REVOLUTION OF ENGINE COOLING AND THERMAL MANAGEMENT SYSTEM

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Abstract

Engine cooling and thermal management system is very essential in an automotive industry. It has been existed for decades but only recently been explored for revolution. This study explores current conventional engine cooling, specifically detailing out specifications for wax type conventional thermostat and engine driven water pump. In conventional cooling study, improvement has been made on thermostat opening temperature. Actual experimental set up has been installed and result recorded. Impact on this change has been studied in term of engine coolant inlet and outlet temperature, radiator, bypass flow rate and also Euro 3 emission compliance.

This study also highlights the limitation of current conventional engine cooling and thermal management system, thus requiring revolution to the system.

Advanced engine cooling and thermal management system is then explored as a revolution of engine cooling and thermal management system. This further brings us to study on electrification of engine cooling components mainly on electric control valve and electric water pump. The control system is also improved through integration between engine input/output and cooling input /output for optimum combination. 2 case studies have been reviewed which are Chevrolet Tahoe, 5.77 litre (Chalgren Jr, 2004) and Ford Excursion 6.0 liter diesel (Chalgren and Allen, 2005). In these two studies, electric water pump, electric valve, dual variable speed fan and also restrictor at bypass to boost heater core coolant flow have been fully examined and effect on engine cooling and thermal management system is observed.

A lot of improvement seen from this revolution namely improvement in fuel consumption, reduced warm up time, better emission control, better cabin temperature during cold start, better coolant temperature fluctuation and also reduction in parasitic loss.

Abstrak

Penyejukan enjin dan sistem pengurusan haba adalah sangat penting dalam industri automotif. Ia telah wujud sejak berdekad-dekad lamanya tetapi hanya baru-baru ini telah diterokai bagi revolusi. Kajian ini meninjau penyejukan enjin konvensional semasa, khusus yang memperincikan spesifikasi untuk termostat jenis lilin konvensional dan pam air yang didorong oleh enjin. Dalam kajian penyejukan konvensional, peningkatan telah dibuat kepada suhu pembukaan termostat. Experimen telah dijalankan dan hasil yang direkodkan. Kesan ke atas perubahan ini telah dikaji dari segi suhu masuk dan keluar bendalir penyejuk enjin, radiator, kadar aliran pintasan dan juga pelepasan pematuhan Euro 3.

Kajian ini juga menunjukkan had penyejukan enjin konvensional dan sistem pengurusan terma yang memerlukan revolusi kepada sistem.

Penyejukan enjin maju dan sistem pengurusan terma kemudiannya diterokai sebagai revolusi penyejukan enjin dan sistem pengurusan haba. Kajian kemudiannya menjurus ke arah elektrifikasi komponen penyejukan enjin terutamanya pada injap kawalan elektrik dan pam air elektrik. Sistem kawalan juga bertambah baik melalui integrasi antara suhu masuk/keluar enjin dan suhu masuk/keluar bendalir penyejuk untuk kombinasi yang optimum. 2 kajian kes telah dikaji semula iaitu Chevrolet Tahoe, 5,77 liter (Chalgren Jr, 2004) dan Ford Excursion 6,0 liter diesel (Chalgren and Allen, 2005). Dalam kedua-dua kajian, pam air elektrik, injap elektrik, dua kelajuan kipas boleh ubah dan juga penghad pada pintasan telah meningkatkan aliran penyejuk teras pemanas. Kesan ke atas penyejukan enjin dan sistem pengurusan terma telah sepenuhnya di periksa dan diperhatikan.

Banyak peningkatan yang dilihat dari revolusi ini iaitu peningkatan dalam penggunaan bahan api, mengurangkan masa pemanasan, kawalan pelepasan ekzos yang

lebih baik, suhu kabin yang lebih baik semasa permulaan sejuk, kenaikan/penurunan suhu bendalir penyejuk yang lebih baik dan juga pengurangan kerugian parasit.

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1.0 INTRODUCTION

Engine cooling is one of the most essential systems in an internal combustion engine. About 35 % of total chemical energy in fuel is converted to useful crankshaft work , and about 30 % is dissipated through exhaust flow , leaving around 30 % to be dissipated through surroundings either through coolant or gas (Pulkrabek , 1997)

Conventional cooling has been applied in automotive industry for ages and it is still the option for major car makers on cooling solutions for their product. This might be driven by the stability of the design, proven part's durability either through bench test and actual development vehicle test or even market fleet test. Commercial factor may also contribute to this option since most of the components are off shelves, requiring almost no development for application bringing the part price relatively cheap as compared to new, customize design. It is also abundant and available at suppliers whether locally or internationally.

However, there are still development and improvement done on conventional cooling system but the impact is quite limited as compared to revolution of cooling system such as total electrification of cooling system components. The investment for the improvement needed on conventional cooling system is not really expensive as it is still workable around the current mechanical system , without any connection to the electrical system.

Since conventional cooling system remains the popular option for adoption in current market, this paper has explored possibility to improve current cooling system in one of our national car maker cooling system. The cooling system used is still a conventional one and the improvement proposed is still feasible to be implemented without major change to the system except for some fan strategy control to optimize cooling improvement gained.

The change has been validated in both engine dynamometer and complete vehicle cooling test. Observation has been done in critical criteria in order to reassure that the change does really improve current system performance.

Apart from conventional cooling system, advanced cooling system is also studied for due to its significant improvement in all aspect except in term of commercial. This is strongly due to the complication of each component and lack of off shelf component available due to small application proportion in today's automotive industry. However, the portion is getting bigger and bigger due to other demands.

Today the worldwide convergence towards stricter fuel consumption and emission regulations is pushing car makers and suppliers into new field of innovation. Many recent advances in the transportation industry arisen from the replacement of mechanical engine, transmission, and chassis components with more effective electro-mechanical elements.

Valeo Electrical cooling (VEC), has enhance its thermal management system towards achieving this goals through advanced engine cooling system that incorporates variable speen PWM fans, electric water pump and electric water valve (Chanfreau, 2001)

Trends have shifted from mechanical parts to electrical or even mechatronics part , combining both mechanical and electonic system for integration. During the past two decades, electric radiator fan,wax based thermostat valves , mechanical water pump have been used to facilittate temperature control. However, the search for increased fuel economy, reduced emissions and horsepower gains demand the consideration of advanced thermal management system architectures featuring adjustable flow control valve, variable speed fans, variable speed electric water pump to control the temperature. A variety of configurations are possible by mixing and matching the conventional and mechatronic elements.

This revolution has resulted in development of new powetrain control module to connect and actively control the advanced cooling in order to gain all the benefit offered.

1.1. Objectives

This study investigates two methods of engine cooling systems which are :-

1.0 Conventional cooling system

To investigate performance of cooling system with improvement in wax type thermostat options in term of :-

1.1. Coolant IN and OUT engine temperature
1.2. Flow rate for radiator and bypass line
1.3. Emission performance comparison

2.0 Advanced cooling system and thermal management system

To investigate experimental data from two case studies :-

2.1 Chevrolet Tahoe , 5.77 litre
2.2 Ford Excursion , 6.0 Litre

1.2 Scope and limitations

The investigation on advanced cooling system only done through literature comparison as current conventional cooling system case study would require a lot of major change in order to get accurate comparison.

However, only experimental data from literature is used for advanced cooling investigation .This is to ensure that only realistic data investigated as compared to numerical data which is still not proven to be realistic yet.

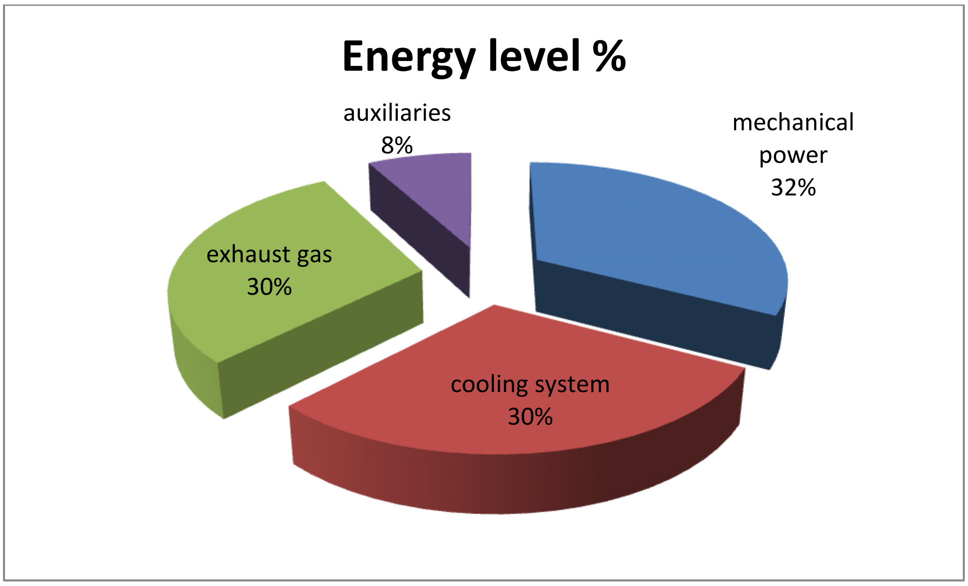
No experimental data tested on conventional thermal management system. Thermal management experimental data only available in advance engine cooling and thermal management system through literature review.

2.0 LITERATURE REVIEW FOR CONVENTIONAL ENGINE COOLING

Internal combustion engine at best can transform about 25 to 35 % of chemical energy in fuel to mechanical energy. About 35 % of heat generated is lost to cooling medium , remainder being dissipated through exhaust and lubricating oil (Ganesan , 2004)

Average of 20 % to 30 % of heat generated in the engine cylinder is transferred to cylinder bores and cylinder head during each combustion cycle (Heinsler, 2004). This matches graph of energy balance by (Descombe, 2003) who also stated that cooling system covers approximately 30 % of energy balance of an automotive engine at full load.

Figure 2.1 : Energy balance of an automotive engine at full load (Descombe, 2003)



The average temperature of combustion products in a gasoline engine is about 800°C (Karamanggil,2005). Due to various engineering limitations and lower endurance limit of various engine components, this temperature needs to be cooled down.

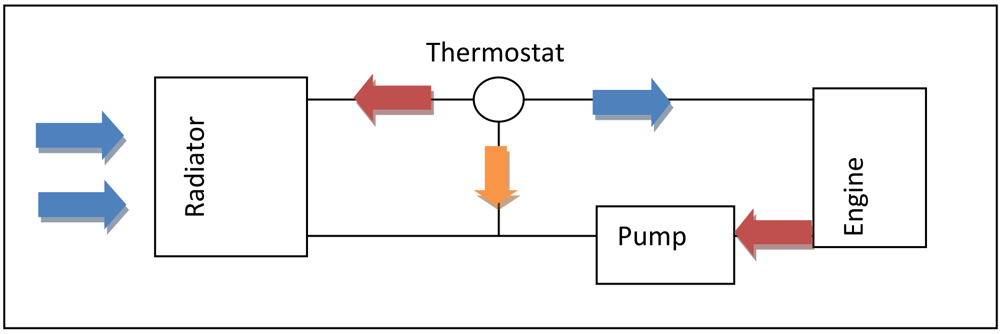
Mode of heat transfer , based on (Makkapati, 2002) apart from dominant mode which is forced convection heat transfer on gas and coolant sides , other factor such as a) intermittent heat transfer from valves to cylinder head, b) heat transfer from piston to cylinder bores c) gap conductance between valve seats and cylinder head d) valve guide and cylinder head and etc. All these heat transfer modes contribute to the coolant jacket volume required for cooling requirement of specific engine. The author stresses on an importance of CFD (computational fluid dynamic) analysis to accurately design and analyze the coolant jacket volume.

In this study, focus area of study will be in liquid cooled method due to relevancy of vehicle engine cooling rather than air cooled engine which is primarily used as power source for construction machinery, agricultural machinery, industrial machinery and so on (Kiura, 2005) .

2.1. Conventional engine cooling system

In forced circulation cooling system which is largely used by most of car makers, the flow from radiator to water jacket is by convection assisted by a pump.

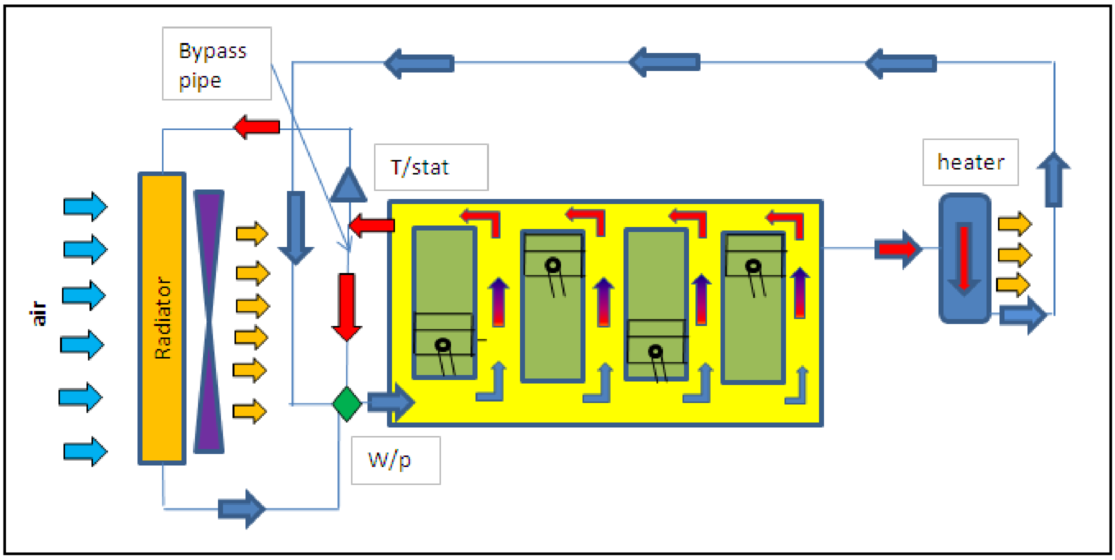
Figure 2.2 : Principle of forced circulation cooling system using the thermostat (Ganesan, 2004)



The coolant is circulated to water jacket around the combustion chamber area by motion of centrifugal pump which is directly driven by the engine. The water is passed through the radiator where it is cooled by air drawn through the radiator by fan and by air draft due to forward motion of the vehicle. A thermostat is used to control the temperature required for cooling

More detailed conventional spark ignition cooling system configuration is illustrated as in figure 2.3 whereby it shows all conventional cooling system components such as radiator, radiator fan, wax type thermostat , bypass pipe, water jacket , heater core for non-tropical country application and heater valve.

Figure 2.3 : Spark ignition engine liquid cooled system configuration (Wagner, 2003).



Main heat coming from cylinder side walls where it is the closest to combustion chamber area. The amount of heat transferred from cylinder wall is important to determine overall performance, size and cooling capacity needed for a specific internal combustion engine. This is done through calculation using either Woschni expression or Annand and Hohenberg expression (Sanli,2008)

Main component of conventional engine cooling are:-

2.1 Thermostat

2.1.1 Thermostat characteristic and working principle

The conventional thermostat used is of wax element type as in figure 2.4. The core of the wax element consists of a pressure – resistant housing that is filled with special wax.

Figure 2.4 : Conventional wax type thermostat

After the engine has been started, the coolant heats up and the wax liquefies at a predefined temperature. This causes the wax to expand so that it acts upon a pin that serves as a working piston. The pin is pressed out of the housing and pushes against a plate valve that opens the coolant throughput so that the engine is kept within the optimum temperature range. When the coolant drops below the predefined opening temperature, a spring pressing against the plate, pushes the pin back into its original position, the coolant circuit is now interrupted. The design principle of wax element can be further understood from figure 2.5 and 2.6.

The wax liquefaction produces a working range of 12°C to 15°C. However, the thermostat can be designed so that the wax element can be adapted to different regulating ranges. This allows all flowing media to be held in optimum operating range in various applications reliably and cost efficiently. The modeling of transient temperature response of thermostat opening has proven to be complex based on (Nelson,1997)

Figure 2.5 : Thermostat design principle of wax element (Wahler,2003)

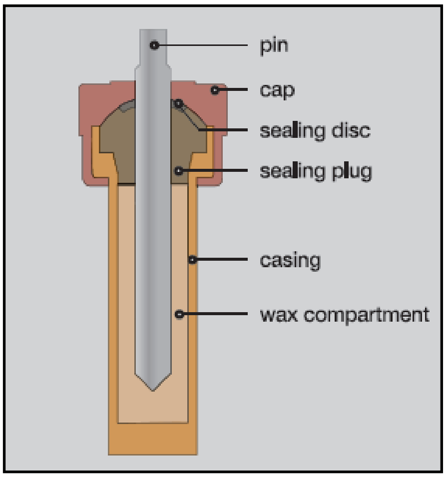
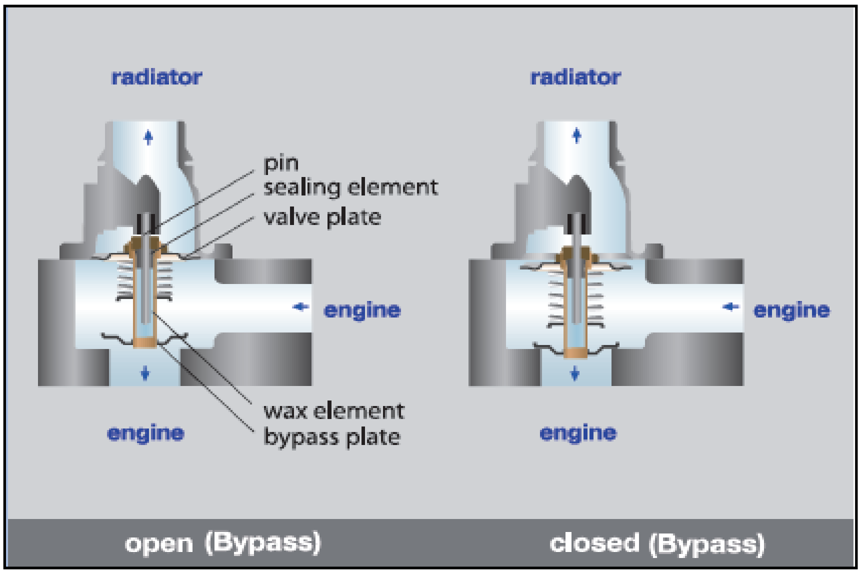


Figure 2.6 : Working principle of conventional wax thermostat (Wahler,2003)



The thermostat operation is governed by the lift versus temperature curve as shown below in figure 2.7. The wax actuator is not an instantaneous device. Wax temperature is not equivalent to coolant temperature. In operation, the temperature of wax sensor varies with the change of coolant temperature but lack behind in time.

Furthermore, the lift versus temperature curve in heating mode is different than in a cooling mode. This effect caused by phase changed of the wax is known as hysteresis effect shown in figure 2.8. Based on

(Chiang,1990) , the cooling curve often experience at least 3 degree shift for hysteresis.

Figure 2.7 : Thermostat lift opening curve

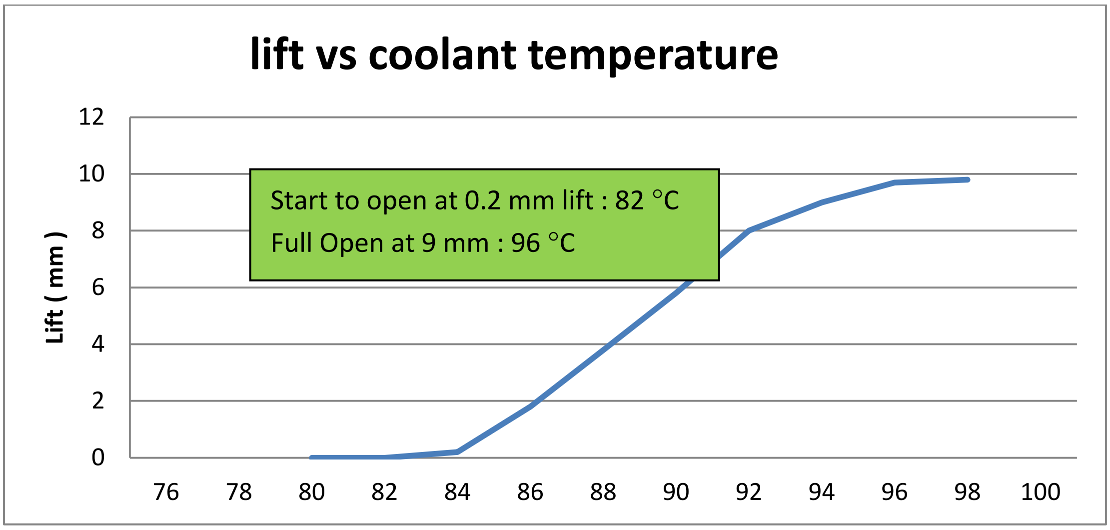
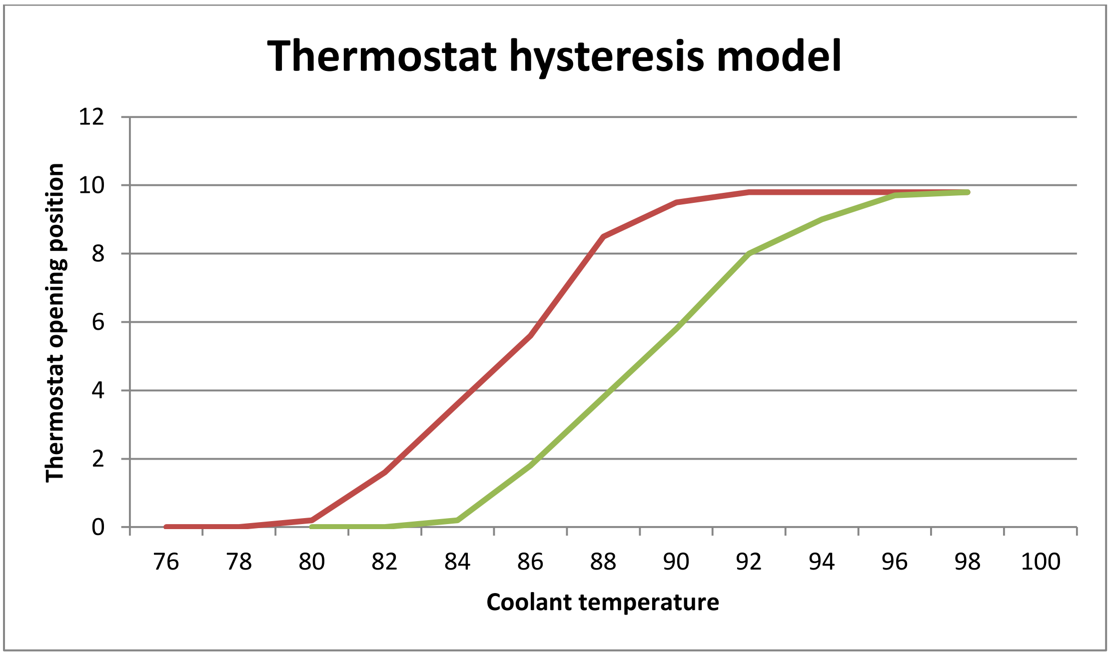


Figure 2.8 : Thermostat hysteresis and linear model (Chiang,1990)



2.1.2 Thermostat Type

a. Permanent Bypass

This type is also known as inline type whereby the bypass line will permanently flows regardless of radiator flowing or not. The response of thermostat is not really accurate due to mixing of hot water from bypass and cold water from radiator. This strategy also tends not to maximize cold water from radiator due to bigger split portion > 0 lpm to bypass path. As been referred by (Cehreli,2007) as one of the potential cause for overheat is insufficient flow from radiator due to excessive flow from bypass .

b. Variable Bypass

This type completely close bypass line once the radiator flows in. This will enable better temperature control at wax bulb and at the same time, increase flow from radiator path due to zero flow coming from bypass line. (Heinsler,2004) has shown this type of thermostat which is using disc type to seal the bypass line completely to avoid hot and cold coolant mix up.

2.1.3 Thermostat positioning

There is 2 types of thermostat positioning whether at outlet or inlet type as in figure 2.9 The pros and cons of these 2 positioning is tabulated as in table 2.1

Figure 2.9 Thermostat positioning a) Outlet type thermostat and b) Inlet type thermostat

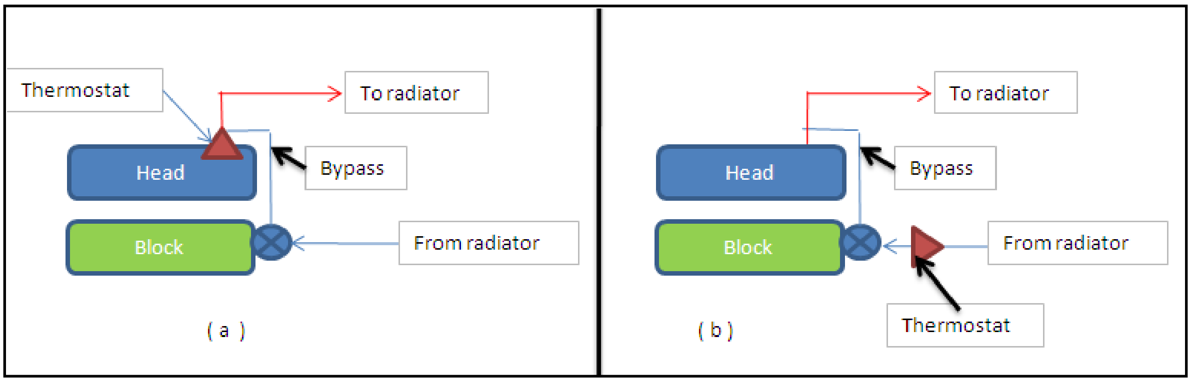


Table 2.1 : Comparison between inlet and outlet type of thermostat positioning

	Outlet side	**Inlet side (RECOMMENDED)**
Temperature Cycling	🚫 Increased – T'stat is located far from coolant source	√ Reduced – close proximity to incoming coolant
Durability	🚫 Lower – due to increased temp of thermostat 88°C	√ Higher – due to lower temp of thermostat 82°C
Bypass requirement	√	🚫 Large bypass required to avoid cavitation
Radiator pressure	🚫 Higher	√ Lower
T'stat design	√ No additional features	🚫 High preload spring to avoid t'stat being stucked open

Thermostat is designed to restrict the flow of coolant until the engine warm up. When it rises, it opens to allow water to flow through radiator to maintain a steady temperature. Outlets and inlets to thermostat can varies from one engine to another, Example of outlets and inlets to thermostat for a 5 cylinder engine is shown by (Ebrine,2007) as :-

- From engine out
- From EGR/Heater return
- To Degas
- To EGR / Heater

- To radiator

2.2 Water pump

Apart from control valve, water pump is also a key component to conventional engine cooling. The pump functions as to maintain the circulation of the water through the system. The bottom of radiator is connected to the suction side of water pump. The power is transmitted to the pump spindle from a pulley mounted on the end of crankshaft. A positive supply of water is achieved in all conditions by centrifugal pump placed in the system as in figure 2.10.

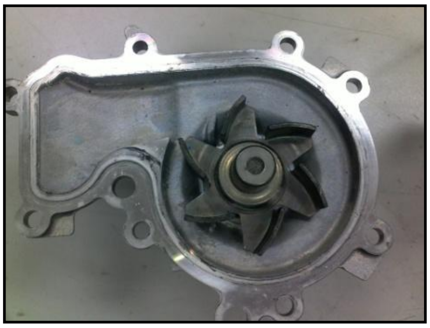
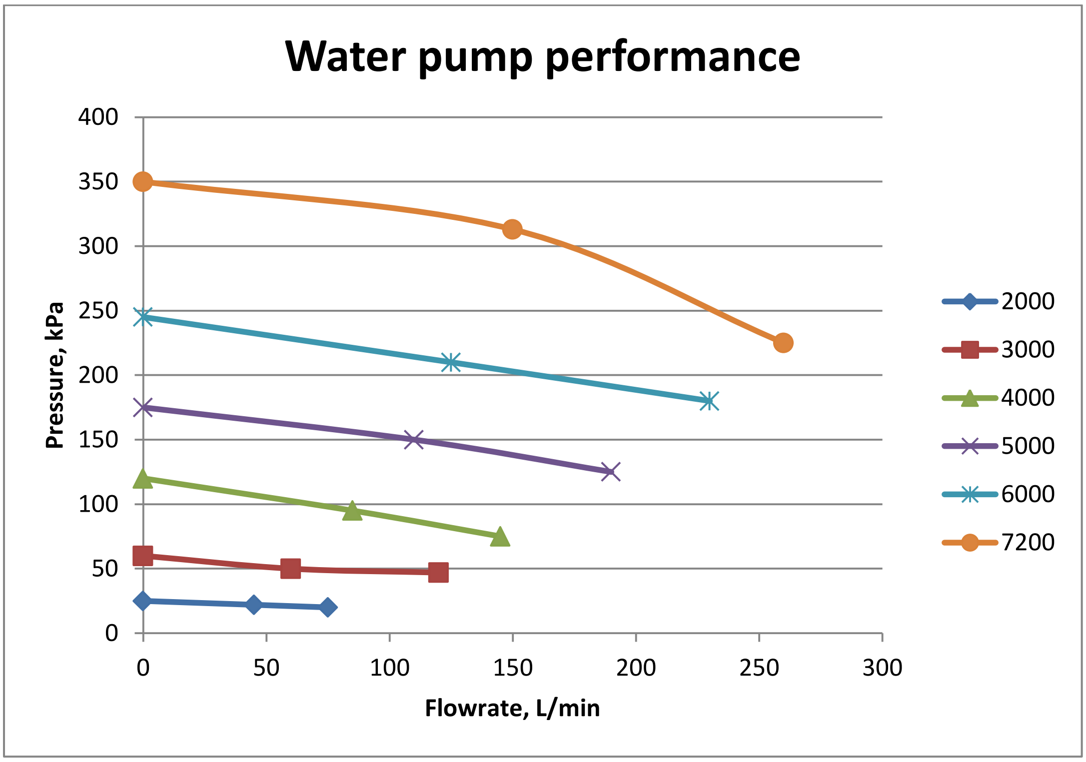


Figure 2.10 : Water pump

Water pump performance is dependent on engine speed as illustrated in performance curve below – figure 2.11. The pump flow increase as the engine speed increased (Henry,2001). This means that, for the same pressure and as the engine speed goes up flow rate increases but at a lower rate than engine speed rate. This is the fact that the pump power is limited and that its efficiency decreases at the high speed end due to increased losses. Conventional water pump provides adequate coolant flow rate only for about 5 % during its life, which is extreme condition. Other than that, the pump is supplying more that required coolant resulting cooler metal component that desired (Lehner,2001).

Figure 2.11 : Water pump performance curve (Proton 2009)



2.3 Coolant

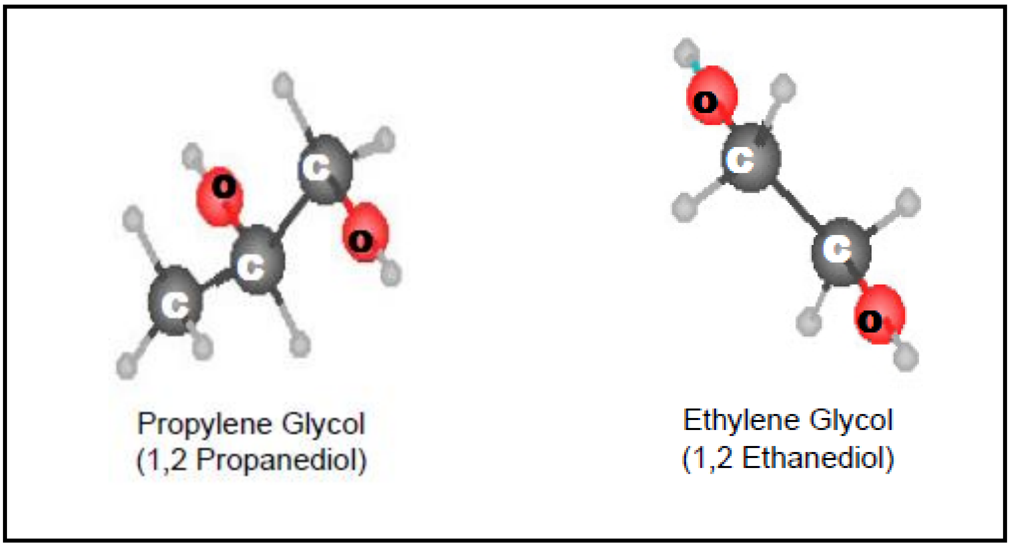
Coolant is used to transfer heat from water jacket and it is unlikely to simply use water as cooling medium even though it has a very good heat transfer property. This is due to some drawbacks in both freezing point of 0°C which is unacceptable in some cold country and also in low in boiling point temperature even under pressurized system. This is undesirable since engine operating temperature is highly likely to reach more that its boiling point. Water is also prone to rust and corrosion in many metal parts in engine assembly.

Ethylene Glycol ($C_2H_6O_2$) often called as antifreeze acts as a rust inhibitor and a lubricant to water pump. When mixed with water, it lowers the freezing point and raising the boiling point, both desirable consequences. Properties of Ethylene Glycol mixture with water is shown as in Table 2.2.

Table 2.2 : Ethylene Glycol – water mixture properties (Pulkrabek,1997)

% Ethylene Glycol by volume	Specific gravity at 101 kPa and 15 °C	Freezing Point at 101 kPa ° C	Boiling Point at 101 kPa ° C
0	1.000	0	100
10	1.014	-4	
20	1.029	-9	
30	1.043	-16	
40	1.056	-25	
50	1.070	-38	111
60	1.081	-53	
100	1.119	-11	197

Figure 2.12 : Ethylene Glycol and Propylene Glycol (Eaton *et al*., 2001)



Some commercial engine also used Propylene Glycol (C_4H_8O) as the base ingredient. It is argued that when coolant system leak or when coolant is disregarded due to ageing factor , these product are less harmful to the environment than Ethylene Glycol. Based on (Eaton et al.,2001) Propylene Glycol is thermally less stable than Ethylene Glycol. Isomer for Ethylene Glycol and Propylene Glycol is shown in figure

2.12. However lesser amount of Propylene Glycol is sold as compared to Ethylene Glycol.

Regardless of which anti freeze that is mixed with coolant, their percentage does the performance of water supply capability and cavitations temperature, whether air or burnt gas is present in the system. Based on (Huang,2004) when liquid flows within engine cooling system, the coolant begins to vaporize and yield air bubbles whenever the local pressure is lower than the saturated pressure corresponds to the coolant temperature. The generated bubbles flow along the surface walls and collide with others to form bubbles.

If the air bubbles flow to position of higher pressure that may cause the bubbles to collapse, cavitations may occur as the liquid forms rapidly from the water vapor. This may damage the internal parts of cooling system especially water pump since it has a big pressure drop from inlet to outlet water pump.

(Huang,2004) has investigated that effect is obvious when rotational speed reaching 3000 rpm. 100 % anti freeze resulted in 6 times better compared to 50 % mixture and no cavitations detected even at 3000 rpm due to high boiling point of anti freeze.

3.0 METHODOLOGY FOR CONVENTIONAL ENGINE COOLING

This study investigates the performance of CAMPRO engine cooling and thermal management system. The working fluid is a 30:70 mixture of ethylene glycol and water as proposed by (Scott, 1996) to be most effective aqueous concentrated solution for maximum heat transfer.

This study examines the effect of coolant temperature inlet and outlet engine temperatures with various improvements done in conventional cooling system. As illustrated in figure 3.1, CAMPRO cooling circuit consists of radiator , conventional engine driven water pump , conventional permanent bypass thermostat valve, flow meters to measure coolant flow rate to radiator and bypass line and temperature sensors to measure both inlet and outlet coolant temperature.

Study has been conducted in 2 methods:-

I. Engine Dynamometer
II. Complete Vehicle Test

3.1 Engine Dynamometer

3.1.1 Experimental Apparatus

This study examines the effect of coolant temperature inlet and outlet engine temperatures with various improvements done in conventional cooling system. As illustrated in figure 3.1, CAMPRO cooling circuit consists of radiator , conventional engine driven water pump , conventional permanent bypass thermostat valve, flow meters to measure coolant flow rate to radiator and bypass line and temperature sensors to measure both inlet and outlet coolant temperature. Actual test set up is shown in figure 3.2.

Figure 3.1 : CAMPRO cooling circuit and points of measurement (Proton,2009)

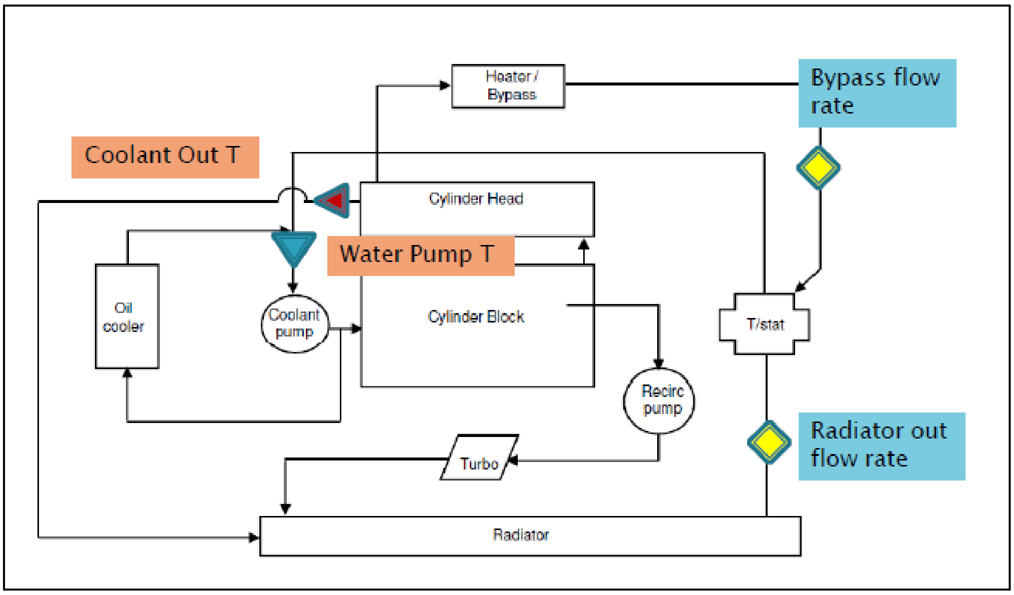


Figure 3.2 : Experimental apparatus

Table 3.1 specifies the design points of CAMPRO cooling system and Table 3.2 specifies the working engine parameters.

Table 3.1 : Coolant design points specification

Coolant design points	
Max Coolant Temp (Continuous)	≤ 110°C
Max Coolant Temp (Peak ; 15 min)	≤ 120°C
Temperature gradient across engine	≤ 8°C
Peak system pressure (gauge)	≤ 1.5 bar
Radiator cap pressure	1.1bar
Thermostat opening temperature - start to open	82°C
Thermostat opening temperature - fully open	96°C

Table 3.2 : Specification of engine in present study

	Engine
Engine	**1.6L CAMPRO**
	Specification
Direction of Rotation	Clockwise (from front)
Number of Cylinders	4
Displacement	1561 cc
Firing Order	1-3-4-2
Bore	76 mm
Stroke	86 mm
Lubricating mode	Full pressure
Cooling mode	Water cooled
Lubricating pump type	Rotary
Thermostat type	Wax bill

During installation, the engine is calibrated in such a way that the center of its crankshaft and the center of the dynamic meter are at the same horizontal position , as proposed by (Huang *et al*., 2004), temperature sensors are installed at the outlet engine at cylinder head connector for measuring engine outlet and at water pump to measure engine inlet temperature. Flow meter placed at radiator out hose for main flow and at bypass hose for secondary, bypass line flow rate.

The dynamometer chiller – BOWMAN is disabled in order to see the actual effect with actual radiator. Radiator has been applied with blowing fan to replicate actual air movement during actual driving condition. Furthermore this is needed in order to ensure that the full engine sweep temperature and flow rate is recorded without having the dynamometer switched off due to exceeded coolant temperature ≥ 110°C. Therefore, the recorded temperature is relatively lower than normal but the main comparison will be done on temperature and flow rate difference from one change content to another but still using exactly the same set up and same engine dynamometer. The effect of blowing the radiator can be treated as negligible.

3.1.2 Experimental procedures

1) Circularly clean the wet sleeve in the engine and remove all foreign materials from the conduit.

2) Prepare cooling water with 30 % of Ethylene Glycol aqueous mixture with water.

3) Ensure the coolant capacity is met – in this case 7.0 litre.

4) Remove the residual air bubbles from engine cooling system prior to beginning of experiment.

5) Activate the engine upon completion of the start- up procedure and check the computer and test equipement. Set the rotational speed of the engine with increment of every 500 rpm maintaining tolerance of ± 500 rpm.

6) Record the flow rate and temperature by taking average experimental values of three tests as to ensure that the result is stable and consistent.

7) Plot the experimental data.

3.1.3 Change content test details

Different change content effect has been studied using the same bench test. This is done back to back to ensure that the changing temperature and flow rate is solely contributed by the change content. Summary of change item is tabulated in Table 3.3.

Table 3.3 : Change content of experimental set up

Test No	Change Content
1	Base data – production content cooling system ; 82°C SOT thermostat
2	Earlier opening thermostat ; 78°C SOT
3	Longer 82°C SOT thermostat ; 3 mm extension of wax element
4	Restrictor at Bypass line thru heater restriction
5	Forced Open Thermostat
6	No thermostat

3.2 Complete vehicle test

3.2.1 Experimental apparatus

Test has been conducted using vehicle with Gross vehicle weight of approximately 1640 kg . Most severe test condition has been chosen which is Hill climbing pattern which in this case referred to Genting Highland route hill climbing.

This pattern is considered extremely critical to engine cooling test due to limited air passing through engine bay to cool down coolant and engine bay temperature .It is also critical due to higher engine load applied to climb up the slope thus resulting more heat being generated by engine to drive the vehicle.

Figure 3.3 indicates the package space required by heat exchanger stack and fan, which is considerable amount of space , leaving minimum room for cooled air to flow through the crowded engine compartment. This engine bay package limitation has also been highlighted by (Chalgren Jr,2005) as a limitation to current conventional engine cooling and thermal management system.

Figure 3.3 : Conventional cooling system (1 : inlet grill, 2 : heat exchanger pack , 3 : fan pack , 4 : room for exhaust , 5 : engine)

In complete vehicle testing, only temperature readings have been recorded due to complication of installing flow meter on a dynamic vehicle. Measurement recorded by thermocouples are listed as per table 3.4

Table 3.4 : Points of measurement in complete vehicle test

Thermocouple no	Point of measurement	Parameter measured
1	Cylinder head connector to radiator	Coolant outlet engine
2	Water pump connector	Coolant inlet engine
3	Roof Top	Ambient Air
4	Oil sump	Engine oil

Figure 3.4 shows the test set up done on complete vehicle test. Besides coolant, engine oil and ambient air temperature, other measurements also taken such as intake air temperature, hood mapping but not compared in this study since not much related to engine cooling effect study.

Figure 3.4 : Experimental set up for complete vehicle test

3.2.2 Experimental procedures

1) Measurement done on different days but as the ambient temperature is recorded , relative result can be predicted. Difference of 2- 3°C ambient temperature is considered to be acceptable.

2) Test conducted in GVW condition , under hill climbing speed of 40 kph.

3) Prepare cooling water with 30 % of Ethylene Glycol aqueous mixture with water.

4) Ensure the coolant capacity is met – in this case 7.0 litre.

5) Remove the residual air bubbles from engine cooling system prior to beginning of experiment through thermostat bleed screw. This is to ensure the accuracy of data recorded.

6) Results gained plotted against time and test was conducted approximately around 30 minutes before key off.

7) Temperature after key off is not considered in this test due to key off strategy being applied by engine management system through engine control unit.

8) Record the flow rate and temperature by taking average experimental values of three tests as to ensure that the result is stable and consistent.

9) Plot the experimental data.

3.2.3 Change content test details

Not all change content tested in engine dynamometer being tested in complete vehicle. Selection has been made from best test result in engine dynamometer for complete vehicle test together with other tested configuration that is more accurate if tested in complete vehicle compared to engine dynamometer. Table 3.5 summarizes the change content for complete vehicle test

Table 3.5 : Summary of change content for complete vehicle testing

Test No	Change Content
1	Base data – production content cooling system ; Permanent Bypass 82°C SOT thermostat and 16 mm radiator thickness
2	Permanent Bypass 82°C SOT Thermostat with 27 mm radiator thickness
3	Permanent Bypass 78°C SOT Thermostat with 16 mm radiator thickness
4	Permanent Bypass 82°C SOT Thermostat with intercooler fan
5	No thermostat
6	Variable bypass thermostat – 4G9 thermostat with 16 mm radiator thickness

Apart from temperature measurement, emission performance test is also conducted to verify 78°C performance as compared to 82° C thermostat.

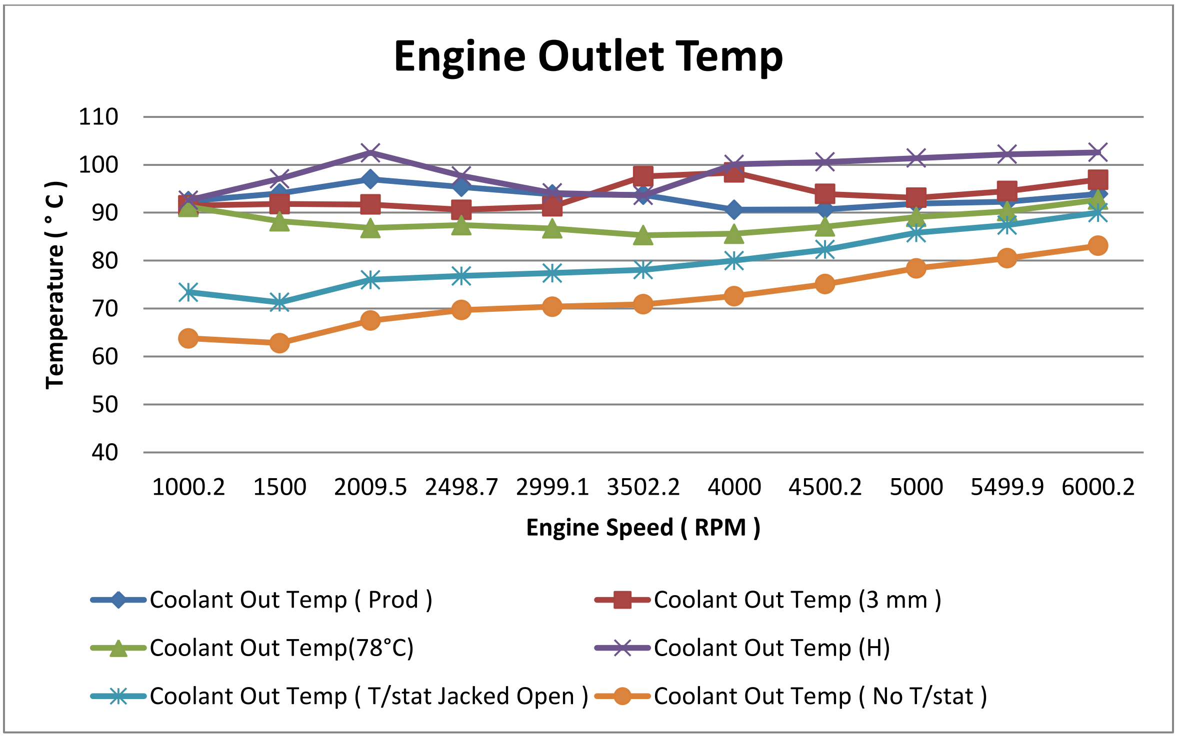
4.0 RESULT AND DISCUSSION FOR CONVENTIONAL ENGINE COOLING

4.1. Engine dynamometer test results

<u>4.1.1 Coolant temperature</u>

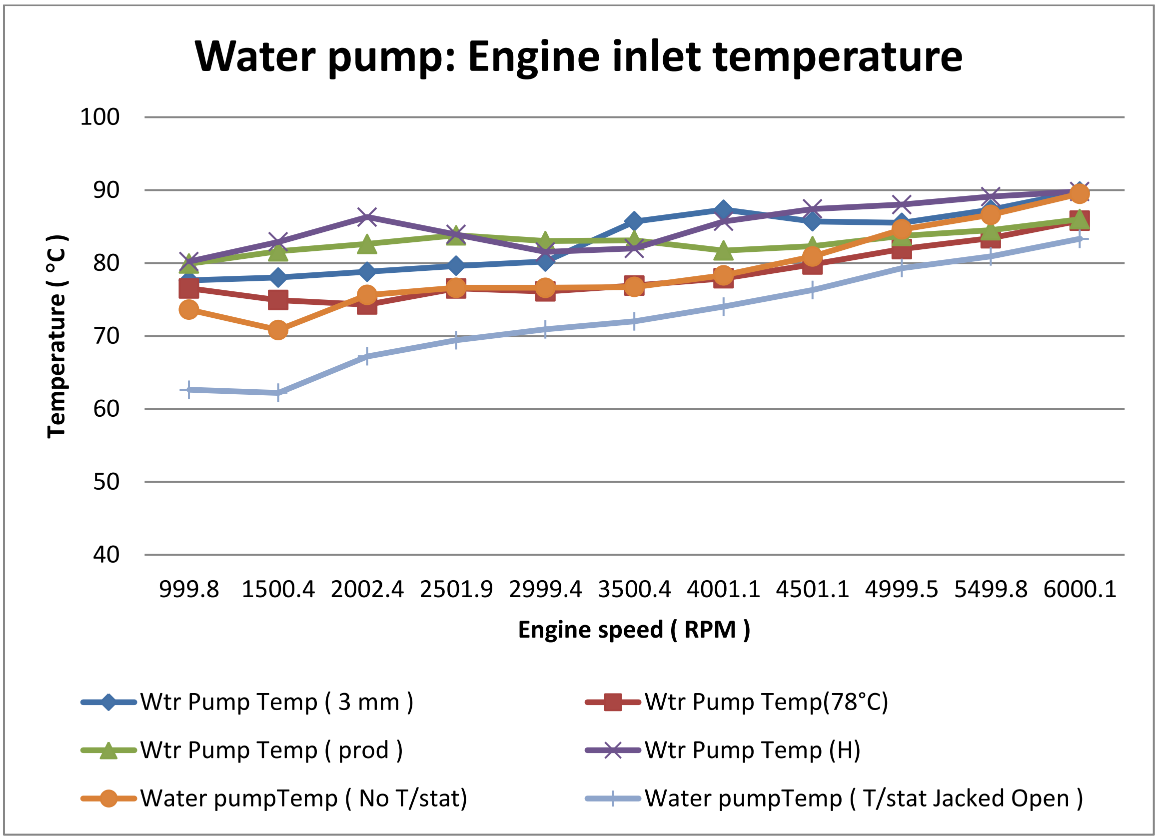
Important engine parameter results have been plotted with respect to rotational engine speed. Figure 4.1 shows the comparison of engine outlet temperature with different change content setting that has been explained earlier in methodology section.

Figure 4.1 : Engine outlet temperature for different test configurations



In figure 4.2 , coolant at engine inlet , named as water pump temperature has been plotted against engine rotational speed with different test configurations.

Figure 4.2 : Engine inlet temperature for different test configuration



It is shown clearly shown that set up with No thermostat and thermostat jacked open will have the lowest engine outlet temperature. If it is viewed in term of temperature aspect, then these configurations turn out to be the best. However, cold coolant will result in poor warm up performance thus resulting poor emission performance.

(Luptowski,2005) has also highlighted on the disadvantage of low coolant temperature that will result in high viscosity of engine oil . This can results in increased wear and decreased engine life due to inadequate amount of oil reaching contacting surface.

Besides No thermostat and Jacked open thermostat, 78°C start to open (SOT) thermostat is seen to have the lowest both inlet and outlet engine temperature but still meeting cold start requirement. This has been summarize in Table 4.1 as below ; measured at 2500 rpm.

Table 4.1 : Comparison of coolant temperature taken at 2500 rpm

Parameter	82 ° C Thermostat (current)	78 ° C Thermostat	ΔT difference to current	No Thermostat (reference)
Coolant Outlet	95.4 ° C	87.4 ° C	8 ° C	69.7 ° C
Coolant inlet	83.8 ° C	76.6 ° C	7.2 ° C	76.5 ° C

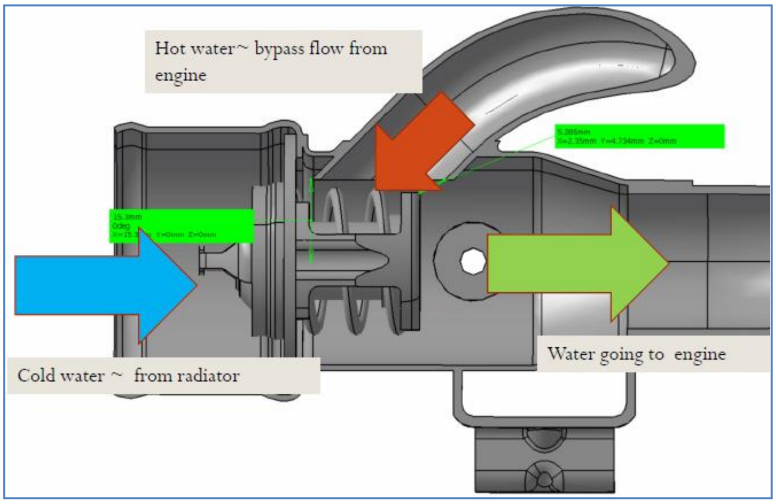
4.1.2 Coolant Flow Rate

Total coolant being circulated in the system is approximately 7.0 Liter. Hot coolant coming out from water jacket in cylinder head is split to two flows; radiator flow as the main flow and bypass flow as secondary flow.

Radiator flow carries an important function to cool down the coolant temperature through heat dissipation at radiator core. As described by (Allen,2001), net effect of radiator or heat exchanger is to lower the coolant temperature passing by while increasing the air temperature that is passing through the core.

Bypass flow in this case is a secondary flow which is of permanent type whereby it will continuously flow regardless of whether the thermostat is open or not. However, there will be a reduction of bypass flow once the thermostat open due to huge flow coming in the pipe line. Cross section of bypass path with regards to thermostat operation is as shown in figure 4.5.

Figure 4.3 : Cross section of thermostat pipe showing bypass path



Bypass functioning as to recirculate hot coolant back to engine during warm up. This is most critical in cold start condition since various complication will occur as a result of poor warm up as highlighted by (Gumus,2009) having an increase in level of toxic emission, increase load to starter and simulator due to high viscosity of lubricant and resistance to motion and also increase level of noise and vibration especially in diesel engine application.

Result on both radiator and bypass flow has been plotted and shown as in figure 4.4 and 4.5 accordingly.

Figure 4.4 : Radiator flow rate

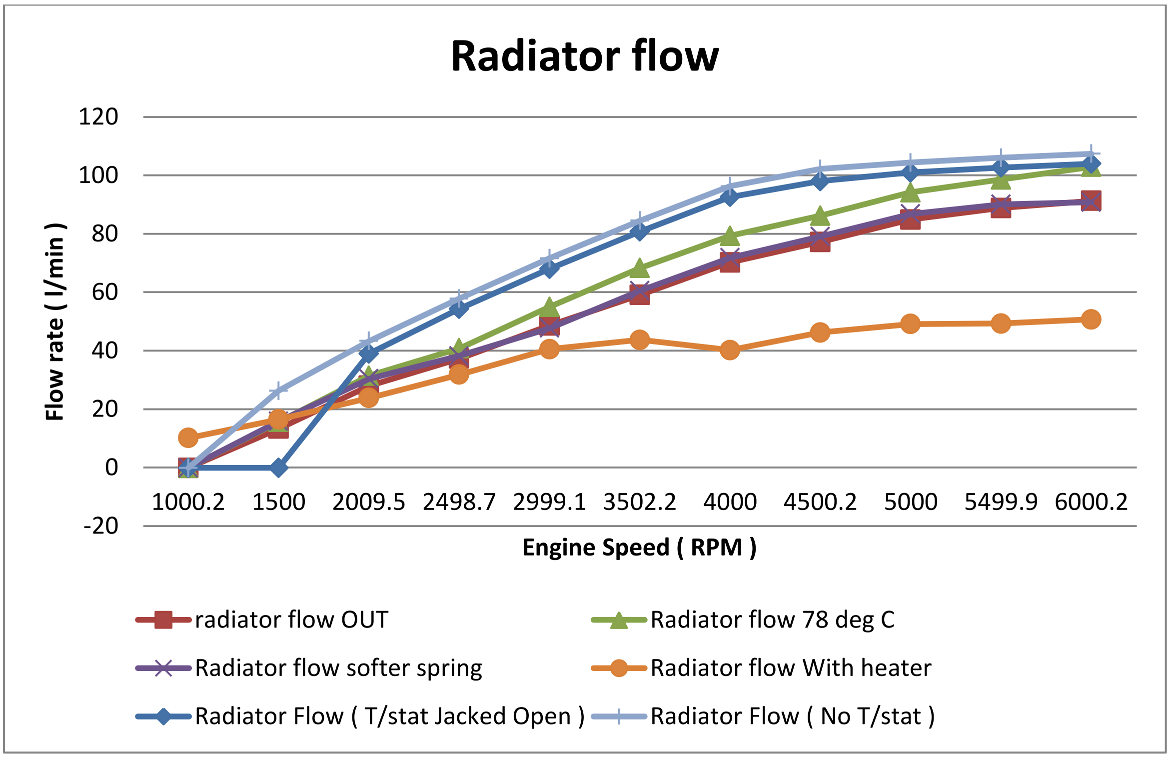
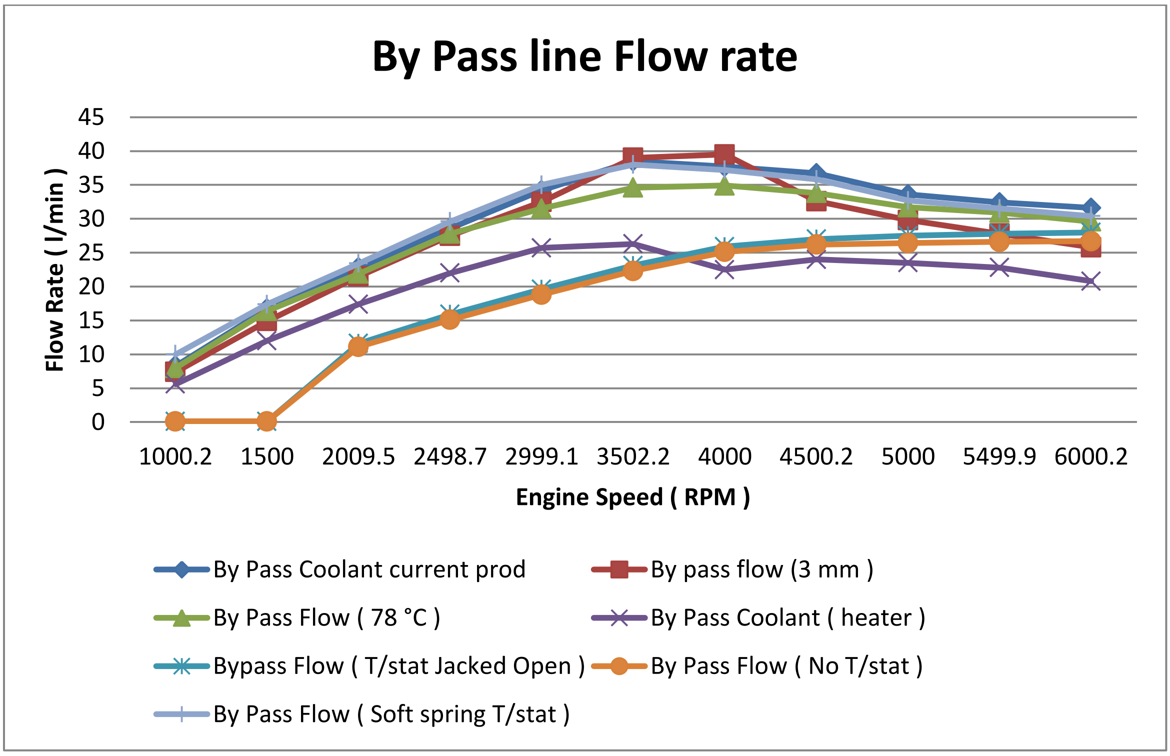


Figure 4.5 : Bypass Line Flow rate



During normal running condition, radiator flow split is expected to have bigger split portion for purpose of heat dissipation at radiator core. Through experiment done, the highest flow next to No thermostat and Jacked open thermostat is thermostat with earlier opening temperature of 78°C. The improvement is seen to be as big as to 5.8 % improvement. This is tabulated clearly in Table 4.2. The increase percentage of radiator flow rate has automatically decrease the bypass flow split percentage. This has directly impacted on coolant temperature as well as explained earlier.

Table 4.2 : Comparison on coolant flow rate taken at 3500 rpm.

Parameter	82 ° C Thermostat (current)	78 ° C Thermostat	difference to current	No Thermostat (reference)
Radiator flow rate (l/m)	59.1	68.3	9.2	84.5
Flow rate split %	60.55	66.37	+5.82	79.12
Bypass flow rate (l/m)	38.5	34.6	3.9	22.3
Flow rate split %	39.45	33.63	-5.82	20.88

Addition of heater matrix is also seen as effective in order to have more gain in radiator flow as heater matrix offered a resistance of 1.3 ± 5 % kPa for water line. This additional restriction has discouraged coolant from flowing through bypass line thus increasing radiator flow. Heater fitted vehicle has least probability of high working coolant temperature which can result in overheating condition due to this benefit of additional resistance .

4.2 Complete vehicle test result

Upon completion of engine dynamometer test, best optimum solution has been identified which is the application of earlier opening temperature thermostat of 78°C. This has been further verified through complete vehicle test and the test result has been plotted in figure 4.6 to figure 4.7.Overall improvement has been seen with adoption of 78°C SOT thermostat. This has been tabulated in table 4.3 below.

Table 4.3 : Improvement of 78 °C thermostat compared to 82°C thermostat

Parameter	82 ° C Thermostat (current)	78 ° C Thermostat	ΔT difference to current
Coolant Outlet (° C) At 12:00 min	92.9	87.7	5.2
Coolant Outlet (° C) At 20:30 min	97.1	91.5	5.6
Coolant Inlet (° C) At 15:30 min	87.6	81.2	6.4
Coolant Inlet (° C) At 22:00 min	92.5	87.3	5.2
Engine oil (° C) At 15:30 min	105.7	101.3	4.4

Figure 4.6 : Coolant Out temp for all variants tested

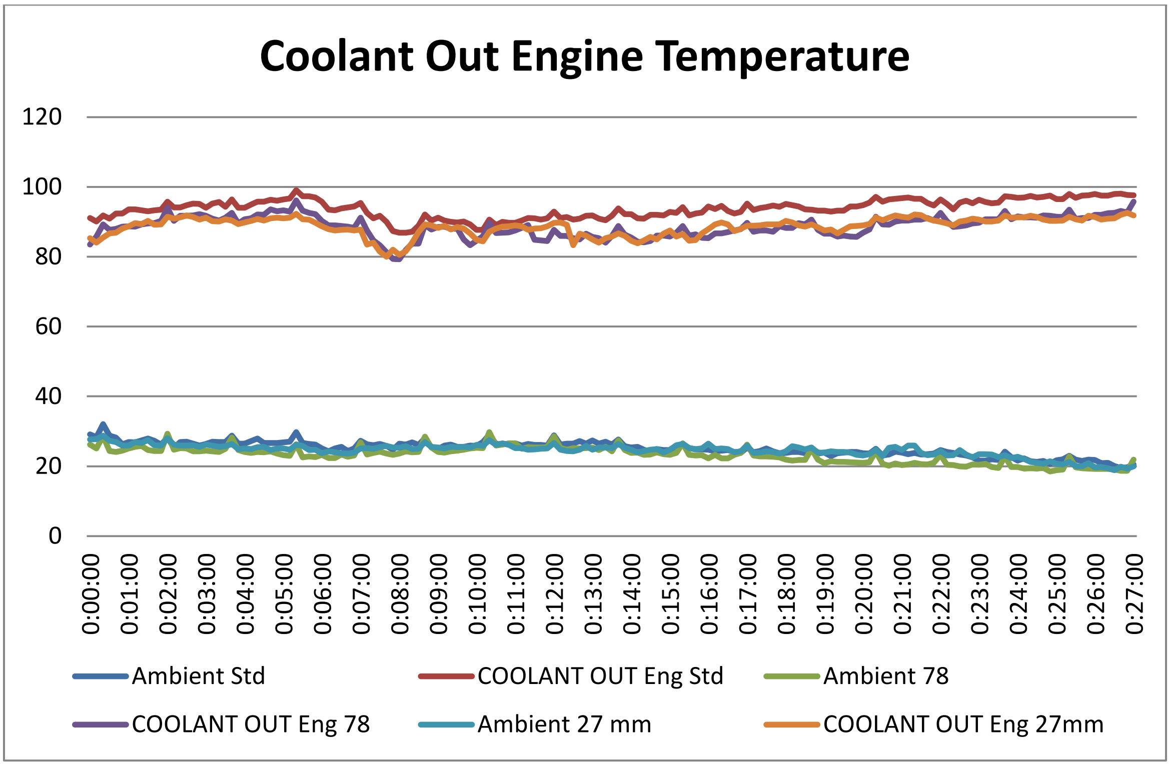


Figure 4.7 : Coolant Out temp comparison between thermostat - 82° C and 78° C

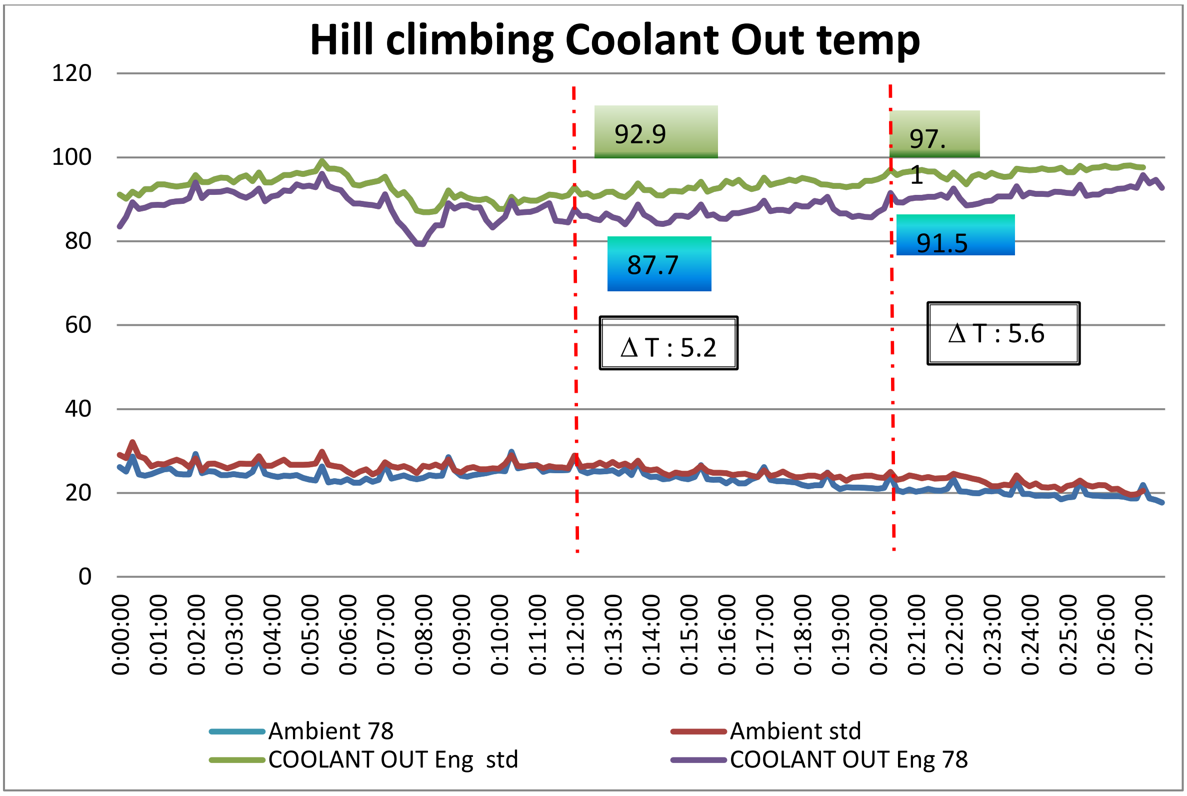


Figure 4.8 : Coolant In temp for all variants tested

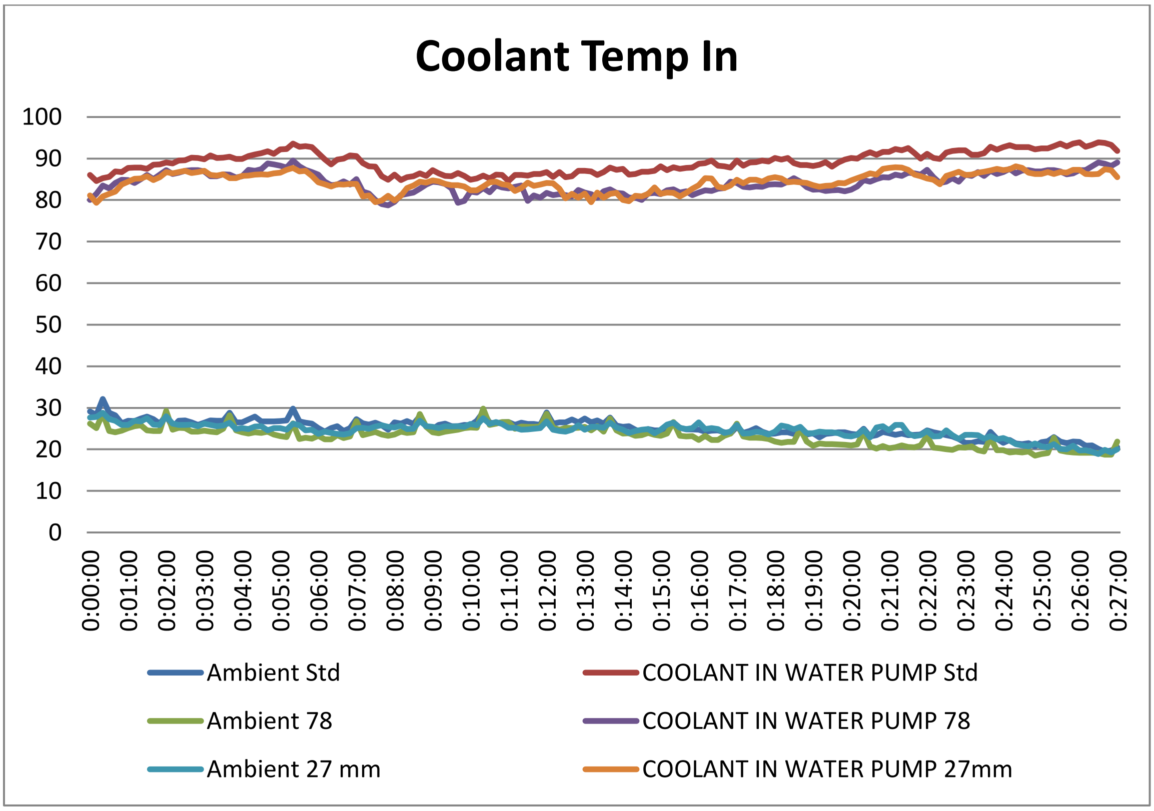


Figure 4.9 : Coolant In temp comparison between thermostat - 82° C and 78° C

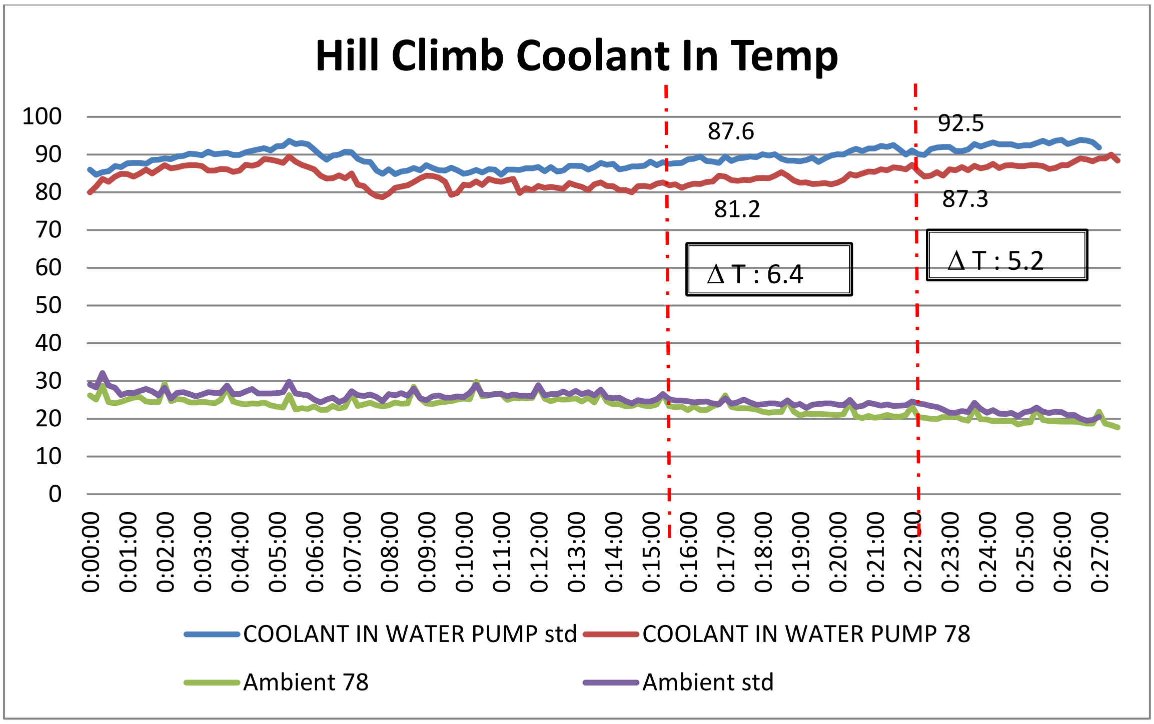
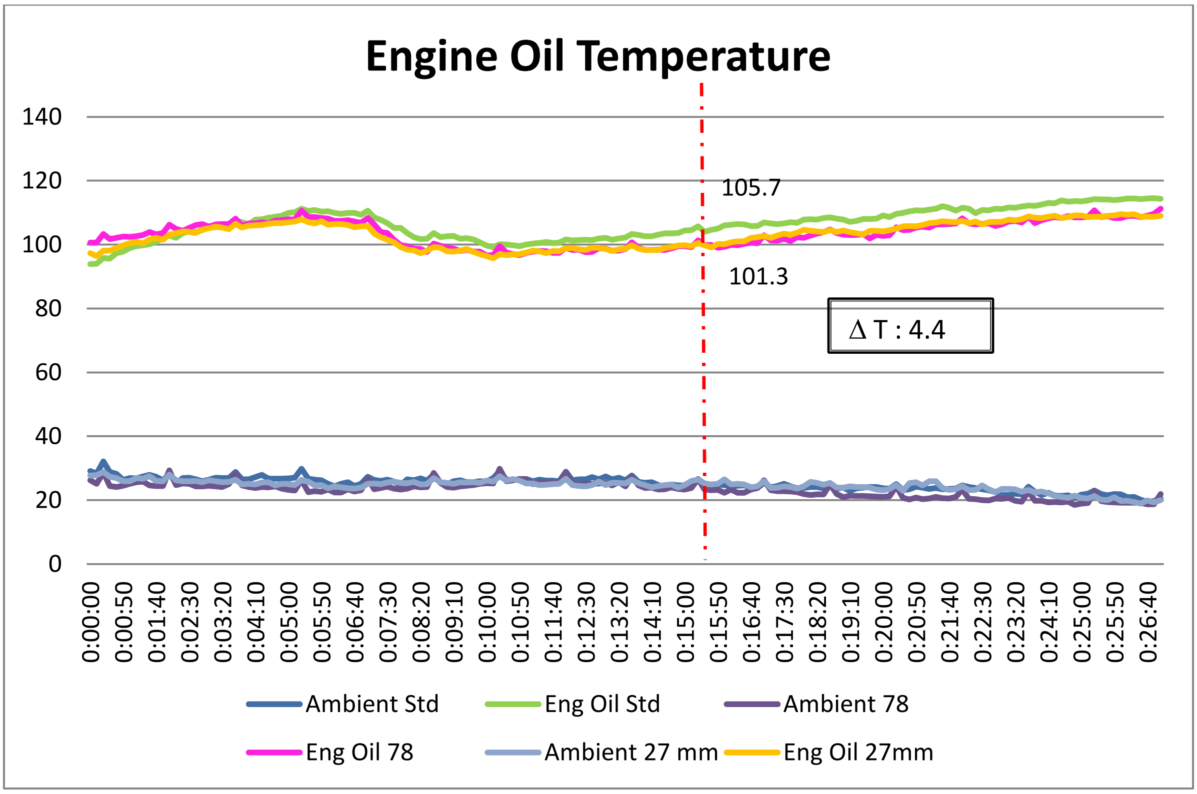


Figure 4.10 : Engine oil temperature effect



In general, it seems that adoption of earlier opening thermostat has bring a relatively better result in terms of temperature in both coolant and engine oil measured in sump. This has agreed with the specification for both thermostat with regards to start to open temperature as shown in figure 4.11

Figure 4.11 : Lift opening curve for 82 °C and 78 °C thermostat

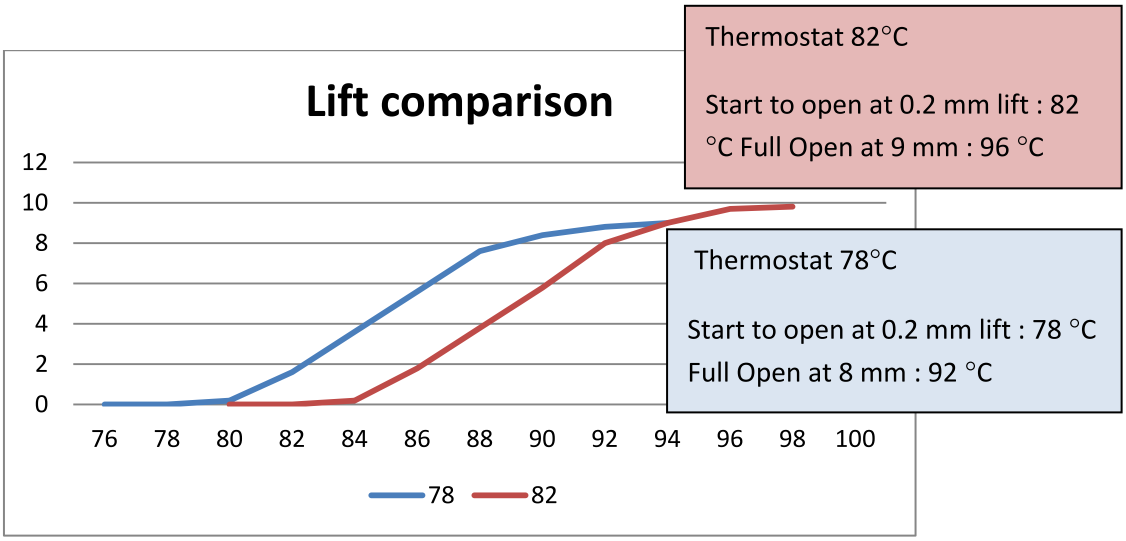
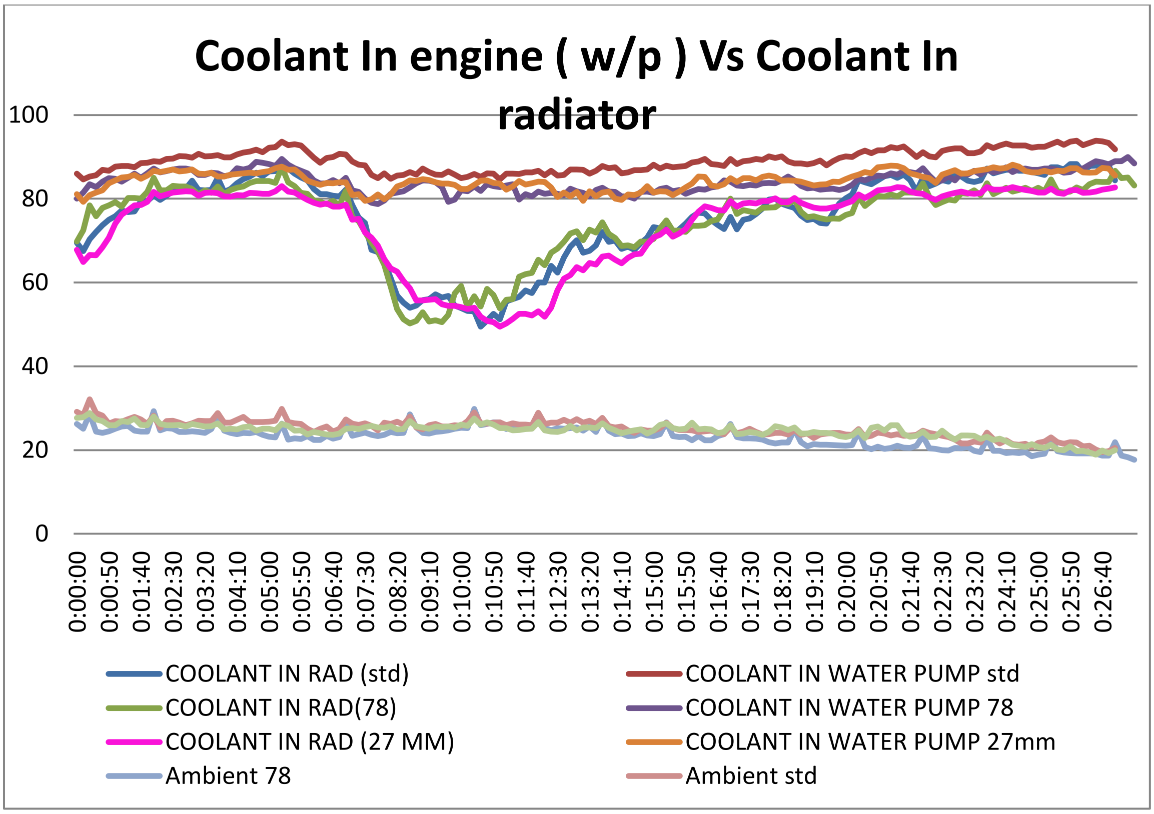


Figure 4.12 : Effect of radiator in coolant IN temperature



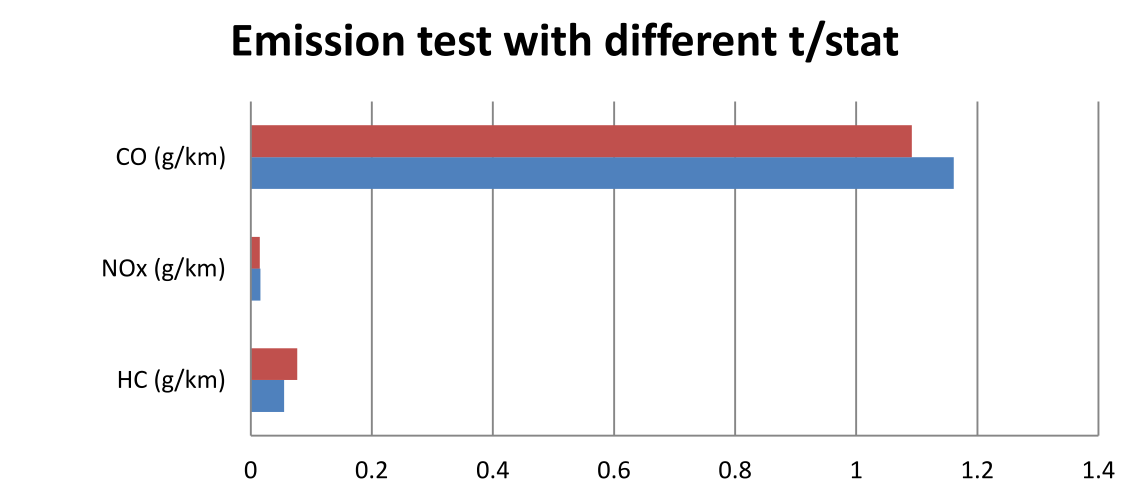
It is also observed that effect of changing radiator thickness alone; in this case from 16mm to 27 mm resulting the same effect as changing thermostat specification from 82°C to 78°C. Effect of radiator is still limited due to thermostat function of mechanically control the entry for cold water from radiator to enter engine .

Since conventional permanent bypass type of thermostat design is used in this experiment, bypass flow will continuously flowing , mixing with cold coolant from radiator. This mix based on (Chiang,1990) will result in an increase of coolant temperature entering engine ; measured at water pump. 78°C thermostat will allow faster opening to cold water compared to 82°C thermostat and of equal performance with 27 mm thickness radiator.

Emission test also has been checked in order to verify that the new proposed thermostat still complying current domestic requirement which is Euro 3 emission standard. Specification for Euro 3 compliance is :

a. HC : 0.2 g/km
b. NOx : 0.15 g/km
c. CO : 2.3 g/km

Figure 4.13 : Emission test result



	HC (g/km)	NOx (g/km)	CO (g/km)
78deg Thermostat	0.077	0.015	1.092
82deg Thermostat	0.055	0.016	1.161

As expected there will be a deterioration in emission test result as a result of colder coolant temperature circulated during cold start. Nevertheless it still meeting Euro 3 requirment for domestic market. It is not proposed for cold climate export market due to emission performance result.

Eventhough emission performance is deteriorating, but the cooling result shows improvement with this 78°C thermostat adoption. This is hoped to overcome market issue of overheating and high coolant temperature indication .

In term of commercial , increase of radiator thickness from 16 mm to 27 mm will incur higher cost as compared to lower down the opening temperature of thermostat from 82°C to 78°C. Based on this judgement, 78°C has been chosen for improvement for current conventional cooling system.

5.0 LITERATURE REVIEW FOR ADVANCED COOLING AND THERMAL MANAGEMENT SYSTEM

5.1 Advanced engine cooling and thermal management system configuration

The internal combustion engine has been optimized for more than 100 years. The fact that combustion engine provides less mechanical energy than the released heat is one of the main point stated by critics(Donn,2011). It is also a fact that in many cases the heating demand can be easily fulfilled through the released heat itself provided the engine cooling and thermal system is integrated well.

Main revolution is on water pump and thermostat. Electric water pump is adopted to vary flow rate independent of engine rotational speed but dependant on the required cooling that is more related to engine load.

(Chalgren,2004) has used brushless DC electric water pump in his study replacing the production pump as in figure 5.1. Advantage of this electric water pump is the stresses on the shaft are greatly reduced compared to mechanical pump, which carries additional loads from the belt and fan (and engine torsional load for gear driven pump). Apart from that, the reliability of bearings and seal is also greatly improved.

Figure 5.1 : Prototype BLDC electric water pump (Chalgren,2004)

The earlier version of thermostat revolution was proposed by (Thomlinson,1996) through close loop feedback of coolant temperature via solenoid operated thermostat as opposed to the conventional open loop system which is very much dependant on the characteristics of radiator and thermostat . Through engine cooling revolution, electrical valve is proposed to have more accurate control of temperature and can instantaneously act once actuated.(Chalgren,2004) has also adopted electric flow control valve to replace function of thermostat in proportioning the coolant flow between bypass and radiator flow. The valve is flexible in packaging as being its advantage but it is best packaged closed to the electric water pump inlet. The 2-way electric flow control valve is illustrated as in figure 5.2

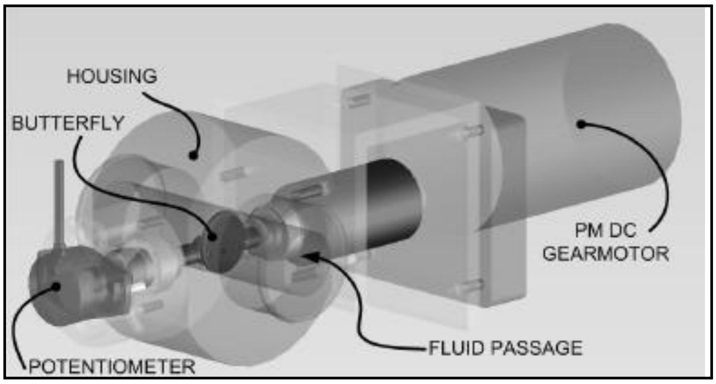
Figure 5.2 : Electric flow control valve (Chalgren,2004)

(Cortona,2000) has modeled thermal behavior of two different configurations of cooling system. In her model, both conventional cooling and another model with electrical cooling pump and electrical bypass valve replacing thermostat has been studied. Aim of her study is to reduce fuel consumption and mechanical wear during cold start and part load operations.

In her study, the author has created a system whereby there is secondary cooling circuit that cools down the cylinder wall before it re-enter engine. To avoid excessive cooling, a heat exchanger is installed. This flow partitioning between bypass and heat exchanger is realized through bypass.

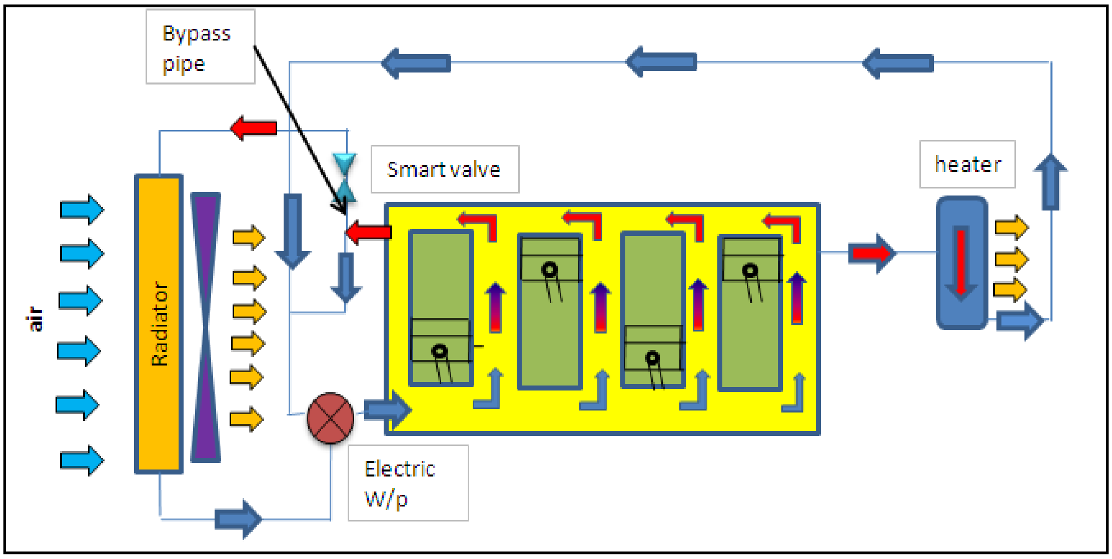
A butterfly valve , electrically controlled has been designed by (Chastain and R.W, 2006) controls the pressure drop in the bypass loop. Controlling the bypass pressure drop regulates the flow through radiator and bypass loop. Through this valve, it will no longer restrict the mixing flow to coolant temperature and allow more sophisticated control of engine temperature.

Figure 5.3 : Prototype smart valve assembly with integrated servo-motor and rotational potentiometer.



Smart thermostat valve as referred by (Wagner *et al*,2003) , permits the engine operating temperature to be regulated by adjusting the fluid flow rate through the radiator or bypass for custom heat transfer. The valve maybe controlled in real time through engine control unit (ECU). The study also covers conversion of mechanical pump to variable speed electric pump to minimize parasitic losses. Greater flexibility may be realized by decoupling the pump's operation from the crankshaft in term of operation independent of engine speed especially during coolant circulation during hot engine shut off and minimal fluid flow during cold start. This electrification has been combined in a circuit as shown in figure 5.4

Figure 5.4: Advanced Spark Ignition engine thermal management system architecture. (Wagner *et al*,2003)



Vehicle climate control system which combines air conditioning system and engine cooling system has been proposed by (Qi *et al.*,2007). The author has developed a computer program consisting of the MAC (Mobile air conditioning) and engine cooling system to simulate the performance of the vehicle climate control system.

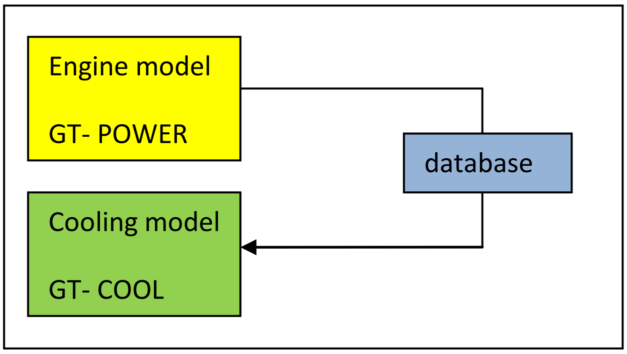
The mobile air conditioning is mainly composed of laminated evaporator, a parallel flow condenser, a fixed displacement reciprocating compressor and externally equalized thermostatic expansion valve. While the engine cooling system mainly composed of an engine, serpentine type radiator and oil cooler tube.

5.2 Advanced cooling system simulation

Apart from parts revolution, system's modeling also evolved as coupled modeling between engine and cooling system is becoming critical due to the consideration for vehicle system interactions intensifies. Vehicle cooling can be coupled to vehicle powertrain in many locations, including the cylinder structure, oil cooler, mechanical coolant pump, mechanical fan, EGR cooler and others.

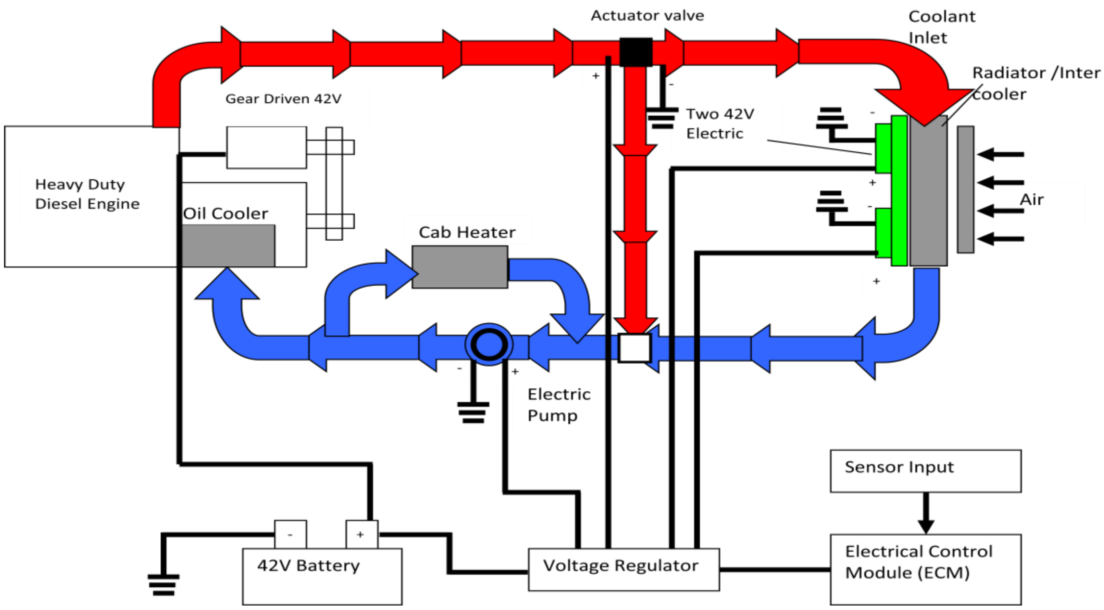
(Luptowski and Adekeye, 2005) has addressed this issue of lack in a linkage between 2 models which are engine model and cooling model.

Figure 5.5 : One – way coupling schematic



(Luptowski and Adekeye, 2005) in another paper has designed a fully coupled detailed engine and cooling system model. This is needed due to increasing complexity of vehicle engine cooling system which results in additional system interactions. Vehicle Engine Cooling System Simulation (VECSS) initially developed by Michigan Technological University has been enhanced to fully coupled detailed engine and cooling system performance as the engine performance affects the cooling system and vice versa. This enhancement is called E-VECSS. In his study, he has investigated a fully electrical cooling system with 42 volt as shown in figure 5.6 below.

Figure 5.6 : Schematic of electric cooling system (Luptowski and Adekeye, 2005)



5.3 Advantages of advanced engine cooling

5.3.1 Fuel consumption

Depletion of fossil fuel and environmental pollution has resulted in aggressive action taken to improve fossil fuel consumption. Two strategies have been outlined by (Elgendy and Schmidt , 2010) to solve this issue which are either to explore other alternative energy source or to improve energy efficiency of parts that use fossil fuel. This is possible through electrification of cooling system.

The heat dissipation capacity of conventional engine cooling is designed for maximum power operating conditions. However, since vehicle engine most often operates under partial load conditions, such system are in fact oversized, entailing unnecessary losses, mechanical losses as well as parasitic losses from high rotational speed operation of mechanical component.

The electric pump offers true flow control capability independent of engine speed. Unlike mechanical pump which will deliver a flow and pressure directly related to the engine speed. The pump also offers potentially lower system operating pressure with the reduced pump flow rate at high engine speed. The controllable electric pump will operate as a function of engine cooling requirements adjusting coolant flow based on need, not engine speed.

Fan ON time will also be decreased due to application of controlled cooling system. This will definitely improve fuel consumption as cooling fan on an 8 liter diesel can draw as much as 21 kW while fan on 15 liter engine consumes up to 45 kW to draw air through the radiator (Allen and Lasecki , 2001).

5.3.2 Better warm up time

Various inconveniences come out at cold start particularly at cold weather such as increase in fuel consumption, increasing concentration of toxic emission, increase lubricant viscosity and resistance to motion thus resulting increase load into starter (Gumus, 2009).

A controllable pump could allow the coolant flow to be completely stopped during cold start and warm up operating periods enabling the engine to reach operating temperature quicker. There are still issues with this strategy which include potential localized boiling around the exhaust valve and port , potential cavitations around cylinder liners due to reduced system operating pressure , and loss of flow to the vehicle cabin heat exchanger (Allen and Lasecki , 2001).

During warm up, the actual thermostat valve opens as a function of wax expansion. It was verified by (Ribeiro *et al.*, 2007) that the instantaneous open/close time (fraction of second) has enable us to leave the valve close up to engine reaching optimum temperature then only open the valve due to its fast response.

Shortening the engine starting and warm up time can be crucial in meeting new requirements and regulations, since these phases involve the greatest fuel consumption (Carasena *et al*., 2011).

Team from Ricardo UK (Revereault, 2010) has shared their experience through extensive vehicle testing on chassis dynameters dictates that over the NEDC (New European Driving Cycle) , hot start fuel consumption will be between 7 % to 12% lower than the same vehicle over a cold start. This is equivalent to performing a cold start test with engine friction reduced by 30 %. This shows that there is potentially significant fuel consumption saving from improved oil warm up.

Fast engine warm up will also improve passenger's comfort in cabin heating performance. As guided by (Jaybhay *et al.*, 2011) the current performance of conventional heating performance is +10°C to +15°C in head zone and +15°C to +20°C in foot zones of occupant. This is to be achieved in 15 minutes after the vehicle start , prior to which the vehicle has been cold soaked for 10 hours at ambient of -25°C.

5.3.3 Eliminate overcooling during part load

Through advanced cooling system, the system is designed to cool down the engine at the highest thermal load and the least coolant. Studies have shown that the engine thermostat is only open 10 % of the time for a loaded vehicle travelling down the highway with a 25°C ambient temperature and the engine unable to maintain consistent temperature when the thermostat opens (Allen and Lasecki , 2001). The controllable pump will allow cooling flow control in real time engine temperatures, ambient temperature and utilize engine load and fuel rate to further predict and control cooling system response.

5.3.4 Eliminate hot soak after shutdown.

A controllable cooling pump that is electrically driven also offers the opportunity to circulate coolant through engine while the engine is switched off. This is beneficial to engine bay after pulling heavy load, and subjected to high engine load ; example after hill climbing. This key off strategy will help to increase the design limitation of engine components since hot spots now has been eliminated.

5.3.5 Better engine temperature control

Dispersion of convectional thermostat is around 10° C while only 5° C dispersion observed through electric valve. With the smaller dispersion, the use of electric valve permits more accurate control of engine temperature due to its fast response. Comparison of these two dispersions is clearly seen in figure 5.7 and figure 5.8 below.

Less chances for overheating since this concept can be a normally open valve that is fail – safe for example in case of valve failure, engine will not overheat.

Figure 5.7 : Conventional thermostat valve dispersion

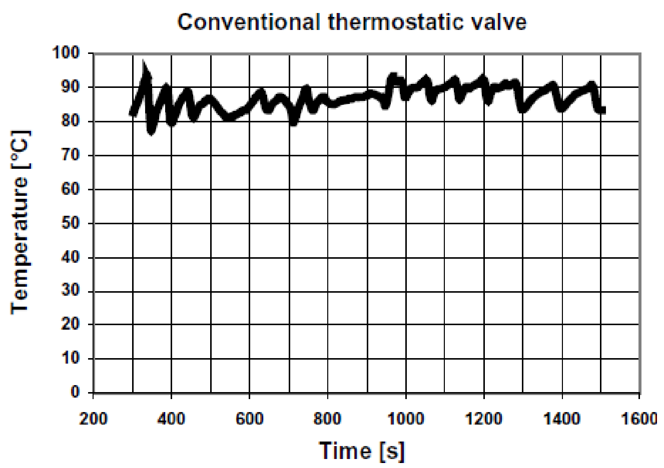
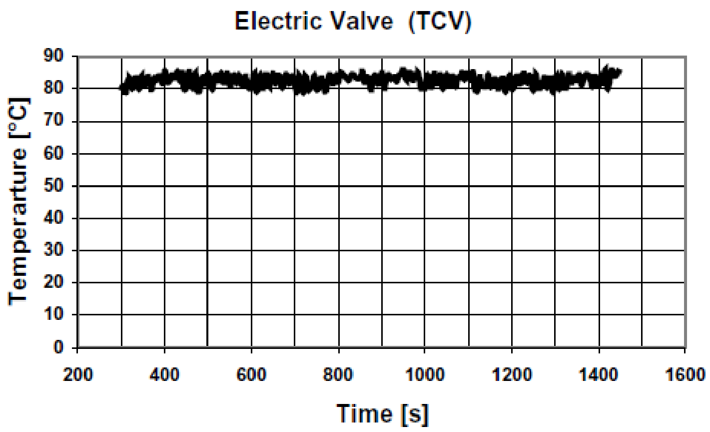


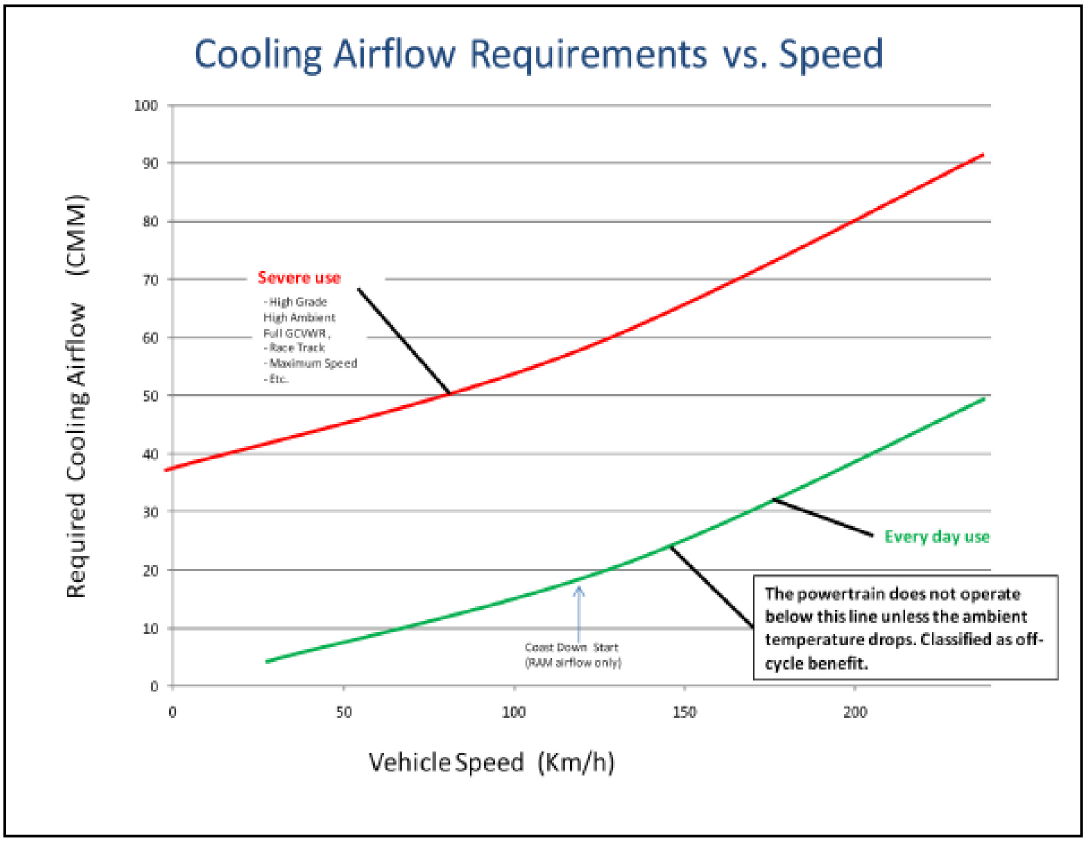
Figure 5.8 : Electric valve dispersion



Overheating will occur when boiling developed beyond nucleate regime. Boiling is a heat transfer process accompanied by a phase transformation. Nucleate boiling has such characteristics as low temperature difference and high heat transfer coefficient (Li *et al.*, 2009). Employment of a small power electrical pump (60 – 100 W) becomes very attractive to increase the flow rate in order to reduce cylinder – to- cylinder temperature difference (Amelio *et al*., 2001). The electric pump is also flexible in rotational speed dependant on control strategies from engine control unit.

Controllable fan will also help to increase air flow which will result in better control of coolant temperature and engine bay according to real time need. This varies fan speed operation is controllable through engine control unit, ECU. Higher possibility of supplying adequate air flow as per guided by (Charnesky , 2011) would be fulfilled.

Figure 5.9 : Severe use vs everyday use example



5.3.6 Lower emission level

Better thermal control of the engine will enable combustion performance optimization by narrowing the temperature operation range. Greatest advantage would be the application of thermal management control technology to intake temperatures which enable control of fuel ignition delay in diesel and also allow to take full advantage of ignition timing for NOx and HC emission control.

A cold engine has also increased exhaust emission comparing to warmer one due to low temperature of catalytic converter leading to low efficiency of catalytic converter.

As been highlighted by (Choi *et al.*,2007) on 20 % reduction of emission in zero flow during warm up. Zero flow take two minutes faster than traditional flow rate , showing that it can reaches the optimum engine temperature much faster than conventional cooling system. However , NOx was increased as expected. This result is shows that lower coolant flow rate makes the cylinder temperature higher. This higher metal temperature enhances combustion in a diesel engine.

Figure 5.10 : THC effect (Choi *et al.*,2007)

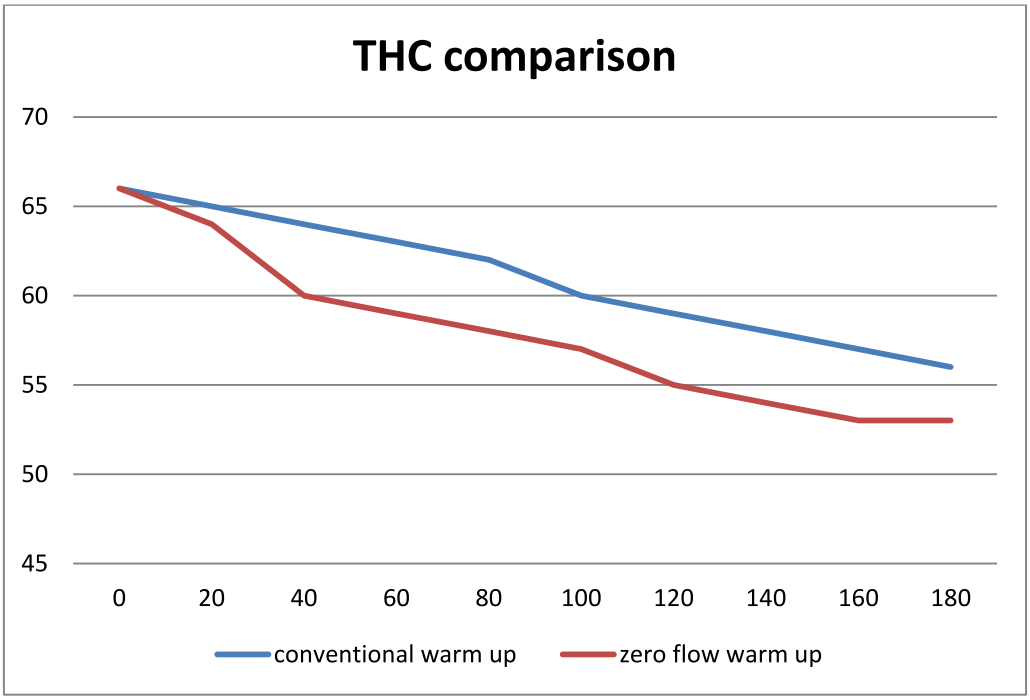


Figure 5.11 : CO effect (Choi *et al.*,2007)

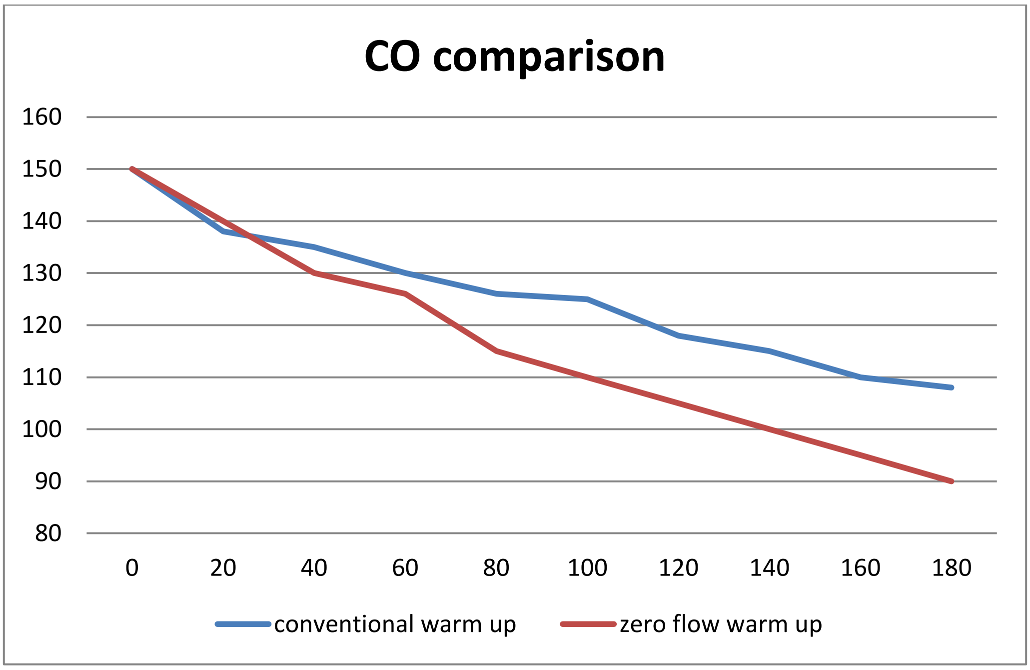


Figure 5.12: NOx effect (Choi *et al.*,2007)

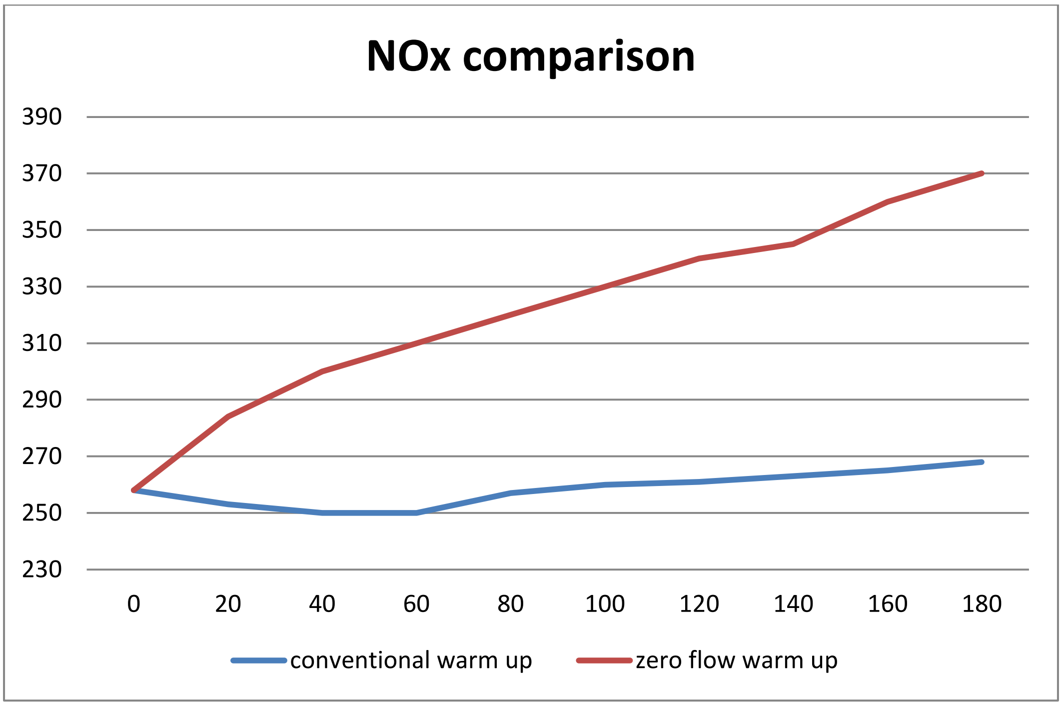
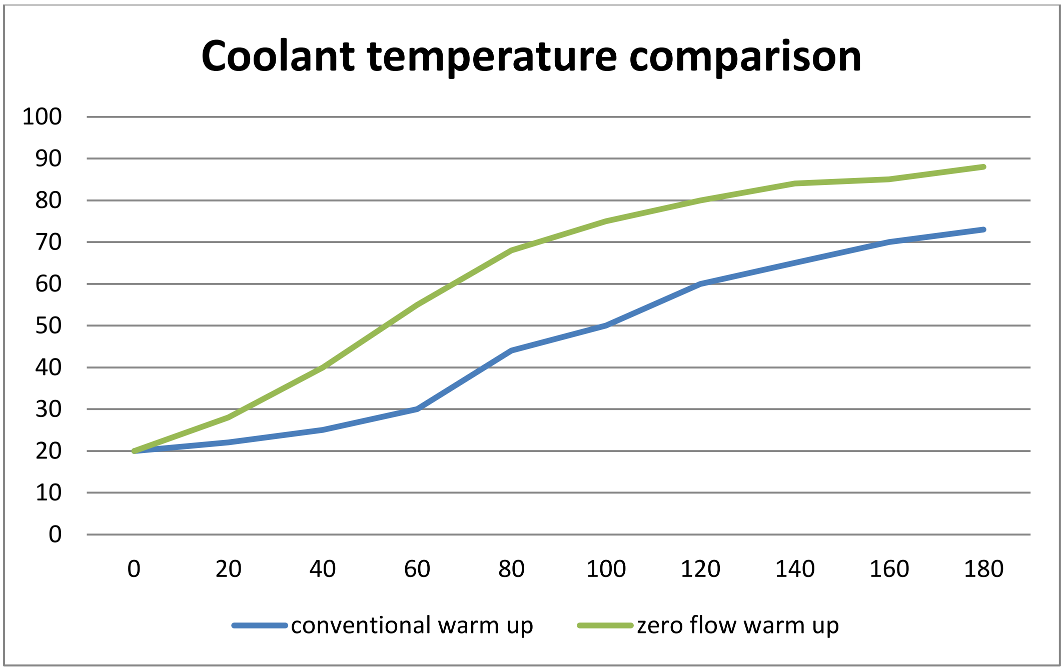


Figure 5.13 : Coolant temperature effect (Choi *et al.*,2007)



5.3.7 Combustion chamber temperature fluctuation

Integration of variable speed electric water pump and servo-motor thermostat valve allows minimizing the combustion chamber fluctuations due to engine speed changes and permitting quick heating of a cold block.

(Wagner *et al.,* 2002) has introduced a controller architecture to regulate these two components through mathematical model. Results shows that the coolant temperature displayed a small fluctuations proportional to engine speed variations and the magnitude of change is smaller in comparison to common thermostat valve.

It is observed that the coolant temperature displays a smaller peak-to-peak fluctuation 2.4°C or a 20 % improvement compared to common thermostat valve.

5.3.8 More accurate result on thermal management system

This is possible through combination of MAC and engine cooling system models known as vehicle climate control by (Qi *et al.,* 2007). These two models are interrelated so that they cannot be modeled separately for better result accuracy.

Figure 5.14 : Comparison of COP (individual MAC and MAC coupled with engine cooling)

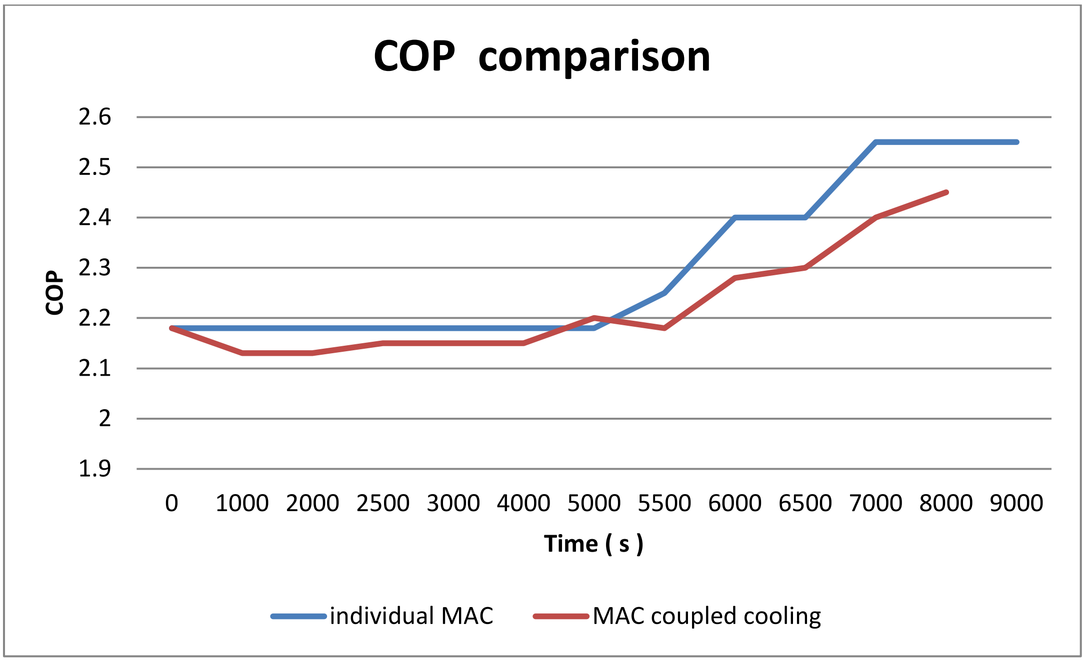


Figure 5.15 : Effect on radiator heat output

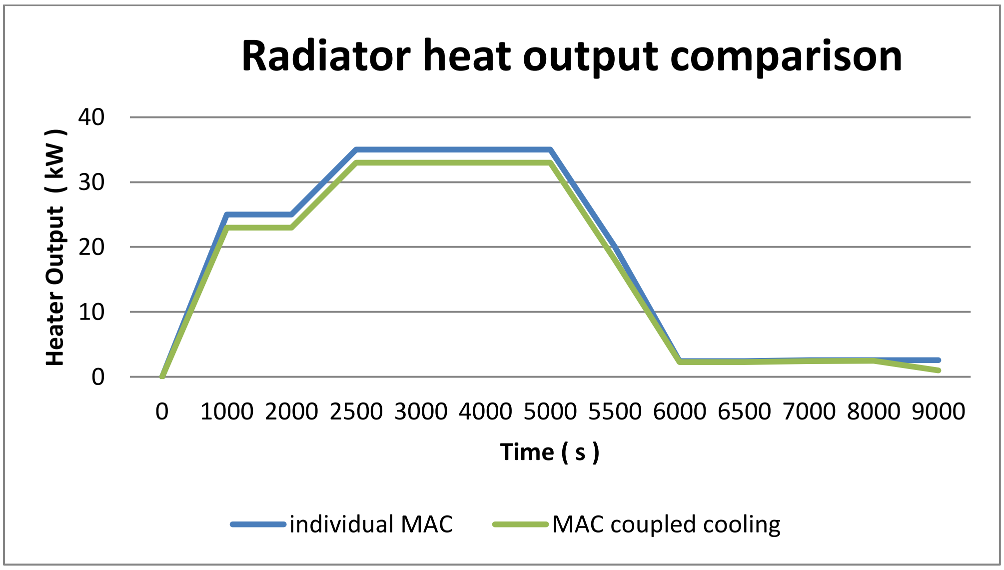
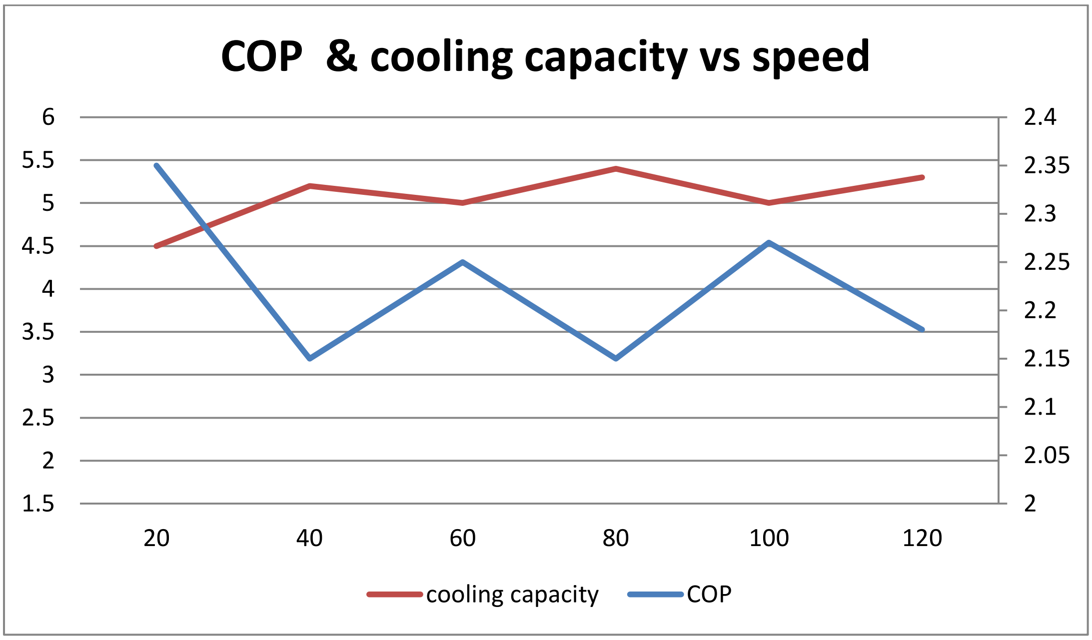


Figure 5.16 : Relationship between COP and cooling capacity against engine speed



The results shows that the effect of engine cooling on the coefficient of performance

(COP) of MAC decreased especially during low vehicle speed and idle status up to 10 %. This can be referred to figure 5.14 and the relationship of vehicle speed to ac performance can be clearly seen in figure 5.16. Engine cooling effect also shown in figure 5.15 has different radiator heat output. Individual MAC shows higher heat output as a result of exit air temperature of the condenser being higher than the environmental air temperature, which decreases the temperature difference of heat transfer on the air side of radiator.

6.0 METHODOLOGY OF ADVANCE ENGINE COOLING AND THERMAL MANAGEMENT SYSTEM

No actual test performed for advance engine cooling system due to limitation of current vehicle and engine set up available. However, few cases cited from other automotive companies have been compared in this section.

6.1 Large SUV Chevrolet Tahoe , 5.77 litre

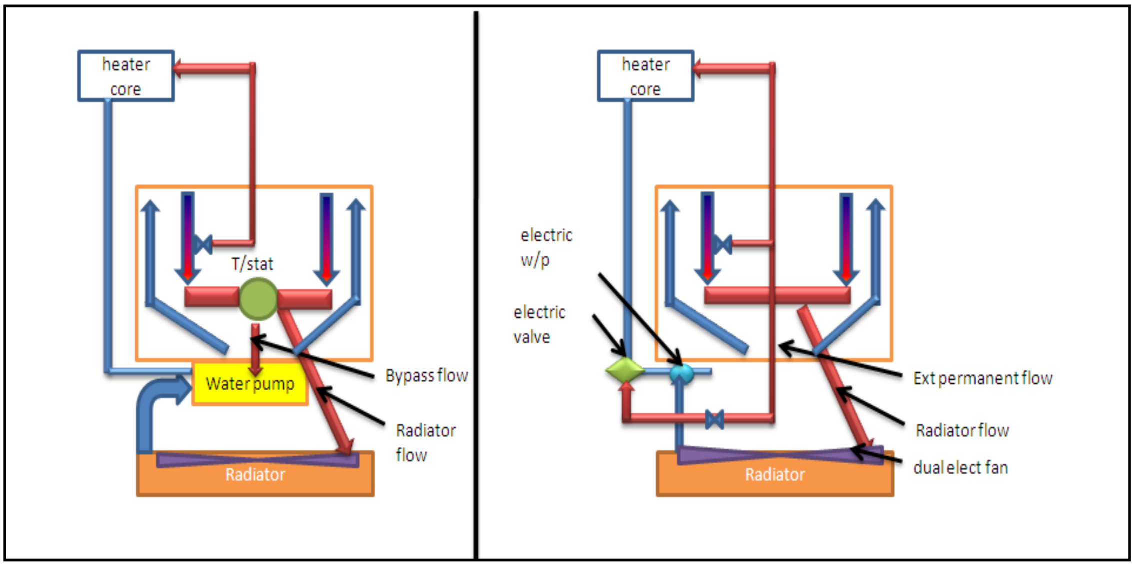
6.1.1 Experimental apparatus

Effect of advance cooling system to improve thermal management ; specifically on heater performance has been studied by (Chalgren Jr, 2004) using Chevrolet Tahoe in which managed to compare the benefit of advanced cooling to thermal management system. Modification from base to advance cooling specification as listed in table 6.1 below.

Table 6.1: Engine specification studied by (Chalgren Jr, 2004)

Item	**Specification (base)**	**Specification (advanced)**
Water pump	Belt driven	300W C20 electric water pump
Flow control valve	Wax type with external bypass	44.5 mm 2 – way electric flow controlled valve
Cooling package	Production condenser and 800 x 445 x 28 mm radiator	Production condenser and 800 x 445 x 28 mm radiator
Fan	Viscous clutch fan mounted to the water pump	Dual 335mm variable speed BLDC electric fans (250 W)
Heater	Standard heater system	Added bypass restrictor – to boost more flow to heater core; and heater core boost pump (20 W)

Figure 6.1 : Base and Advanced system schematic comparison. (Chalgren Jr, 2004)



Main difference other than advanced engine cooling specification is the added bypass restrictor which will make the heater core supply less restrictive therefore increasing the flow to the core. Heater core boost pump also added to boost the coolant flow in the heating mode.

6.1.2 Experimental Procedure

Experiments done to evaluate both warm up and flow performance in several circuit design:-

- Additional of heater core boost pump
- Modified flow circuit design
- Differing pump speed
- Base cooling and HVAC system

Warm up test has been conducted in upper Michigan after overnight cold-soaked. Due to unavailability of climatic control chamber, several iterations have been made for consistency of the result gained.

Test cycles performed:-

- Idle warm up test following an overnight cold-soak
- Drive cycle warm up following an overnight –soak

6.2 Ford Excursion , 6.0 litre diesel

6.2.1 Experimental apparatus

Table 6.2 : Thermal system design configured by (Allen and Lasecki, 2001)

Item	Specification (base)	Specification (advanced)
Water pump	Mechanical – 2.2 kW	EMP C21 electric water pump
Flow control valve	Wax type with external bypass	Electric thermostat
Cooling module	Stack of 4 heat exchangers:- • Ac condenser • Air-oil transmission cooler • Air-to-air charge air cooler • Radiator Small room for cooling air to flow	• compact headed flat tube condenser • variable speed ac condenser • water cooled CAC – WCCAC • radiator positioned 200mm ahead of base configuration

6.2.2 Experimental Procedure

- Road testing conducted for thermal performance and temperature control comparisons. Road test consisted of 9090 kg GVW trailer tow test at Military Hill in upper Peninsula of Michigan.

- Emission lab test for Fuel consumption and emission comparison. These tests were conducted with a velocity wind simulator and hood shut to better simulate the actual on road cooling performance.

7.0 RESULT AND DISCUSSION FOR ADVANCE ENGINE COOLING AND THERMAL MANAGEMENT SYSTEM

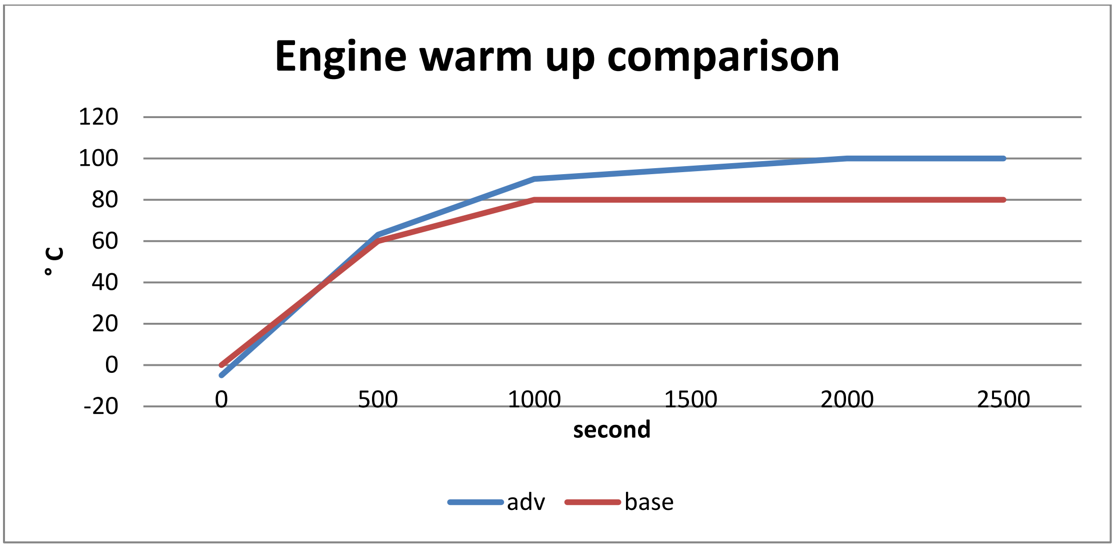
7.1 Chevrolet Tahoe , 5.77 litre (Chalgren Jr, 2004)

7.1.1 Engine Warm up at idle

Observation has been made on engine warm up rate , cabin warm up rate and heater performance. It is desirable to have a low coolant flow to engine which will also result in reduction of pump parasitic losses while maintaining sufficient flow to heater during cold weather operation under light engine load. It is best controlled by an elevated temperature of coolant to heater core. However, since heater is a branched flow circuit, there is a potential that the heater core flow rate is not sufficient at low pump speed. In experiment conducted by (Chalgren Jr, 2004), shows that there is a significant improvement of heater core performance through management of coolant flow rate and temperature to heater core.

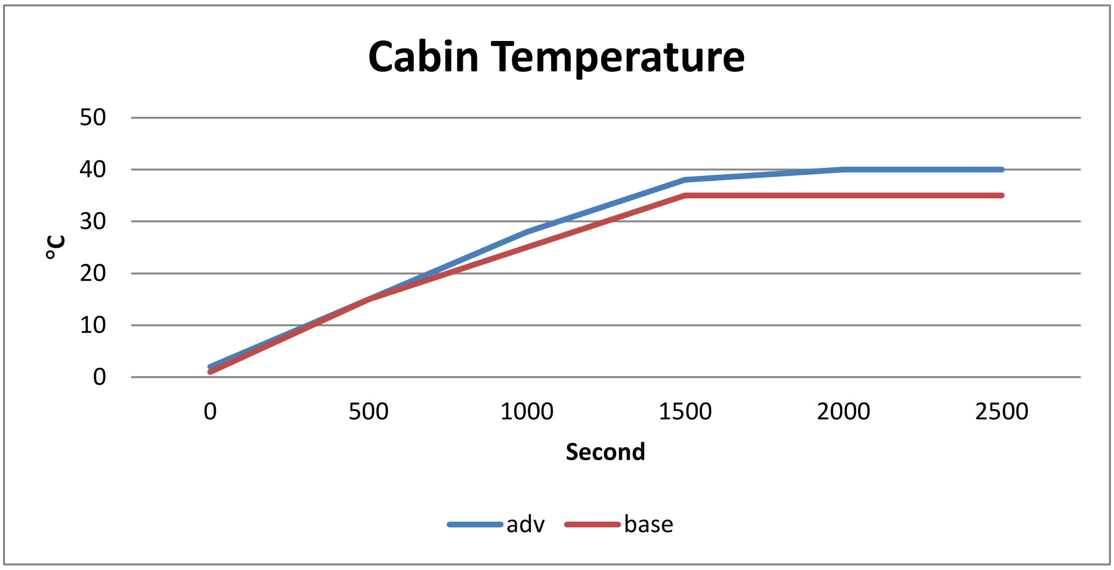
During warm up, electric cooling system has little impact on initial rate of engine warm up, as shown in figure 7.1. However, as the temperature reaching 40°C, the advanced cooling system rises faster than the base. This might be due to weakness of conventional cooling that may has a slight leakage through mechanical thermostat, limited air flow around the engine due to mechanical fan and higher coolant flow rate through mechanical water pump.

Figure 7.1 : Engine outlet temperature during warm up



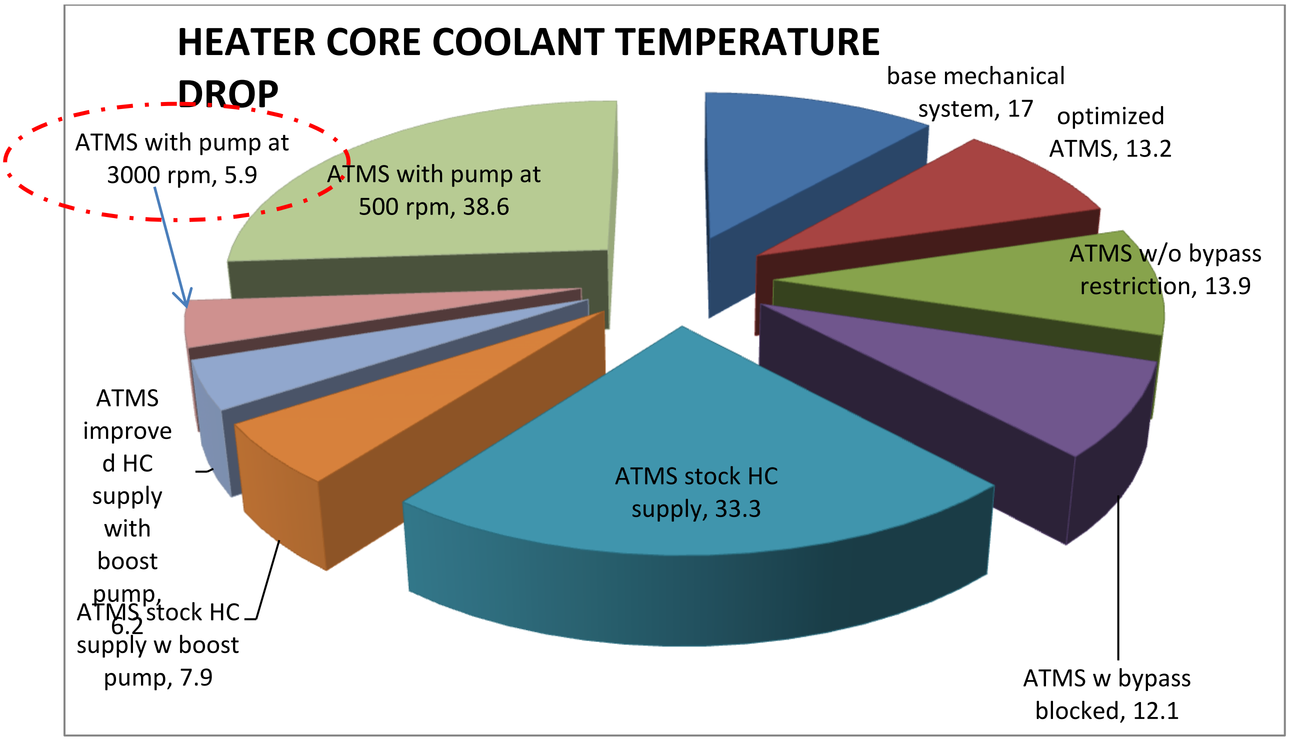
7.1.2 Cabin warm up at idle

Figure 7.2 : Driver inboard ear temperature during idle warm up



The cabin temperature is also improved due to higher coolant temperature and increased flow to heater. The increased flow can be indicated through the temperature drop across the heater core as summarize in figure 7.3. It shows that the highest heater core flow was the advanced cooling with 3000 rpm pump speed with heater core boost pump.

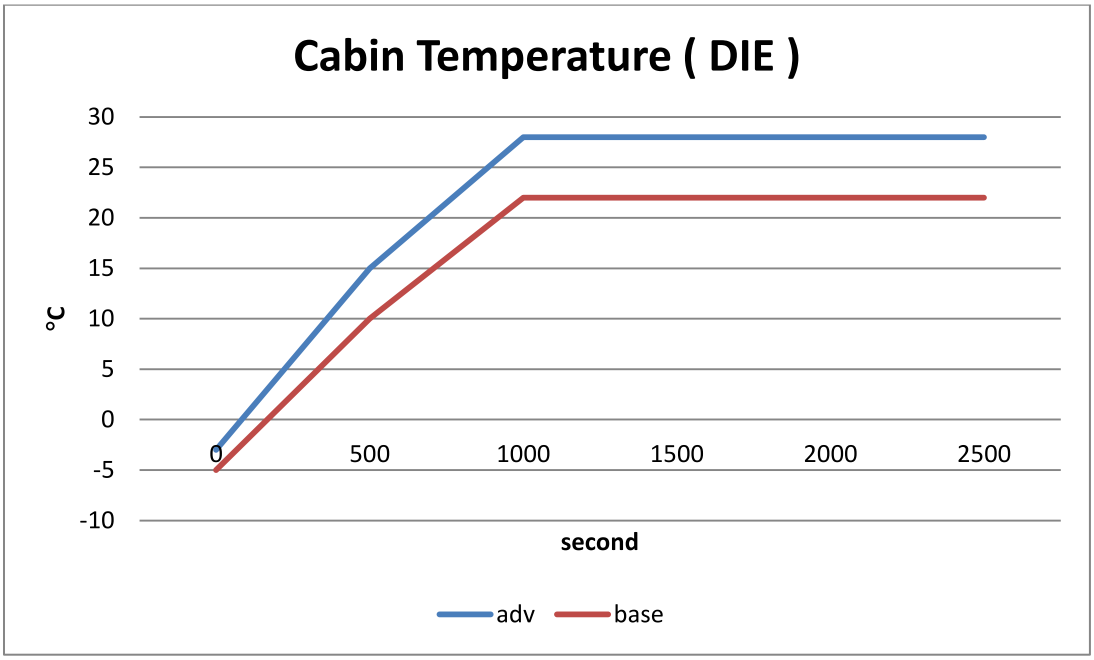
Figure 7.3 : Stabilized heater core coolant temperature drop.



7.1.3 Cabin Temperature in Drive cycle

The ATMS also improved passenger thermal comfort over the suburban driving cycle through increasing cabin temperature up to 5 ° C. This is shown in figure 7.4 below.

Figure 7.4 : Drive cycle cabin temperature comparison



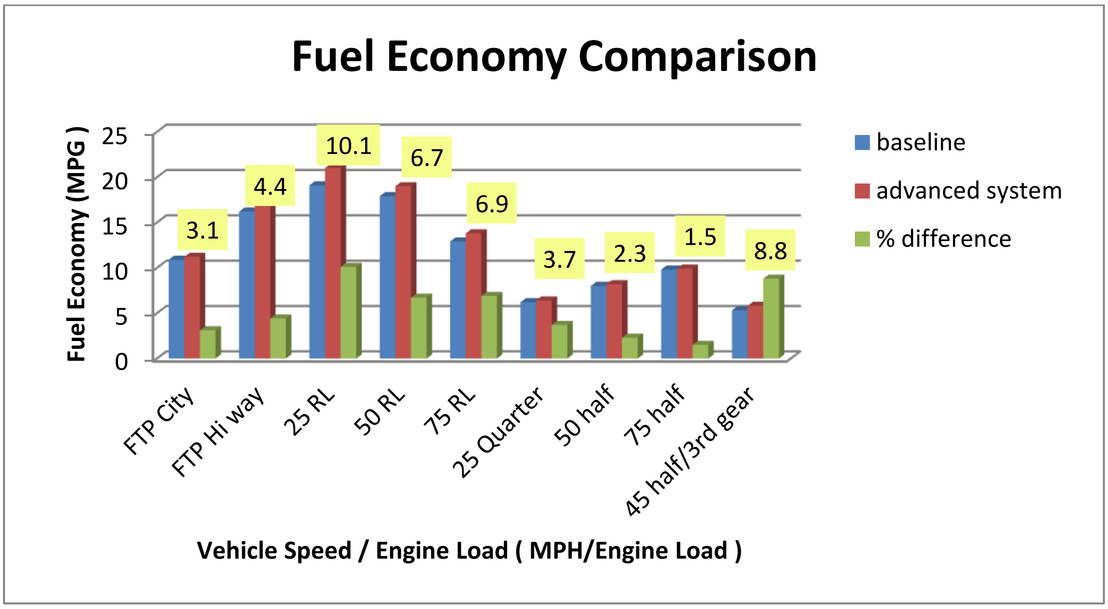
7.2 Ford Excursion. 6.0 Liter (Chalgren Jr and Allen, 2005)

7.2.1 Fuel economy and emissions

The tested truck with advanced cooling system has improved its fuel consumption in all cases tested but varied in percentage of difference. Steady state testing at 25 mph road load showed improvement up to 10 % but this percentage tends to drop as engine load increase due to parasitic cooling system losses are a smaller percentage of total engine load.

Non – standard highway road test showed improvement up to 8.8 %. This is more realistic figure as the pattern is more realistic to our daily practice. Fuel economy comparison can be best represented through figure 7.5 below.

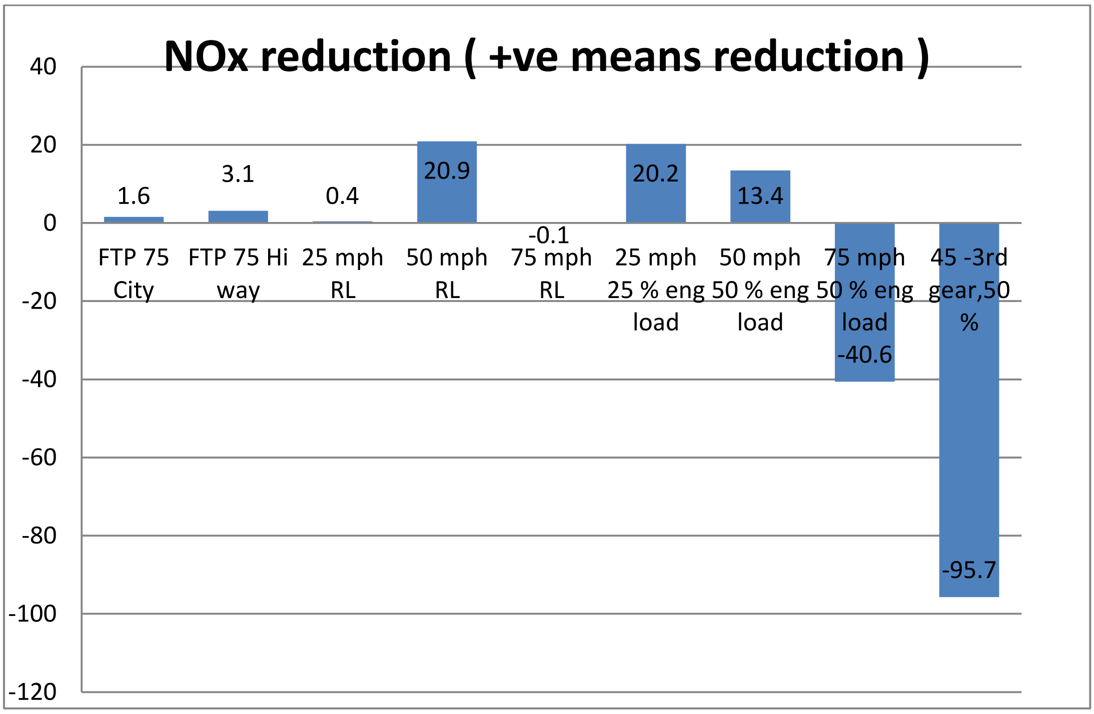
Figure 7.5 : Fuel Consumption comparison



NOx reduction shows mix result , might be due to the fact that the calibration has not been optimized for each configuration. All test conducted based on one single calibration. NOx reduction shown in figure 7.6

At test point 8 and 9 , significant increase in NOx that relates to higher engine speed and EGR mass flow which may have been less in base configuration due to hydrodynamic characteristics of the advanced and base configuration would be more pronounce at higher speed and load.

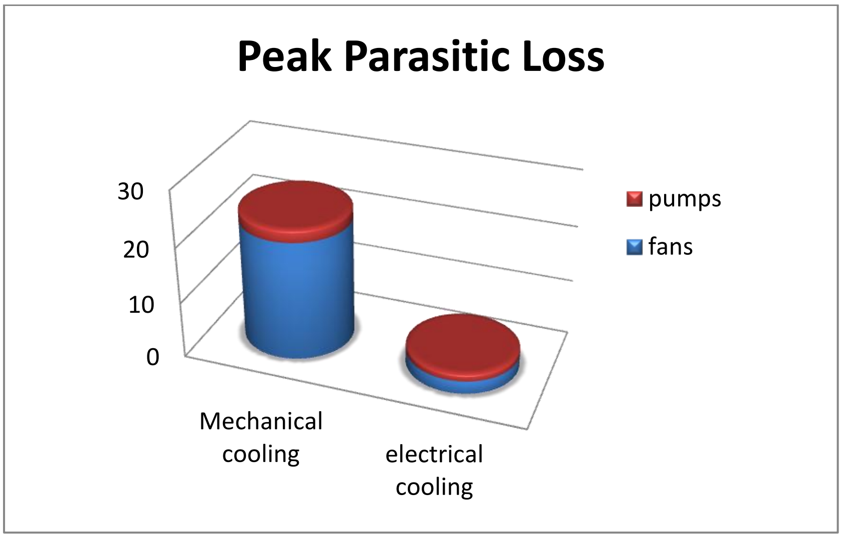
Figure 7.6 : NOx reduction comparison



7.2.2 Parasitic Losses

Reduction of total losses close to 85 % is observed comparing mechanical cooling and electrical cooling , being the most losses from the mechanical, viscous clutch activation fan which covers almost 91 % of total mechanical cooling losses.

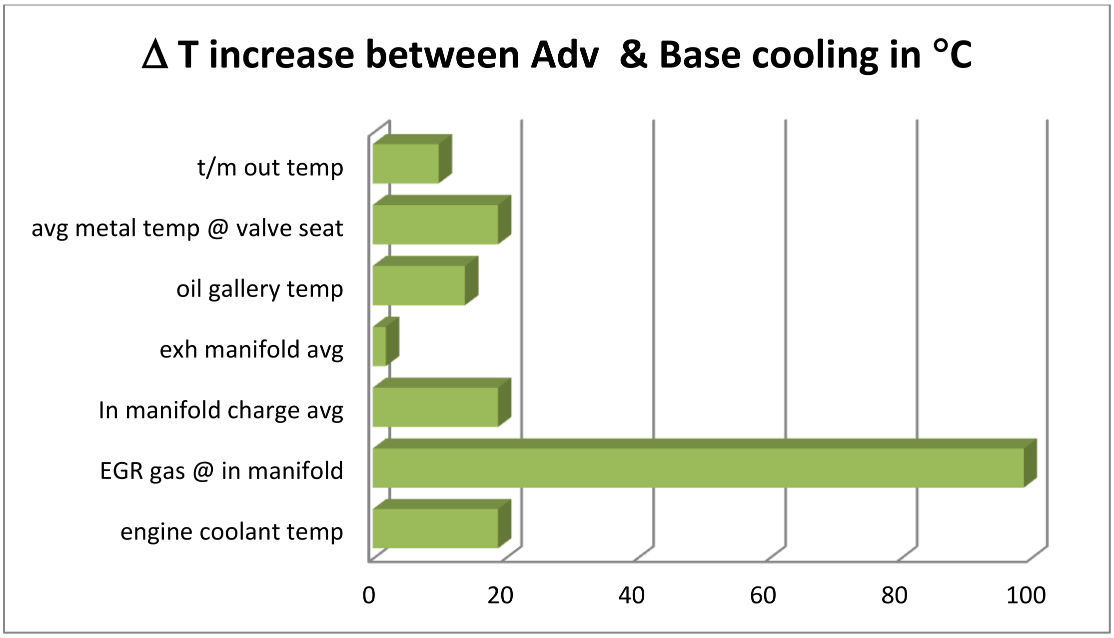
Figure 7.7 : Peak parasitic loss comparison at 3300 rpm



7.2.3 Thermal management and temperature control

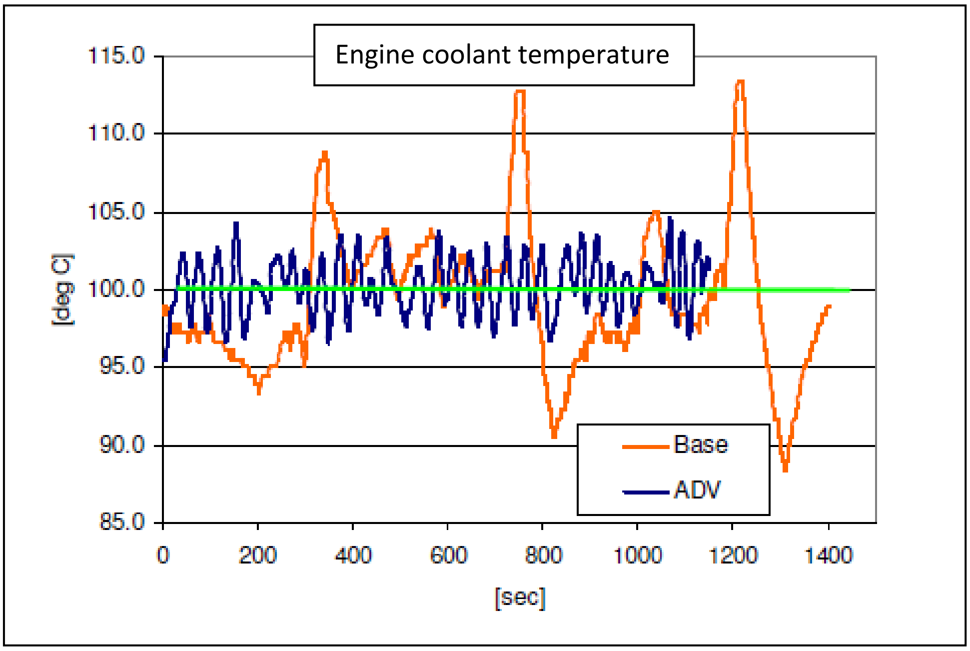
Heat rejection capability between base and advance cooling is greater by a significant margin. At peak engine coolant temperature, difference of 19 °C is observed. This is due to improved air flow through the radiator and the well distributed heat load from active cooling control. The difference of advance and base cooling is tabulated in figure 7.8 below.

Figure 7.8 : Full load tow trailer temperature comparison of base and advances system.



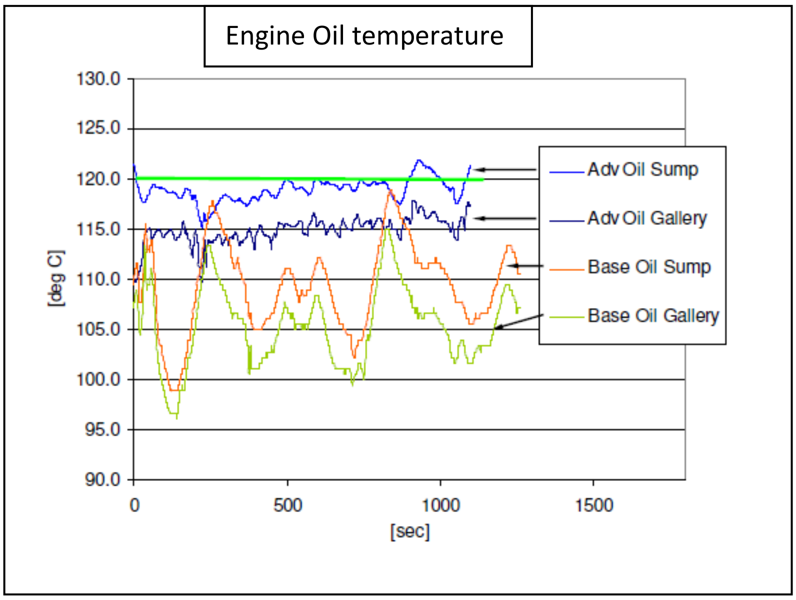
The variation of engine coolant amplitude is also observed to be significantly reduced in figure 7.9 through advanced cooling via its active control system. This variation reduction may improve emissions, engine efficiency and heat exchanger life. As for mechanical system, any accelerations or deceleration can cause temperature to fluctuate, especially during this trailer tow testing which provides the most disturbances to the temperature.

Figure 7.9 : Engine coolant amplitude variation



Oil temperature control with advance system is much closer to ideal oil temperature of 120°C for reduced viscous losses. This temperature tends to drop in mechanical cooling due to coolant flow to oil cooler is not controlled. This can be clearly seen in figure 7.10 below.

Figure 7.10 : Engine oil temperature comparison



8.0 CONCLUSION

8.1 Conventional engine cooling system

Experimental work has been done on thermostat with earlier opening temperature of 78°C in both engine dynamometer and complete vehicle cooling test. Several important parameters have been observed and the following conclusion can be derived as follows:-

a) Thermostat 78°C opening temperature has improved both coolant temperature by 5 °C lower compared to thermostat 82°C opening temperature. This will help to solve high coolant temperature experienced in current engine cooling system under high engine load.

b) Thermostat 78°C opening temperature has also improve coolant volume split to radiator through reduction of bypass flow. This has given an impact in lower coolant temperature.

c) Emission performance for 78°C opening temperature is deteriorating from thermostat 82°C opening temperature. However it is still complying to domestic emission level of Euro 3 standard.

8.2 Advanced engine cooling and thermal management system

Experimental result quoted from two cases on advanced engine cooling and thermal management system observed.

a) Chevrolet Tahoe, 5.77 liter

Through advanced engine cooling and thermal management system, several improvements has been observed in :-

- Engine warm up temperature during idle and drive cycle
- Cabin warm up temperature
- Heater core coolant temperature drop

b) Ford Excursion , 6.0 liter

Addition of electric water pump, electric valve and compact cooling module has shown significant improvement in author's experimental result. It can be concluded that the advance engine cooling and thermal management system has improved as observed in :-

- Fuel economy
- Parasitic Losses reduction
- Thermal management and temperature control

REFERENCES

Ali Sanli, Ahmet N. Ozsezen, Ibrahim Kilikascan, Mustafa Canakci (2008) ." The influence of engine speed and load on the heat transfer between gasses and in-cylinder walls at fired motored condition of an IDI diesel engine. " Applied Thermal Engineering **28 :** 1395-1404

Brian J.Luptowski, Deji Adekeye (2005) ." Coupled engine/cooling system simulation and its application to engine warm up. " SAE Technical Paper (2005-01-2037)

Brian J.Luptowski, Oner Arici, John H. Johnson, G. Parker (2005) ." Development of the enhanced vehicle and engine cooling simulation and application to active cooling control . " SAE Technical Paper (2005-01-0697)

Chad Lehner, Gordon Parker, Oner Arici, John H. Johnson, G. Parker (2001) ." Design and development of a model based feedback controlled cooling system for heavy duty diesel truck application using a vehicle engine cooling system simulation. "SAE Technical Paper (2001-01-0336)

Edward C.Chiang, John R. Keller (2005) ." The thermostat characteristics and its effect on low flow engine cooling system performance . " SAE Technical Paper (900904)

Christian Donn, Wolfgang Zulehner, Daniel Ghebru, Ulrich Spicher (2011) ." Experimental heat flux analysis of an automotive diesel engine in steady state.operating and during warm up " SAE Technical Paper (2011-24-0067)

David J Allen, Michael P. Lasecki (2001) ." Thermal management evolution and controlled coolant flow " SAE Technical Paper (2001-01-1732)

Dr Ali Aslan Ebrinc, Dr Zeynep N. Chehreli (2007) ." Overheating investigation on a 5 cylinder engine " SAE Technical Paper (2007-01-2570)

Dr Zeynep N. Cehreli (2007) ." Cooling system optimization on a 5 cylinder engine. " SAE Technical Paper (2007-01-2600)

E. Elgendy, J. Schmidt (2010) ." Experimental study of gas engine driven air to water heat pump in cooling mode . " Energy **35 :** 2461-2467

Eduardo Gubbiotto Ribeiro, Joa Luiz de Carvalho, Ayres Pinto de Andrada Filho (2007) ." Electric valve for coolant temperature control (TCV). " SAE Technical Paper (2007-01-2791)

Edward R Eaton, W.H Boon, Chris J Smith. (2001) ." A chemical base for engine coolant / antifreeze with improved stability properties . " SAE Technical Paper (2001-01-1182)

Elena Cortona, Christopher H. Onder (2007) ." Engine thermal management with electric cooling pump. " SAE Technical Paper (2000-01-0965)

F. Carasena, M. Bilancia, C.M Bartolini (2011) ." Numerical method of assessing the potential smart engine thermal management : Application to a medium upper segment passenger car. " Applied Thermal Engineering **31 :** 3559 -3568

Ganesan, V (2004) ." Internal Combustion Engine , Mc Graw Hill

George Descombe, Fadila Maroteaux, Michel Feidt (2003) ." Study of interaction between mechanical energy and heat exchanges applied to internal combustion engine " Applied Thermal Engineering **23 :** 2061-2078

Guo Xiang Li, Song Fu, Yun Liu, Yong Liu, Shu Zan Bai, Lin Cheng (2009) ." A homogeneous flow model for boiling heat transfer calculation based on single phase flow " Energy Conversion and management **50 :** 1862-1868

Heinsler, H (2004) Advanced Engine Technology

Henry R. Rasem, James Khoo , Clayton Richter . (2001) ." Model development, simulation and validation of Powertrain cooling system for a truck application. " SAE Technical Paper (2001-01-1731)

John H. Chastain, John R. Wagner (2006) ." Advanced engine thermal management for internal combustion engine – valve design, component testing and block redesign " SAE Technical Paper (2006-01-1232)

John R. Wagner, Mrudula C. Ghone, Darren W. Dawson (2002) ." Coolant flow strategies for automotive thermal management system " SAE Technical Paper (2002-01-0213)

John R. Wagner, Venkat Srinivasan, Darren W. Dawson (2003) ." Smart thermostat and coolant pump control for engine thermal management system " SAE Technical Paper (2003-01-0272)

K David Huang, Sheng – Chung Tzeng, Wei Ping Ma (2004) ." Effect of antifreeze concentration in engine coolant on the cavitation temperature of water pump " Applied Energy **79 :** 261-273

Kyung Wook Choi, Hyung Min kim, Woon Joon Cho, Ki Hying Li (2007) ." Investigation of emission reduction effect by controlling cooling system in diesel engine " SAE Technical Paper (2007-01-4064)

L.F Scott Jr, T.W. Weir (1996) ." Comparing the performance of ethylene glycol and propylene glycol coolants in heavy duty vehicles " SAE Technical Paper (960139)

M. Amelio, F. Barbara, S. Bova. (2001) ." Comparing the performance of ethylene glycol and propylene glycol coolants in heavy duty vehicles " SAE Technical Paper (2001-01-1795/4216)

M. Gumus. (2009) ." Reducing cold start emission from internal combustion engine by means of thermal energy storage system " Applied Thermal Energy **29 :** 652-660

M. I Karamanggil, O.Kaynakli, A. Surmen (2005) ." Parametric investigation of cylinder and jacket side convective heat transfer coefficient of gasoline engine " Energy Conversion and Management **47 :** 800-816

Matthieu Chanfreau, Alex Joseph, Darren Butler, Richard Swiatek. (2001) ." Advanced engine cooling thermal management system on dual voltage 42V-14V minivan " SAE Technical Paper (2001-01-1742)

Pascal Revereault, Cedric Rouaud, Andrea Marchl. (2010) ." Fuel economy and cabin heating improvement Thanks to thermal management solutions installed in Diesel hybrid electric vehicle " SAE Technical Paper (2010-01-0800)

Proton (2009) Cooling System Specification

Robert D. Chalgren Jr (2004) ." Thermal comfort and engine warm up optimization of a low flow advanced thermal management " SAE Technical Paper (2004-01-0047)

Robert D. Chalgren Jr, David J Allen (2005) ." Light duty diesel advanced thermal management " SAE Technical Paper (2005 -01-2020)

S.P Thomlinson, C.R Burrows (1996) ." Design of a feedback controlled thermostat for a vehicle cooling system " SAE Technical Paper (961823)

Samhaji Jabbhay, Prasanna Nagarhalli, Sangeet Kapoor (2011) ." Practical approach to develop low cost, energy efficient cabin heating for extreme cold operating environment " SAE Technical Paper (2011-01-0132)

Satheesh Makappatti, Steve Poe, Zafar Shaikh, Robert Cross, Tony Mikulec (2002) ." Coolant velocity correlations in an internal combustion engine coolant jacket " SAE Technical Paper (2002-02-1232)

Scott Charnesky, Gregory fadler, Thomas Lockwood (2011) ." Variable and fixed airflow for vehicle cooling " SAE Technical Paper (2011-01-1340)

Toshiro Kiura, Takashi Kushibishi, Kazuyuki Shiomi (2005) ." Research and prediction of cooling air flow in small air cooled utility engine " SAE Technical Paper (2005-32-0023)

Scott Charnesky, Gregory fadler, Thomas Lockwood (2011) ." Variable and fixed airflow for vehicle cooling " SAE Technical Paper (2011-01-1340)

V.A. Nelson R (1997) ." A model to simulate the behavior of automotive thermostat " SAE Technical Paper (971814)

Wahler (2003) Thermostat G.W.G.u.co.kg.Esslingen, Germany

Zergas, E (2008) ." Impact on fast engine cooling of a gasoline engine on exhaust emissions and fuel consumption " SAE Technical Paper (2008-01-2441)

Zhao Gang Qi, Jiang ping Chen, Zhi Jiue Chen (2007) ." Analysis and simulation of mobile air condition system coupled with engine cooling system " Energy Conversion and Management **48:** 1176-1184