91	2401	11029	12938
2003	4866	3963	8829	12	90	2334	11265	13108
2004	4919	4137	9055	13	92	2162	11323	13344
2005	5050	3840	8890	12	93	2426	11422	13537
2006	4893	3959	8852	14	94	2476	11436	13605
2007	4850	4032	8883	16	92	2515	11505	13710
				Average annual percentage change				
1997-2007	**0.6%**	**2.3%**	**1.3%**	**2.1%**	**0.1%**	**2.6%**	**1.6%**	**1.5%**

Table 2 Highway transportation petroleum consumption by mode (thousands of barrels per day)

Source category	1970	1980	1990	1995	2000	2005	Percent of total, 2005
Gasoline powered							
Light vehicles & motorcycles	119.4	98.21	67.24	46.54	36.40	24.19	50.2%
Light trucks	22.27	28.83	32.23	29.81	27.04	21.19	43.9%
Heavy vehicles	21.27	15.35	8.92	5.96	3.42	1.97	4.1%
Total	162.68	142.39	108.39	82.31	66.86	47.35	98.2%
Diesel powered							
Light vehicles	0.01	0.03	0.04	0.02	0.01	0.01	0.0%
Light trucks	0.06	0.05	0.03	0.02	0.01	0.01	0.0%
Heavy vehicles	0.49	1.36	1.81	1.53	1.19	0.85	1.8%
Total	0.56	1.43	1.87	1.57	1.20	0.87	1.6%
Total							
Highway vehicles total	**163.23**	**143.83**	**110.26**	**83.88**	**68.06**	**48.22**	**100.0%**
Percent diesel	0.3%	1.0%	1.7%	1.9%	1.8%	1.8%	

Table 3 Emissions of carbon monoxide from highway vehicles (million short tons)

	2003	2004	2005	2006	2007
Liquified petroleum gas	224697	211883	188171	173130	152360
Compressed natural gas	133222	158903	166878	172011	178585
Liquified natural gas	13503	20888	22409	23474	24594
E85[a]	26376	31581	38074	44041	54091
Electricity[a]	5141	5269	5219	5104	5037
Hydrogen	2	8	25	41	66
Biodiesel	18220	28244	91649	260606	c
Other	0	0	2	2	2
Total	**421161**	**456766**	**512427**	**678409**	**c**

Table 4 Alternative fuel consumption (thousands of gasoline-equivalent gallons)

Figure 1 shows the energydistribution in vehicle engine, only about one third of the total fuel energy finally converted to useful work, another one third of the total energy input is brought away by the coolant of engine cooling system, and the rest of the energy is lost to the exhaust gases. The consumption of Fuel can be reduced if the energy wasted in the coolant or the exhaust gases will be reduced. The engine cooling system ensure that the engineworksatitsoptimaltemperature,whichisaround 80°C-90°C.If the engine cooling system can't bring away the heat quickly, the engine working temperature will increase which leads to more fuel consumption whereas the life of engine will reduce becauseof high working temperature in the engine. If the cooling system brings away the heat too fast, this will lead to an oversized radiator. That means the size and weight of cooling system will increase. More fuel has to be used due to the increasing weight. A good engine cooling system can reduce the engine starting and warming up time, in which the engine reaches its working temperature [8]. Most of the hydrocarbon (HC) and carbon monoxide (CO) are produced during starting and warming up phase [9]. Thus it is important to study the vehicle engine cooling system.

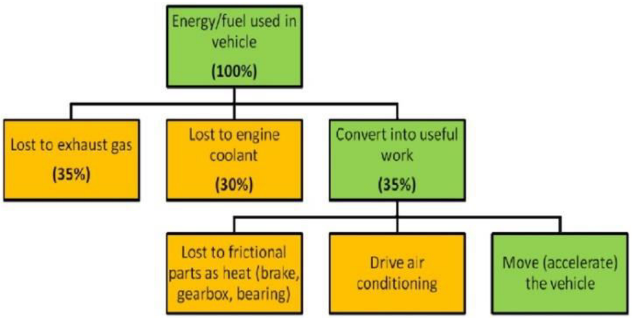

Fig.1 Energy distribution in a vehicle

The rest one third part of fuel energy is lost to the exhaust gas. The exhaust gas recirculation (EGR) reduces the exhaust gas emission in addition to this it also contribute in saving the fuel energy. In EGR process, a part of the exhaust gas goes back to the intake manifold. Before entering the intake manifold, the exhaust gas might be cooled by an EGR cooler to keep the combustion temperature below 1500°C otherwise the reaction between nitrogen and oxygen may form NO_X. The cooling extent of the exhaust gas depends on many factors. The temperature of the circulating exhaustgascanbehigherthantheambienttemperature.In this case, some energy is recovered from the high temperature exhaust gas in the EGR. Thus fuel energy can be saved by the EGR process. But if the EGR cooler has a high flow resistance, the combustion process will become bad and much fuel has to be consumed. Thus it is necessary to analyze EGR and EGR coolers.

The last thing to reduce fuel consumption is to optimize the energywhichisconvertedintousefulwork.Fromthispart of the energy, some is converted into the kinetic energy of vehicles and rest other part is converted into thermal energy by the brakingprocessortransmission(gearbox,bearing)process.

Insomevehicles,thecompressoroftheairconditioningin the compartment is driven by the engine. If the air conditioning is optimized, the compressor will consume less power from the engine. That means the engine can save some energy. Considering reduction of fuel consumption, it is a good option to optimize the friction components (brake, gearbox, bearing) cooling system and the air conditioning system.

This paper summarizes some published results about the cooling systems in vehicles, which include engine cooling system and EGR cooler. In this paper, we will introduce the engine cooling system and EGR/ EGR coolers in Sections 2 and 3 separately. A summary is presented in the final section.

2.Engine cooling system

There are two types of engine cooling systems. One is the air cooling system and the other one is liquid cooling system. Now a days the air cooling system is only used in older cars or some modern motorcycles. The liquid cooling system plays an important role in most automobiles. The liquid cooling system consist of a coolant, a radiator or other forms of heat exchangers, a radiator cooling fan, one or more circulation pumps, a thermostat and so on. Figure 2 shows a standard liquid cooling system for the engine. The radiator is the heaviest equipment in the engine cooling system. It also occupies most space in the cooling system. Thus it has to be analyzed in detail during the optimization of the engine cooling system. The coolant is also considered here. Thus a clear comprehension of the cooling system can be given. In order to optimize the engine cooling system, some technology will be presented for the whole cooling system.

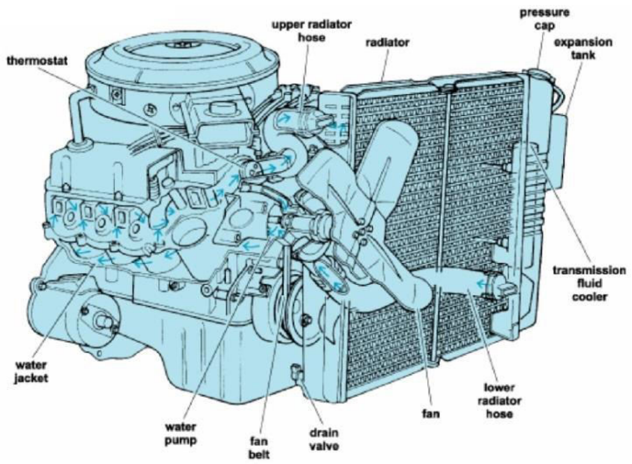

Fig.2 Engine cooling System

2.1Different component analysis
2.1.1Coolant

The engine coolant brings the excess heat from the engine, flows into the radiator where the heat is transferred to the ambient air and the coolant is circulated back to the enginefortransportingawaymoreheat.Inordertoensure that the engine can work in cold weather, the coolant must have antifreezing capability. In this case, the coolant is a mixture of ethylene glycol and water with the ratio of 50%-50%. coolant should have corrosion protection and cavitation protection. In addition to this it should be friendly to elastomer, seal, hose compatibility. Because of the increasing power densities, the vehicle thermal loads had to increase. The coolant flow rates, turbulence and pressure drops also became serious. For the future, the extended life and extended service intervalled coolants would take the place of the conventional and traditional fully-formulated coolant. On the other hand, the nanotechnology would be used to improve the thermal conductivities of the coolant.

2.1.1 Radiator

Ifthecoolantisthebloodoftheenginecoolingsystem, then the radiator would be the heart of the cooling system. This is to illustrate that the radiator plays an important role in the engine cooling system. Due to the space limitation in vehicles, a compact Radiators are favorable. Cowell et al. [13] Introduced some common constraints for the radiator design. Compactness, low pressure drop, low weight, low cost and high volume were considered. Radiator is consist of arrayoftubestocarrythe hot engine coolant with a secondary surface attached to the outside of the tubes. Meanwhile some methods were presented to reduce the cost during the radiator manufacturing. For instance, the brazing process and the mechanical expansion were good for assembling a radiator.

Experimental or numerical methods are employed to investigate what kinds of radiator shapes are economic and efficient. Due to the highcost and the complexity of experiments, numerical methods are preferred by many researchers. Oliet et al. [14] used numerical methods to carry out parametric studies for automotive radiators. The effect ofsomegeometricalparameters(finspacing,louverangle and so on) and the importance of coolant flow lay-out on the radiator global performance were studied. The results showed that the air inlet temperature did not affect the overall heat transfercoefficientU_0 (asshowninFigure 3).Ontheother hand the coolant flow regime (Re number) had a relationship with $U_0$when coolant fluid or coolant flow arrangement varied.Figure 4showsthatU_0 wasincreaseswithincreasing Re, even under different flow arrangement (1 pass arrangement (I), 2 pass arrangement (U), 3 pass arrangement (U_{by-3})).Whentheflowregimewasconsideredacceptable, the U (2 pass flow arrangement) -flow coolant arrangement was not as good as I (1 pass flow arrangement)-flow. Carluccio et al. [15] did a numerical study with a thermo-fluid-dynamicanalysisforanair-oilcompactcross flow heat exchanger, which was used in ground vehicles. The finconfigurationisshowninFigure 5.At theoilside,the geometry of the offset fins did not cause a high level of turbulence, which can increase convective mass and heat transfer. It only increased the surface area. On the air side three different flow rates were used to estimate the influence of the air channel geometry.

Based on a geometrical configuration study, it was found that the heat transfer of the suggestedfins(asshowninFigure 5)canbeenhancedtwice compared to the straight triangular fins.

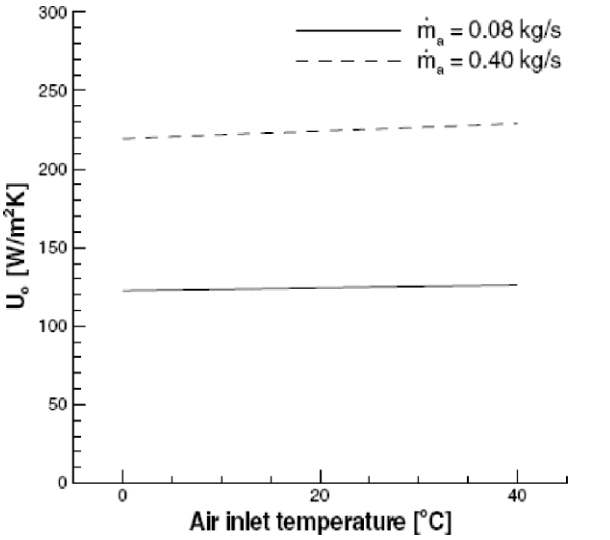

Fig.3 Air inlet temperature influence on the overall heat transfer coefficient (U_0) [14]

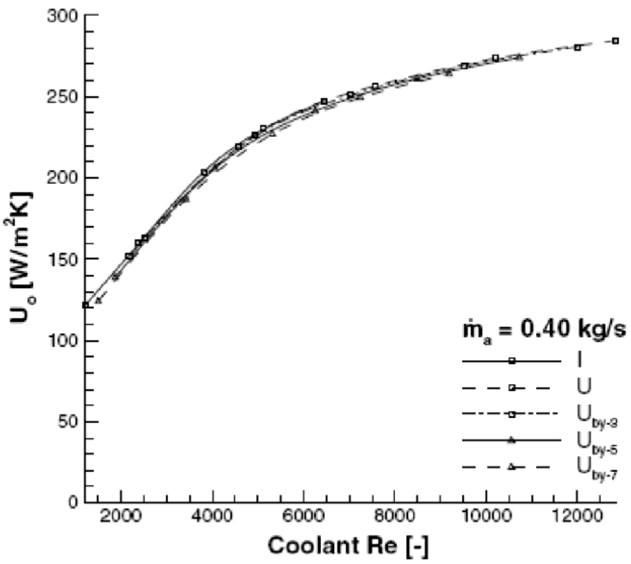

Fig.3 Coolant lay-out influence on the U0 [14]

The major material for a radiator is aluminum or copper, due to the high thermal conductivity. In 1997 Oak Ridge National Laboratory invented a new material (graphite foam) with very high thermal conductivity (1700 W/m.K) and high bulk apparentthermalconductivity(40-150W/m.K). Theweight ofthisfoamisonlyabout1/5thatofaluminum.

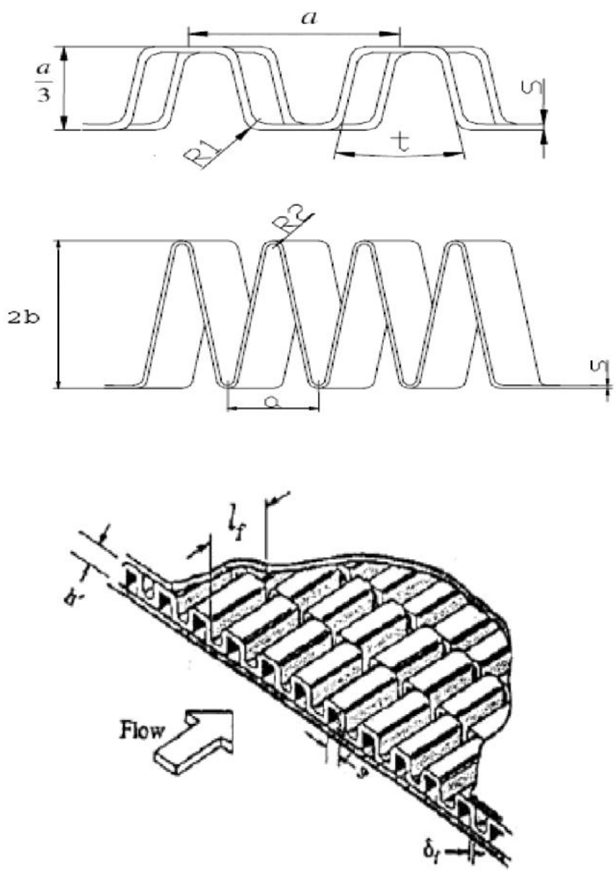

Fig.5 The first one is the fin shape on the oil side, the second one is the fin shape on the air side, the last one is a typical offset strip fin core, for oil side [15]

The major material for a radiator is aluminum or copper, due to the high thermal conductivity. In 1997 Oak Ridge National Laboratory invented a new material (graphite foam) with very high thermal conductivity (1700 W/m.K) and high bulk apparentthermalconductivity(40-150W/m.K). Theweight ofthisfoamisonlyabout1/5thatofaluminum.Theopen and interconnected void structure leads to a special surface area with 5000 and 50000 m2/m3. Klett et al.[16] reported the properties of carbon foams. Figure 6 shows the photomicrographs of the foams. The bubble size affected the

operatingpressure.Thebulkthermalconductivitywas150 W/m.K and the specific conductivity was six times that of copper. Klett et al. [17] suggested utilizing graphite foams for heat exchangers in heavy vehicles. Because of the high thermal conductivity and the low density (0.47 g/cm3) of foam, this new heat exchanger was smaller and lighter than the one made by aluminum or copper. The overall heat transfer coefficient was 2500 W/m2.K, which was much higher than the one of the standard automobile radiator (30W/m2.K). But there was a very high pressure drop inside a foam heat exchanger or heat sink, because of its alveolate structure. Leong et al. [18] analyzed four different shapes of a heat sink as shown in Figure 7.
Highest pressure drop (as shown in Figure 8) appeared for block and baffle foams. On the other hand, the high thermal conductivity capacity of foams only exists in a special direction. More information about foam thermal performance can be found in [19-20].

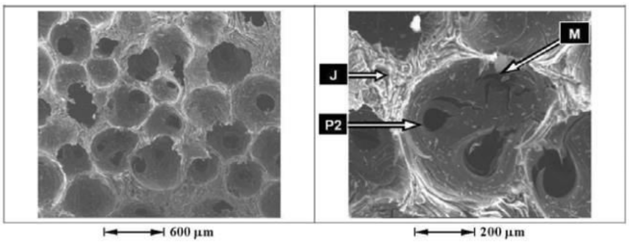

Fig.6 Photomicrographs of the foams **[**16**]**

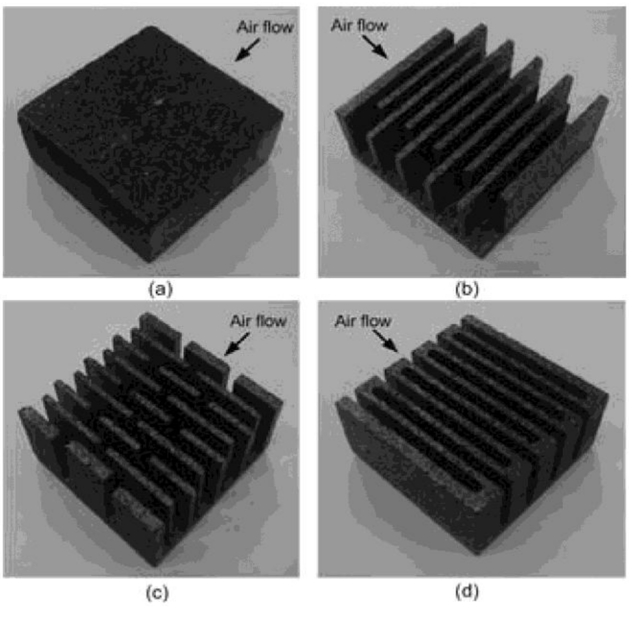

Fig.7 Test graphite foam heat sinksof (a) block, (b)staggered, (c) baffle and (d) zigzag configurations [18]

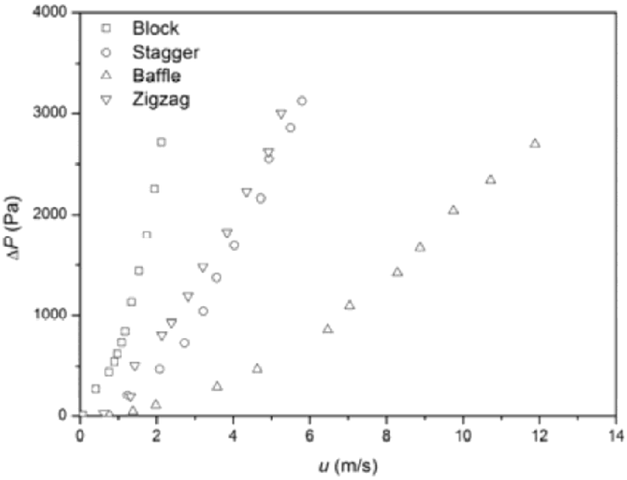

Fig.8 Pressure drop versus inlet flow velocity of air flow through tested configurations [18]

For the radiator, it is very important to find a suitable manufacturing method, which can reduce the cost and improve the heat transfer performance. Witry et al. [21] introduced an aluminum roll-bonding technique for producing automotive radiators. Figure 9 s h o w s s u c h an aluminum roll-bonding design. This method was one of the cheapest methods for heat exchanger manufacturing. For this kindofradiator,theinternalheattransferincreasedbecause of the repeated impingement against the dimple obstructions. The heat transfer also increased for the external flow because of the wider and wavy nature of the surface area. As a whole, higher heat transfer levels, lower pressure drop levels, lower overall vehicle drag, smaller size radiators and cheaper manufacturing were the strengths of the roll-bonding heat exchanger design.

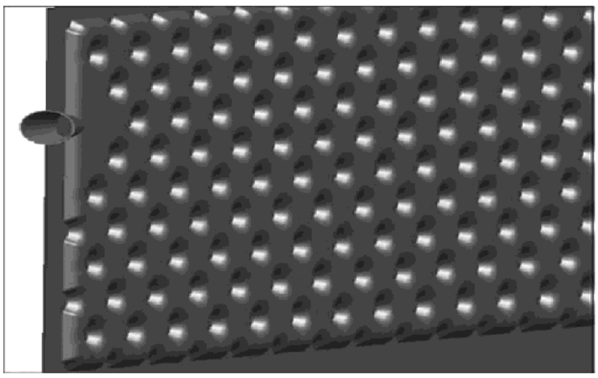

Fig.9 Partial dimple plate geometry [21]

2.2Analysis of whole engine cooling system
2.2.1 Engine cooling simulation

It is useful to analyze the different components of the engine cooling system separately. But an overall comprehensive investigation of the whole engine cooling system would have high possibility to identify the key factors that affect the fuel consumption. Computer simulation is a good tool to understand the cooling performance of a whole cooling system.Kim[22]developeda3DCFDprogramtoanalyze the performanceof the vehicle cooling system. Figure 10 presents the simulation results of flow field around the vehicle. The simulated air speed in front of the radiator only deviated 7.9 % from the test data. The coolant inlet temperature had a linear relationship with the radiator performance. The partial displacement fan or the increased fan power at high speed had no impact on the coolant inlet temperature. Zheng et al. [23] introduced the finite-element method to calculate the thermal field so that the hot spot(s) can be found and the cooling system of the 4QT (a four- quadrant transducer) can be investigated. The result showed that the stator windings were mostly dependent on the water cooling system. However, the forced-air cooling had influence on the inner rotor winding temperature.

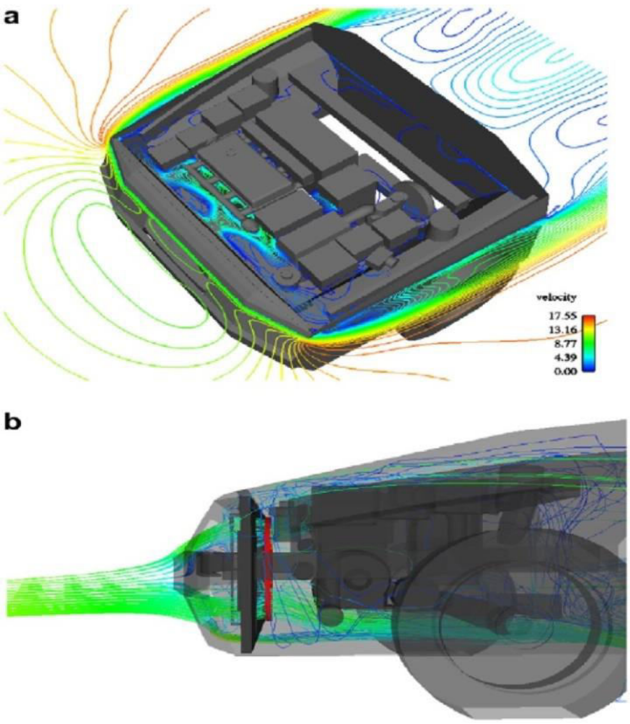

Fig.10 “a” shows the contours of the air velocity in the vehicle model, “b” shows the air particle traces through a vehicle model [22]

2.2.2Important aspects of the performance of Engine cooling systems

Some aspects have great influence on the fuel consumption in vehicles. These include the flow field and the thermal management.

2.2.2.1Flow field

The flow field caused by the movement of the vehicle affects the engine cooling performance. It also has influence on the fuel consumption by the mode of flow resistance. A two dimensional simulation has been performed , two-dimensional simulation to analyze the characteristics of the cooling air through the radiator and the engine. The two-dimensional computation was not an excellent tool for predicting three-dimensional flow field. But it was a fast and efficient tool for predicting the flow rate of the cooling air through the radiator. There was a good agreement between the simulation and experimental methods for predicting the radiator thermal performance, as shown in Figure 11. On the other hand, Figure 12 shows the different changingdirectionsfortheenginecoolanttemperaturea nd the radiator downstream air temperature when the vehicle speed was changing.

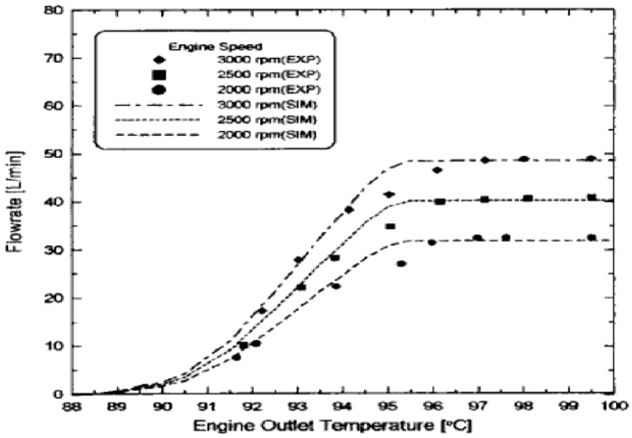

Fig.11 Variation of coolant flow rate with engine outlet coolant temperature [24]

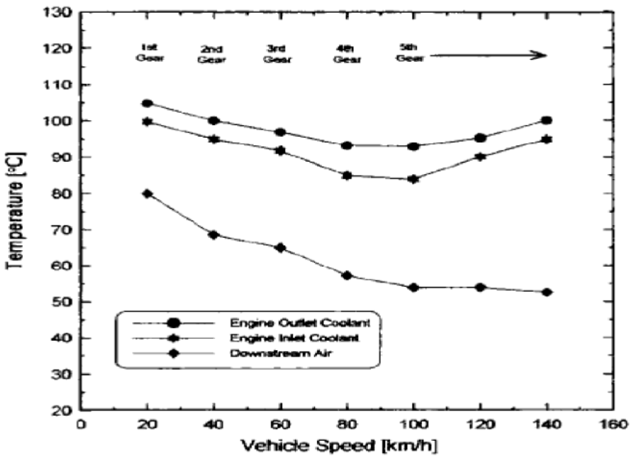

Fig.12 Variation of coolant temperature with vehicle speed [24]

2.2.2.1 Thermal management

Agoodthermalmanagementoftheenginecoolingsystem can extend the life of the engine and the life of the components in the engine cooling system. Also it has impact on the fuel consumption and carbon dioxide emissions. Electrical components in the engine cooling system have great importance in reducing the power consumption in vehicles,comparedtothemechanicalones.Figure 13 shows a thermal management system with an array of small electrical fans insteadofonemechanicalfan.Theresultsshowedthatwhen the engine cooling system was fully electrified. 14.5 kW was savedinthestandarddieselvehicle.Byusinganelectric pump,thepowerconsumptioncouldbedecreasedmorethan 87%, compared to a mechanical pump. Additionally, the radiator size could be reduced by more than 27 % as an electric pump was used. It was found that optimizing the cooling fan arrangement and duty cycle can save energy potentially.

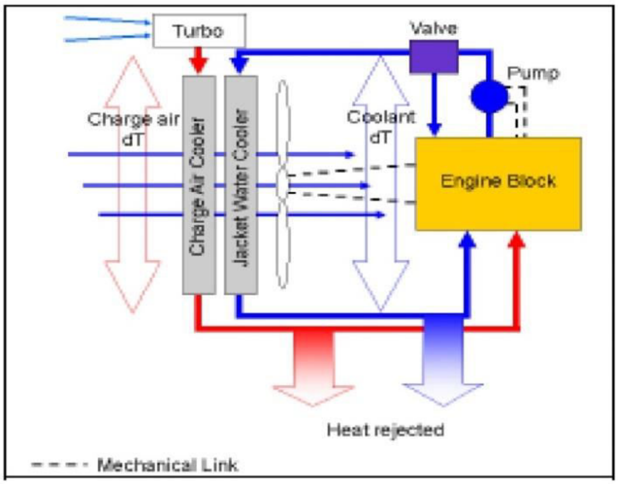

Fig.13 Schematic of a standard diesel engine cooling system

3.EGR

One third of the engine energy is lost to the exhaust gas. Reusingtheexhaustgashasagreatpotentialtoreducethe fuel consumption. Thus EGR is a good option to achieve this goal. Itwasfound that the EGR at high temperature had a negative influence on the brake specific fuel consumption and soot emission. However, EGR cooling had a positive influence on reducing NOx and soot emission. At high EGR rates and low engine speed, the EGR cooling was more important. The cooler was very important for the performance of the EGR. As shown in Figure 15, some part of the exhaust gas was cooled by the heat exchanger before it circulated back to the engine. The intake charge temperature was decreased by using heat exchanger pipes. Because of the heat exchange, the O2 and CO2 were reduced in the exhaust gases, while the CO was increased. The cooled EGR also reduced the percentage of NOx.The optimized cooler geometry improves the water flow path but also strengthened the gas flow. About 20 % of the energy in the exhaust gas can be converted into useful work.

The heat exchanger used in such a system must be capable of meeting high demands in terms of compact design, performance, resistance to high temperatures, corrosion and fouling. Nevertheless the pressure drop in the heat exchanger must be kept to a minimum because the pressure gradient between the exhaust gas and the charge air side of the engine is very small. If the pressure drop in the heat exchanger is too high, the system will not be capable of maintaining an adequate exhaust gas recirculation rate.

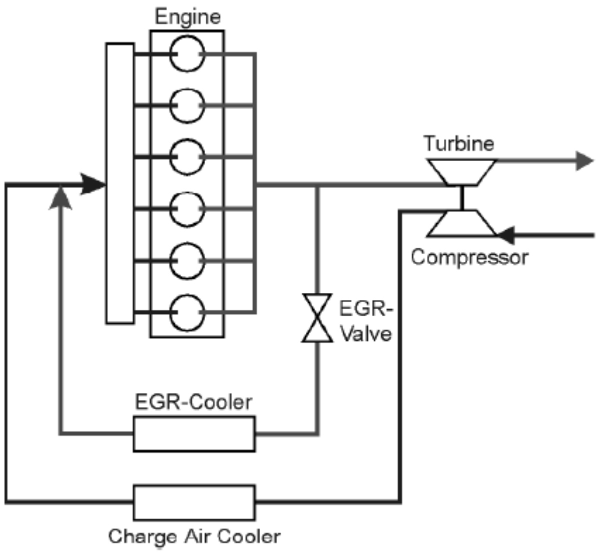

Fig.15 Schematic arrangement of the EGR system

4.Conclusion

About 70% fuel energy in vehicles is lost to the cooling systems, which include the engine cooling system, the exhaustgas,otherfrictionalcomponents(i.e.,brakerotor), and so on. To find out opportunities to reduce the fuel consumption and carbon dioxide emission in vehicles, a literature survey concerning different cooling systems was carried out. Some important/useful results are shown as follows :

1) Engine cooling system keeps the engine work at an optimized temperature with minimized fuel consumption. A radiator is the most important component in the engine cooling system. Compactness, low pressure drop, low cost and new material should be considered in the radiator design.

2) In 10-20 years, the combustion process still will be the major method for generating power in vehicles. Even though EGR has a little effect on reducing the fuel consumption, it plays an important role in reducing emissions. An EGR cooler promotes the EGR application due to the reduced NOx emission.

The design of the engine cooling system will become more difficult because of the increasing power and the space limitation in vehicles. The radiator size will be increased so that more heat can be brought away from the engine. But the space inside a vehicle is limited. For future work, much consideration will be given to the radiator design and the arrangement. In addition, the EGR cooler will be studied too, because of the potential of reducing fuel consumption and emission in vehicles.

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