Review of engine cooling technologies for modern engines

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Abstract: The performance of the conventional engine-cooling system has always been constrained by the passive nature of the system and the need to provide the required heat-rejection capability at high-power conditions. This leads to considerable losses in the cooling system at part-load conditions where vehicles operate most of the time. A set of design and operating features from advanced engine-cooling systems is reviewed and evaluated for their potential to provide improved engine protection while improving fuel efficiency and emissions output. Although these features demonstrate significant potential to improve engine performance, their full potential is limited by the need to balance between satisfying the engine-cooling requirement under all operating ambient conditions and the system effectiveness, as with any conventional engine-cooling system. The introduction of controllable elements allows limits to be placed on the operating envelop of the cooling system without restricting the benefits offered by adopting these features. The integration of split cooling and precision cooling with controllable elements has been identified as the most promising set of concepts to be adopted in a modern engine-cooling system.

Keywords: engine cooling, fuel efficiency, emissions reduction

1 INTRODUCTION

The performance of the engine-cooling system (ECS) has steadily improved as the power output and density of internal combustion (IC) engines gradually increases. With greater emphasis placed on improving fuel economy and lowering emissions output from modern IC engines, engine downsizing and raising power density has been the favoured option. Through this route, modern engines can attain similar power outputs to larger conventional engines with reduced frictional losses and mass.

With increasingly compact engine design and higher specific power, the density of the waste heat generated has increased significantly. Removing heat from an increasingly restricted space is a particular concern at vulnerable regions, such as the exhaust-valve bridge area, as the risk of catastrophic failure in such regions is increased, even with minor failure in the cooling system. This heat rejection problem, which is prominent at wide-open throttle (WOT) conditions, is tackled by optimizing coolant gallery design for optimum heat transfer effectiveness by targeting this region with high coolant-flow velocities. Consequently, hydraulic losses in the ECS is evident at part-load conditions in conventional ECS because of the engine-driven coolant pump, which supplies more than required coolant flow in the system.

The introduction of cold-start legislated, drive-cycle tests has changed the significance of ECSs, due to their impact on test results. Rapid engine warm-up is critical in attaining low fuel consumption and emission readings in drive-cycle tests, as engine efficiency and emissions are poorest in cold start, gradually improving as the engine reaches a warmed-up state. The high demand for heat from the cabin heater in cold-climate conditions to improve cabin conditions, in addition to performing safety functions, such as demisting and de-icing of the windscreen, further prolongs the engine warm-up time.

Recent developments have seen thermal management features integrated into the engine management structure to enable an optimized balance between engine warm-up, cabin condition, catalyst light-off, and emissions performance. Although the current ECS is a passive system, the engine management system controls the heat distribution in the engine and vehicle by compensating engine controls, such as spark timing and air–fuel ratio to regulate engine power output, as well as heat production and distribution to each part of the engine.

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Although the integration of the vehicle and engine thermal management into the ECS significantly improves engine performance, there are limitations to the overall benefit that can be achieved with a simplistic and passive ECS. The ECS can be improved significantly with the inclusion of advanced design and operating features, allowing the ECS to operate efficiently and effectively, indirectly improving fuel economy and lowering emissions output.

2 THE EFFECTS AND FEATURES OF ADVANCED ECS

While conventional ECSs are adopted for their simplicity and reliability in protecting the engine, an advanced cooling system has the additional goal of improving engine fuel economy and emissions. This is achieved through a fine balance between the three main factors bridging the ECS to fuel efficiency and emissions, which are:

1. Frictional losses within the engine.
2. Auxiliary power requirements to operate the cooling system.
3. Combustion system boundary conditions, such as combustion-chamber temperature, charge density, and charge temperature.

In an advanced ECS, these factors can be influenced by the cooling system without compromising the operating limits on the engine structure, a characteristic uncommon in conventional systems.

Advanced ECSs gain advantage over conventional systems by incorporating features in the form of system design and module technologies, as well as operating approach and strategies. These features enable an advanced ECS to positively influence the elements that links the ECS to the engine fuel efficiency and emissions output with greater system effectiveness and operational stability.

With multiple constraints on the performance of the engine, it is not possible to improve all aspects of the engine performance by just manipulating a single variable or aspect of the cooling system. Therefore, a number of features are being incorporated into advanced ECSs to increase its operating flexibility to satisfy most if not all of the constraints on engine performance. Thus, most of these features are neither purely hardware nor software, but they exist as pairs where the operating features are embodied into the design features to complement the effect each produces.

2.1 Temperature set point

Controlling coolant temperature to a predetermined set point is the most common operating approach for the ECS. Although it is commonly perceived that the coolant temperature is representative of the metal temperature, this relationship only holds true at steady state conditions, and for a particular operating speed and load at a particular location in the engine, due to the complexity of the actual temperature distribution in the engine structure. Consequently, the temperature of the metal and coolant varies from one point to another in the engine structure giving a non-uniform temperature distribution.

As the operating limits on the engine structure revolves around the maximum temperature at which the exhaust-valve bridge area can safely operate, it is more desirable to control the ECS based on the metal temperature rather than the coolant temperature on the basis of engine protection. With the ECS designed to cope with the peak-heat rejection rate at WOT conditions, based on a coolant temperature set point, the engine and its cooling system operates at a less than ideal condition at part-load operation, such as city driving or slow cruising, leading to higher fuel consumption and emissions output.

This is an aspect of the ECS that can be improved on by varying the coolant temperature set point to improve the engine and cooling system performance at part-load conditions. With knowledge of the limits on the temperature of the exhaust-valve bridge area, the coolant or metal temperature set point can be shifted, upward or downward, to improve the performance of the engine and the cooling system. Moving the temperature set point in either direction has its own merit, depending on the desired effect to be achieved.

2.2 High temperature set point

Increasing the operating temperature set point has been the most popular route among investigators of ECSs [**1**–**4**]. Raising the operating temperature of the engine has a number of benefits, as it directly influences the elements that dictate the losses in the engine and the effectiveness of the cooling system, as well as the formation of emissions in the engine. The increase in operating temperature will raise the engine oil temperature, lowering frictional losses in the engine, subsequently improving the fuel efficiency of the engine.

The impact of raising operating temperature on the frictional losses can be seen in a number of studies. Finlay *et al.* [**4**] raised the bore temperature up to 195 °C by controlling the coolant outlet temperature to 150 °C to reduce frictional losses. This resulted in 4–6 per cent improvements in fuel consumption. Couetouse and Gentile [3] took a different approach by targeting a maximum 140 °C operating temperature for the engine oil by regulating coolant temperature within the range of 90–115 °C, depending on the engine power output. This allowed reductions of up to 10 per cent in fuel consumption during part-load operation, as shown in Fig. 1.

Raising the operating temperature also significantly influences the effectiveness of the ECS. Increasing the

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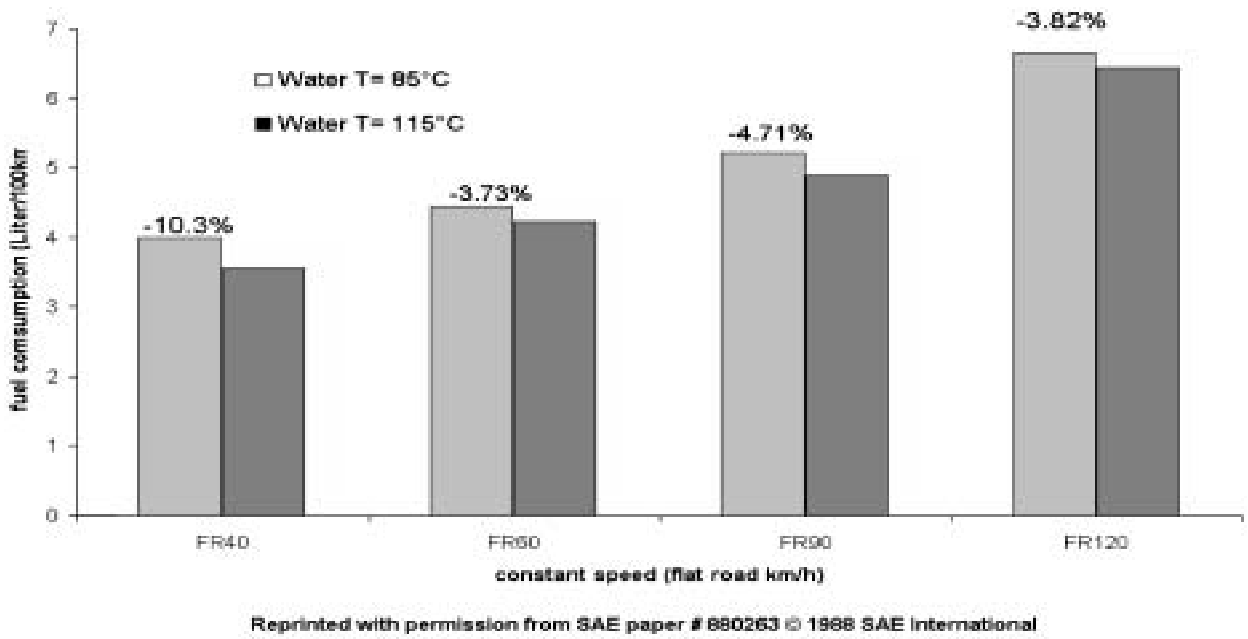

Fig. 1 Comparison of fuel consumption with coolant temperature at 85 °C and 115 °C [3]

operating temperature of the coolant or metal improves the effectiveness of the heat-transfer process in the engine and the radiator, allowing a lower coolant flowrate for a given power condition, and, thus lowering the pumping requirement. This lowers the power consumption of the auxiliary system, which draws a significant portion of the engine power, particularly at part-load conditions. In addition, a different mode or regime of heat transfer can be employed to further reduce the coolant flowrate requirement.

The benefit of raising the operating temperature is illustrated in the study by Chanfreau *et al.* [**2**], where an electric water-pump rated at 600 W is used for a 3.8 L gasoline engine with a power output of 180 hp, in place of a mechanical coolant pump, typically rated at 2–3 kW. The reduction in coolant flowrate with a smaller coolant pump is made possible by raising the coolant operating temperature from about 90 °C to 110 °C. This represents significant fuel savings, particularly at part-load conditions where a mechanical coolant pump would draw a significant portion of engine power to cool the engine even when it is not required.

The change in heat-transfer mode represents a more radical and aggressive approach to deliver fuel savings from lowering auxiliary power requirement. Ap *et al.* [**1**] were able to replace the mechanical coolant pump, rated at about 1 kW, for the 1.2 L gasoline engine with a smaller electric coolant pump, rated at 30–80 W, by employing an evaporative cooling system. The advanced cooling system, abbreviated REROM, was realized with a large step reduction in coolant flowrate and circuit pressure (Table 1), intensifying evaporative effect. The low flowrate and circuit pressure reduces hydraulic losses significantly, allowing the system to have at least 25 per cent of the original flowrate even when pump power is less than 10 per cent of the original system.

The more critical aspect of raising operating temperature is its impact on the formation of emissions by-product in the engine. The carbon monoxide (CO) and unburned hydrocarbon (uHC) output from the engine drops as operating temperature is raised. The higher chamber temperature vaporizes fuel that adheres to the wall, as well as raises the average charge temperature, and thus promotes further oxidation of CO and

Table 1 Engine cooling performance of 1.2 L gasoline engine in climatic wind tunnel [**1**]

	13% hill climb PTMA, Ta = 30 °C		Maximum speed, Ta = 35 °C	
	Standard	REROM	Standard	REROM
Cylinder head temperature (°C)	147	151	142	152
Engine coolant flow rate (L/h)	5300	1300	4300	1400
Coolant pressure (mbar)	660	100	180	70
Oil sump temperature (°C)	136	138	129	136
Engine coolant temperature (°C)	102	107	87	101

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uHC particles. Chanfreau *et al.* [**2**] reported a 15 per cent reduction of CO output and a 17 per cent reduction in uHC output in a FTP75 + HWFET drive-cycle test, with the higher operating temperature set point. In steady state conditions, about 10–20 per cent reduction in HC is achieved by Couetouse and Gentile [**3**], while Finlay *et al.* [**4**] manages a reduction of up to 35 per cent in HC output.

On the other hand, nitrous oxides (NO_x) output from the engine rises in tandem with any increase in operating temperature. This is due to the temperature-dependent factor of the formation of NO_x in the combustion chamber. Couetouse and Gentile [**3**] explains that the 10–20 per cent increase in NO_x output with the increase in operating temperature was due to the knock-on effect on the peak in-cylinder temperature. Chanfreau *et al.* [**2**], however, reported no increase in NO_x, indicating that the reduction in frictional losses and volumetric efficiency could be contributing factors in maintaining NO_x levels by keeping similar levels of peak in-cylinder pressure and temperature.

2.3 Low temperature set point

Lowering the temperature set point goes against all the benefit that can be achieved by increasing operating temperature. Nevertheless, there are merits in reducing the operating temperature of the ECS, which includes improved engine breathing or volumetric efficiency and lower charge temperature, two factors that strongly influence the combustion process and its output in fuel efficiency and emissions terms. In addition, the operating margin of the engine is increased with a lower temperature set point, increasing the life of engine components.

By reducing the coolant temperature feed to the head to 50 °C, Finlay *et al.* [**4**] reported that knock protection improves by up to 2° of spark angle, indicating lower charge temperature and the potential to recalibrate spark timing for improved fuel efficiency and lower emissions. Kobayashi *et al.* [**5**] claim similar improvements, with 3° spark angle increase in knock protection and 2 per cent improvement in charging efficiency by dropping the head temperature to 50 °C. This improvement in the engine operating envelope would allow the compression ratio and operating settings to be optimized for better fuel consumption and emissions.

2.4 Precision cooling system

The precision cooling system is an engine cooling concept that is embodied in both the coolant gallery design and the operating design of the system. In a precision-cooled system, thermally critical areas, such as the exhaust-valve bridge are targeted with high coolant flow speeds to promote heat transfer without steep temperature gradients or high heat flux, effectively lowering temperatures around these regions. This is achieved by reducing the cross-sectional area of the coolant passage in these regions to attain high flow speed without high bulk flowrate.

The key design point of a precision cooling system involves the sizing of the coolant gallery and matching of the coolant pump to ensure that the heat-removal rate of the system can satisfy the limiting constraint on the operating temperature in vulnerable regions at low speed, WOT conditions. The coolant flow speed in this region can vary considerably with engine speed, from less that 1 m/s at idle condition to a high of 5 m/s at maximum power condition. Thus, the design of the gallery and the cooling system as a whole must complement each other to maximize the potential benefits.

The benefit of employing a precision cooling system is shown by Finlay *et al.* [**6**], where 40 per cent reduction in coolant flowrate requirement can be attained with lower metal temperatures across the engine speed range (Fig. 2). The use of finer coolant galleries in the cylinder head pushes the coolant flow speed from a maximum of 1.4 m/s in a standard gallery design to more than 4 m/s in a precision-cooled head, greatly promoting heat transfer and thus reducing the metal temperatures in the cylinder head by up to 60 °C. Clough [**7**] claims an even larger reduction in coolant pump power requirement of 54 per cent and a difference in maximum metal temperature of 100 °C with precision cooling system.

2.5 Split cooling system

The split cooling system is another form of ECS, whereby a combination of system design and operation approach is employed to maximize the potential of the features. In a split cooling system, the head and the block of the engine are cooled by independent circuits, thereby allowing flexibility in regulating the temperature of each section of the engine. A split cooling system gives a unique advantage to an engine as it allows each sections of the engine to operate at its optimum temperature set points, maximizing the overall effect of the cooling system to the engine performance. Each circuit would operate with a different coolant temperature set point or flowrate to create the desired temperature distribution in the engine.

The desired thermal operating condition for the engine is to have the head running cooler, while having the block running warmer relative to the standard condition. By running the head cooler, volumetric efficiency improves, increasing the mass of trapped air, albeit at lower temperature. The increase in trapped air mass at a lower temperature allows a more rapid and complete combustion, reducing CO, HC, and NO_x formation, while increasing the output power. Higher block temperature would reduce frictional losses, contributing to fuel efficiency improvements and indirectly lower the peak in-cylinder pressure and temperature, which has a strong association with NO_x formation.

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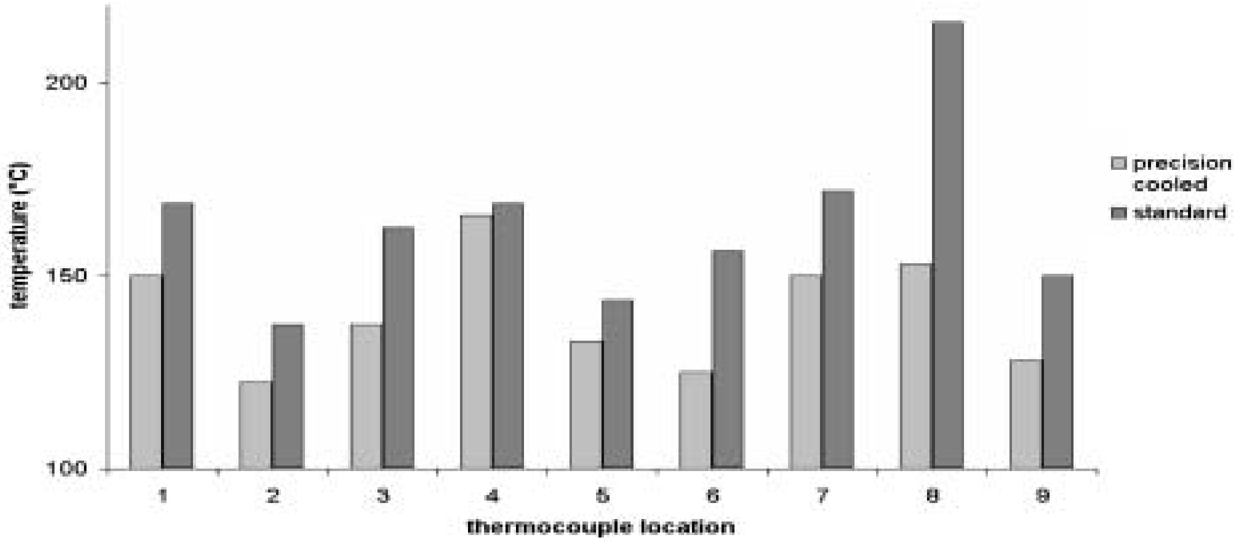

Fig. 2 Comparison of coolant side metal temperature from standard and precision-cooled cylinder head at WOT, engine speed of 5000 r/min [**6**]

Finlay *et al.* [**4**] demonstrated that split cooling allows contrasting temperature set points of up to 100 °C temperature difference between the head and the block. The temperature of the coolant was set as high as 150 °C for the block and as low as 50 °C for the head, reducing frictional losses and subsequently the fuel consumption rate. The high block temperature reduces fuel consumption by 4–6 per cent and uHC output by 20–35 per cent at part-load conditions. At WOT, milder coolant temperature set points of 50 °C and 90 °C at the head and block respectively offers all-round improvement on fuel consumption, power output, and emissions (uHC and NO_x) instead of the high block temperature set point.

Kobayashi *et al.*'s [**5**] success in raising the compression ratio, reducing fuel consumption, and increasing engine torque band was derived from lowering the coolant temperature of the feed to the head to 50 °C, while maintaining the block temperature feed at 80 °C. This approach preserves the engine frictional-loss, while improving charging efficiency and knock protection. The compression ratio was raised from 9:1 to 12:1, raising the efficiency of the cycle to give a 5 per cent improvement in fuel consumption at part-load and 7 per cent at idling. The peak WOT output of the engine was also raised by 10 per cent without deteriorating part-load performance relative to the baseline engine.

2.6 Controlled engine cooling and elements

The conventional ECS still used on modern engines is a passive system designed for simplicity and cost effectiveness. The controllability of the ECS is a desirable feature for a number of reasons, which mainly relate to deficiencies of the current system. With the ECS designed to cope with WOT conditions, excess cooling potential generated during part-load operation is dissipated in the system, leading to inefficiencies that are notorious at this part of the engine-power curve. This problem is more prominent for light duty vehicles, as these vehicles are operated mostly for city driving, at part-load operation, which uses a small proportion of the available engine power, incurring high losses in the cooling system.

Potential improvements in legislated drive-cycle results are one of the main motivations for the introduction of controllability to the ECS in mass-produced vehicles. Oversizing of the current ECS to cope with the possibility of engine overheating under certain remote circumstances leads to further inefficiencies in the cooling system, which increases the power requirement of the cooling system, as well as retarding engine warm-up rates, which are crucial to meet legislated limits. As with any control system, the elements in the system include sensors, actuators, and controller, with electrical and electronic modules favoured to replace their mechanical counterparts, due to the ease of implementation of a controllable system.

The advantage of a controllable ECS is clear, with its ability to compensate for the engine operating condition, minimizing losses by adjusting cooling supply to match demand, and thus reduce auxiliary power requirement without sacrificing engine protection. It also enables an unique operating regime and characteristics to be programmed into the ECS to give the desired effect. In a controllable ECS, the actuators, namely the coolant pump and thermostat, are normally being replaced by an electric coolant pump and flow-control valves, enabling flexibility in the response from the cooling system. Temperature sensors are an integral part of such system, to allow rapid updates on the thermal state of the engine to be relayed to the controller.

Controllable elements, such as electric water pump in the ECS allowed Chanfreau *et al.* [**8**] to run with a higher

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coolant temperature set point of 110 °C, in comparison to 90 °C in conventional ECS, with fuel saving of 2–5 per cent, 20 per cent reduction of CO, and 10 per cent reduction on HC. Metal temperature was consistently 10 °C higher that a conventional system when running at steady conditions. The confidence of operating with a higher metal temperature closer to the operating limit is drawn from the ability in a controllable system to respond to changes quickly by maintaining coolant temperature within ± 2 °C to the set point. The ability of the system is highlighted by the fact that coolant temperature can be reduced by 10 °C from 110 °C in 2 s. This allows the system to run closer to the operating limits of the engine and reduce warm-up time by up to 200 s. The ability to regulate coolant or metal temperature to a narrow range is also beneficial to reduce metal fatigue arising from thermal cycling load, thus prolonging component life.

With the ability to respond, Ap *et al.* [**1**] were able to employ an evaporative ECS. The system employs a smaller electric pump and a dilatable expansion tank with a electric cooling fan and shutters to regulate coolant temperature to a narrow operating range. The 0.8 L dilation capability of the system limits the system primary operating zone in the range of the subcooled region to the limiting point of close to complete vaporization to maximize the potential of the system without excessive vapour generation. Metal temperatures are marginally higher by 10 °C, as higher surface temperature of the coolant gallery is required to induce the evaporative effect, while still remaining within safe operating limits. The ability to respond is critical for an evaporative cooling system, as the coolant state is operating very close to the critical point where film boiling and critical heat flux occurs, which could result in sudden, catastrophic failure.

The use of electrical modules, such as the electric water pump and electric flow-valve, to function as a controllable ECS in mass-produced vehicles is not implemented in practice, mainly due concerns about the high operating temperature associated with these systems. This can be observed in numerous works where the controllable elements are electrical modules [**1**–**3**, **8**]. ECS using electrical modules needs to raise the operating temperature of the engine to take advantage of the higher heat-transfer effectiveness at higher temperature to compensate for the low efficiency of powering electrical modules on vehicle. The use of electrical energy in vehicles is inefficient, due to the conversion losses when mechanical energy from the crank produce electrical energy in the alternator, which is converted back into mechanical energy in the coolant pump. In addition, the current demand of a water pump rated at 1 kW on the current 12 V electrical system in vehicles would be in the order of a few hundred amperes, which leads to high transmission losses.

Thus, it is unavoidable that ECS that utilize the electric water pump operate at much higher temperatures than conventional cooling systems. Although there is numerous documentation that there are workable ECS that utilize electric water pumps that enable reduced fuel consumption and emissions, automobile manufacturers are reluctant to adopt these solutions, due to a number of reasons. One of the main reasons is the cost effectiveness of these systems. The cost of an electric water pump is significantly higher than a conventional mechanical pump, besides the obvious issue of robust performance in arduous under-bonnet conditions. In addition, the increase in operating temperature of the engine with the adoption of the electric water pump, reduces the knock protection, as reported by Finlay *et al.* [**4**], and it also raises the possibility of the need to reoptimize the engine control parameters, as in Chanfreau *et al.*'s [**2**] work.

On the other hand, there are reasonable arguments in favour of the adoption of electrical ECS, such as those reported by Ap *et al.* [**1**] and Chanfreau *et al.* [**2**], especially in light-duty vehicles. The concerns of high operating temperature should not arise for these engines as the engine operating condition, such as maximum engine output or high percentage hill climb with maximum-rated load in which these significantly higher temperatures are seen, is either extremely short or non-existent. As the engines in automotive vehicles are oversized to give good acceleration performance, there is a sizeable portion of the engine power that is not being used most of the time during cruise and slow city-driving condition. Thus, the extended use of maximum engine power is rare and it would be much more reasonable to use metal temperature seen under intermediate engine power as a comparison. As metal temperature does vary, depending on the operating speed and load of the engine, as shown by Clough [**7**], the system proposed by Ap *et al.* [**1**] and Chanfreau *et al.* [**2**] only shifts the metal temperature seen in the higher power conditions of conventional system and control to these metal temperatures across the engine speed and load in the proposed system. Therefore, the adoption of the proposed system is feasible in light-duty vehicles.

3 DISCUSSION

The various features of advanced ECS described clearly harbour significant potential to improve the performance of the ECS and the engine as a whole. Improvements in fuel economy or emissions can be easily attained by adopting any one of the features described, but the benefit that can be derived by employing a single design or operating feature has been traditionally limited by the need to provide engine protection over the operating envelope. By adopting and integrating these features constructively, the balancing act of providing sufficient

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engine protection under all conditions, and improving fuel efficiency and emissions, can be eased considerably.

The key element required to achieve such an effect is to integrate the hardware and design features with the operating approach and strategy by introducing controllability to the cooling system. With controllability over the ECS, limits can be applied to key operating variables of the structural integrity protection system, such as metal temperature, coolant temperature, and oil temperature, to ensure that the engine is operating within safe limits even when elaborate schemes are being employed to harness the maximum potential of the ECS. Within the assigned operating limits, the cooling system then has the flexibility in its response to derive maximum fuel savings and reduction of emissions output without compromising the integrity of the engine.

Among the competing design and operational features for an evolutionary ECS, the integration of split cooling with precision cooling has the strongest potential to provide the desired level of engine protection, while gaining improved fuel economy and emissions. This arrangement is favoured for its ability to create the desired temperature distribution in the engine for the optimum fuel efficiency and emissions trade-off. Direct coolant feed for the head from the exhaust side to the exhaust-valve bridge and ports minimizes the temperature variation in the cylinder head and induces a more uniform temperature distribution in the head.

By introducing controllability to this ECS configuration, the coolant feed into the valve-bridge region can be regulated to ensure that the region is controlled to its safe operating temperature range with minimum hydraulic losses. The controllable element can also be employed to maintain oil and block temperature within its design-operating range for low frictional losses and emissions impact. Though this is an ideal arrangement for the engine cooling structure itself, the design and requirement of external circuits have considerable influence on the performance of the whole ECS. Thus, the circuit design of the complete ECS would need to be optimized with the requirement of the engine cooling structure.

4 CONCLUSION

A set of novel design and operating features from alternate ECSs are identified and examined for their potential to improve engine protection, fuel efficiency, and emissions. Detailed investigation into these features has shown that they hold significant potential to extend the performance of modern engines even further. The integration of split cooling and precision cooling with controllable elements to run a cooler head and warmer block is singled out as the most promising concept to meet the expanding requirement on the performance of the ECS.

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