ANALYSIS OF ENGINE SPLIT COOLING SYSTEMS FOR INTERNAL COMBUSTION ENGINES: FOCUS ON TEMPERATURE DISTRIBUTION AND PERFORMANCE OPTIMIZATION

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ABSTRACT

This research focuses on the optimisation and analysis of internal combustion engine (ICE) split cooling systems to enhance thermal management, improve engine efficiency, and reduce emissions. Split cooling systems separate the coolant circuits for the cylinder head and engine block, allowing for differential cooling that maximises warm-up time and operational efficiency. A one-dimensional flow model of the cooling system was developed using GT-Suite simulation software to analyze coolant flow, pressure drops, and temperature distribution across a range of engine speeds (from 1,000 rpm to 5,000 rpm). The simulation results indicate that the split cooling system accelerates the warm-up process, with the cylinder head temperature reaching 260°C compared to 250°C for traditional systems, representing a 10°C improvement in thermal efficiency. Additionally, the split system exhibited a 20°C higher piston temperature (210°C versus 190°C) during warm-up. This configuration enables the use of a higher compression ratio and improved thermal efficiency. The study identifies the limitations of conventional cooling systems in managing heat at elevated engine outputs. In contrast, the split cooling system demonstrates a more uniform temperature distribution and maintains superior performance under increased engine loads. Validation of the simulation results against design targets confirms that split cooling systems significantly enhance engine performance and thermal management, with implications for broader automotive thermal management applications. Future research should focus on on-road testing and further applications to advance engine efficiency and sustainability.

Keywords: Split cooling system, internal combustion engine, thermal management, emission efficiency.

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1.0 INTRODUCTION

Simulation software is a key element in the modern world of technology, as it provides an accurate representation of complex systems, such as engine thermal management. Engine cooling simulations have significantly enhanced engine performance and efficiency in recent years. For instance, an intelligent load-speed-sensitive cooling map was developed, which optimised thermal management by modulating the cooling flow as a function of engine speed and load, leading to enhanced overall engine performance and fuel economy [1]. Optimisation of vehicle performance through advanced thermal management strategies, particularly for internal combustion engines (ICEs), has focused on reducing thermal losses and enhancing energy utilisation [2]. Similarly, fuel consumption reduction approaches have been proposed by utilising optimised cooling strategies to improve the energy efficiency of automotive systems [3].

Additionally, research on combined cooling, heating, and power systems (CCHP) with ICEs has emphasized the contribution of cooling systems towards energy efficiency as well as environmental sustainability, in addition to the economic benefits of enhanced cooling methods [4]. Split cooling systems, coupled with exhaust heat recovery, have been proposed for improving fuel economy and controlling emissions [5].

Moreover, certain frontier research studies have assisted in the development of high-resolution simulation models of warm-up processes in engines. A high-resolution warm-up simulation model for gasoline engines with advanced thermal control has facilitated the optimization of engine cooling [6]. Furthermore, the virtual development of cooling systems for the BMW Z4 has enhanced the predictive power of cooling system simulations in the automobile industry [7]. A numerical simulation method for complex car cooling systems has paved the way for more advanced simulation techniques for car thermal management as well [8].

The objective of this research is to compare and optimize the thermal performance of split cooling systems, where the cylinder block and head are cooled by two separate circuits, and conventional cooling systems. Unlike previous research, this study differs in that it discusses the advantages of differential cooling methods, which maintain the cylinder head cool and the block warm, to achieve optimal thermal control for improved engine efficiency. The novelty of the research lies in the use of cutting-edge 1D simulations to compare the warm-up behaviour and performance of split cooling systems, demonstrating their potential in reducing warm-up time, improving engine efficiency, and contributing to lower emissions. Furthermore, this research offers insight into the application of split cooling systems in achieving improved thermal control, faster warm-up, and enhanced combustion efficiency, thereby providing an effective remedy to existing engine technologies.

2.0 METHODOLOGY

2.1 Engine Model Setup

These were achieved with the help of 1D-simulation software GT-SUITE from Gamma Technologies, a CAE tool used for simulating engine performance in development and research activities. A 1D flow circuit model was created using GT-Suite for simulating the cooling system, incorporating the radiator, thermostat, and water pump as major components. Temperature sensors were installed in the system to detect temperature ranges on both the engine head and block. The prespecified flow circuit, with respective settings, starts the system simulation run. Results obtained from the system temperature gauges are compared. Different models of engines were simulated to compare and contrast the advantages of various cooling systems, specifically regular and split cooling. This approach aligns with the research methodology put forward by Jalal et al.[9] who used simulation techniques to optimize engine cooling and reduce warm-up time.

2.2 Strategy to Simulate the Cooling System: Normal Cooling System Layout

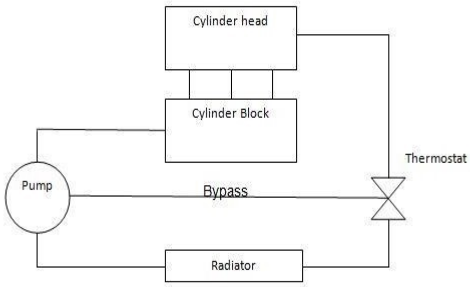

Figure 1: Basic layout of a normal cooling system

Figure 1 shows the normal cooling system configuration, where the coolant flows from the engine block to the cylinder head. The thermostat opens when the temperature reaches the proper operating temperature, allowing the flow of coolant. The water pump circulates the coolant through the system, and once it reaches the correct temperature, the thermostat opens, allowing the coolant to flow through the complete circuit. The layout ensures that the engine components, such as the cylinder head and block, are maintained within a favorable temperature range during operation.

2.3 Split Cooling System Layout

As will be shown, the divided cooling system-operated flow circuits in both the cylinder head and engine block (see Figure 2) provide an option to set two different components to various temperature targets independently from each other. Instead, this method sends all pumped coolant directly to the cylinder head; some engines bypass it all to the block during warm-up. Due to the specified temperature that the coolant reaches, the valve is installed at the outlet of the cylinder block, allowing the flow control to enable the return of coolant to the radiator [10]. The arrangement allows for a quicker warm-up time for the cylinder head, while the engine block heats up more slowly; hence, it is efficient and effective in performance.

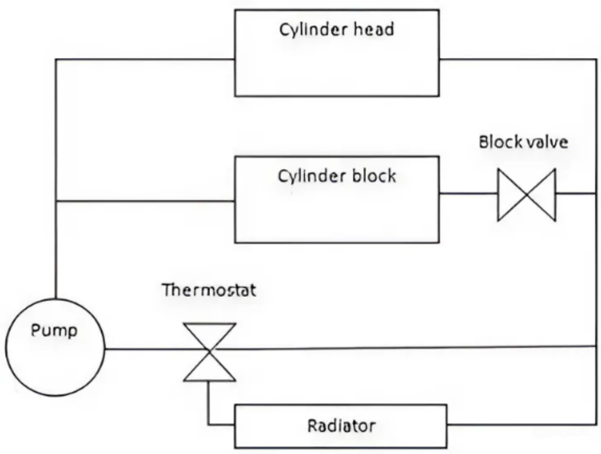

Figure 2: Basic layout of split cooling system

Figures 3 illustrate the GT-Suite simulation [11] configurations of the conventional cooling systems, respectively. This GT-Suite simulation layout represents a standard automotive cooling system, designed to model and optimize the thermal management of an internal combustion engine. At the core of the system is the coolant pump, which circulates coolants through the circuit to absorb heat from the engine and dissipate it via the radiator. The engine block component simulates the heat transfer between the engine and the coolant, while the thermostat regulates the flow of coolant based on temperature. During a cold start, the thermostat directs coolant through the bypass line, skipping the radiator to help the engine warm up quickly. Once the engine reaches its optimal operating temperature, the thermostat opens, routing hot coolant to the radiator, where heat is dissipated into the surrounding air. Coolant flow and temperature are monitored at various points, with components such as the coolant mixing node ensuring a uniform temperature distribution. Headers manage the branching of coolant flows into and out of subsystems such as the radiator and bypass line. This simulation enables engineers to analyse critical parameters, such as coolant temperature, flow rates, pump efficiency, and heat dissipation, under various operating conditions. By replicating real-world behaviors, the system helps identify performance improvements, optimize thermal efficiency, and prevent potential failures.

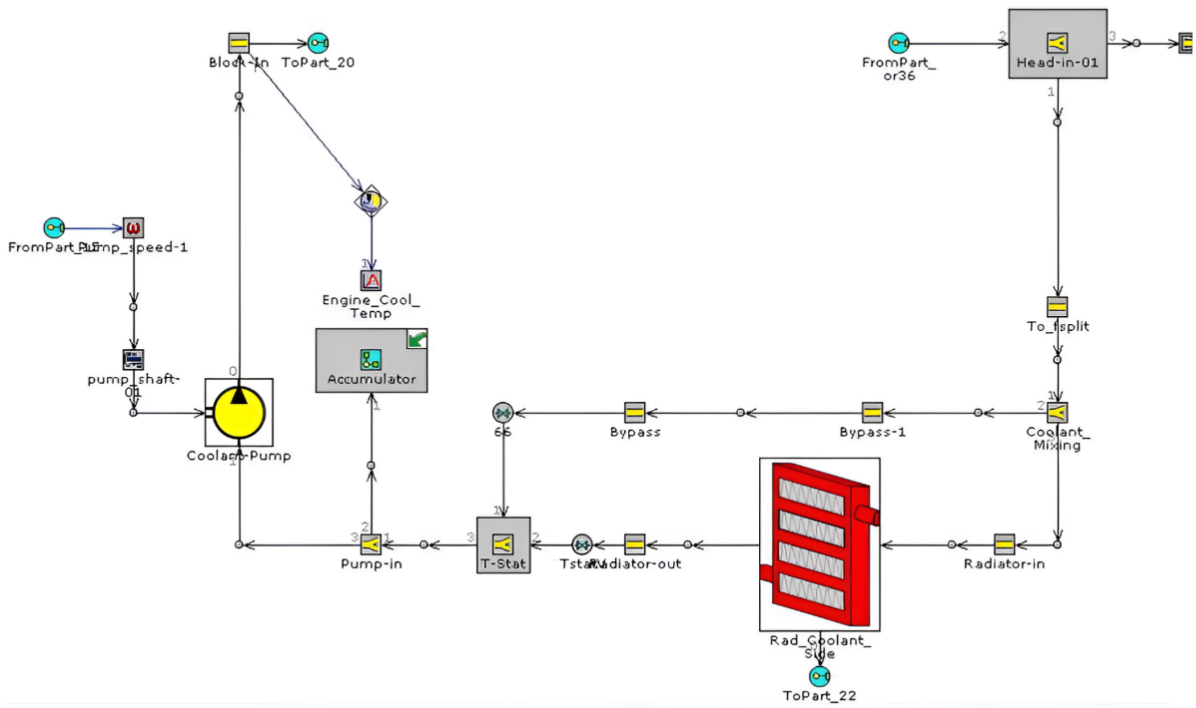

Figure 3: GT-Suite simulation layout for normal cooling system

Figure 4 illustrates the GT-Suite simulation layout, which features a split cooling system. This sophisticated thermal management approach separates the coolant flow to the engine block and cylinder head, allowing for precise temperature control and improved efficiency and performance. The coolant pump circulates coolant through two distinct branches: one dedicated to the engine block and the other to the cylinder head, with each branch independently regulated. Thermostats and flow control devices manage these branches, directing coolant based on temperature and operational demands. During cold starts, the system prioritizes the bypass line, allowing the engine to warm up quickly by avoiding the radiator. Once the engine reaches optimal operating temperatures, coolant is directed through the radiator to dissipate excess heat. Components such as "Wall Temperature" and

"Engine Thermaldist" simulate heat transfer between engine surfaces and the coolant, capturing complex thermal gradients and material interactions. The coolant mixing node ensures uniform temperature before returning it to the pump, thereby optimising overall system performance. Split cooling systems offer significant benefits, including faster warm-up times, reduced thermal losses, and enhanced efficiency by preventing overcooling and maintaining uniform temperatures [12, 13]. This configuration is particularly advantageous for modern high-performance and downsized engines, where precise thermal control is essential. The simulation enables engineers to analyse flow rates, temperature distributions, and component interactions under various conditions, thereby supporting the design and refinement of robust thermal management strategies. The establishment of this simulation involves several motives, including creating a layout that delivers accurate results concerning the flow circuit, whose nature allows for accurate temperature variations in key areas of the system.

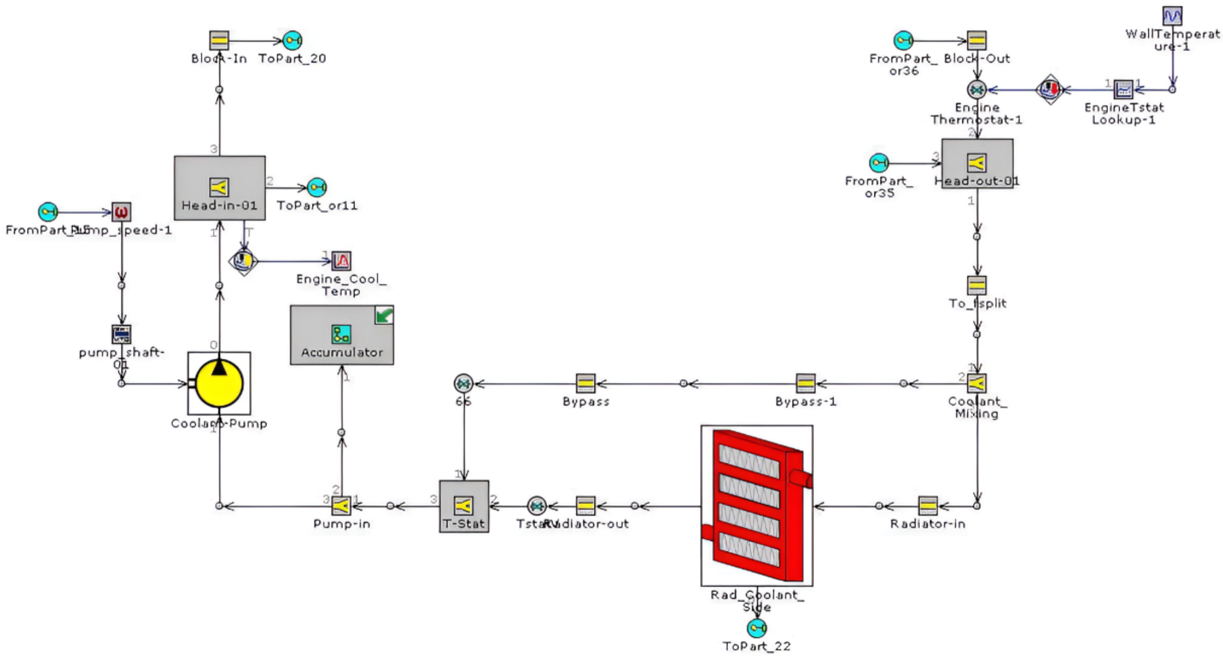

Figure 4: GT-Suite simulation layout for split cooling system

2.4 Control Strategies

A pump controller, in simulation, is utilized to regulate the target flow rate of coolant. This target flow rate is contingent upon the required head flow rate, as illustrated in Figure 5. The dynamic adjustment of coolant flow is achieved through a proportional-integral (PI) controller, which ensures optimal thermal conditions for any engine load. Previous studies have identified that advanced cooling methods, including active coolant flow management, are essential for ensuring the optimal performance of internal combustion engines by reducing thermal losses and enhancing energy efficiency.

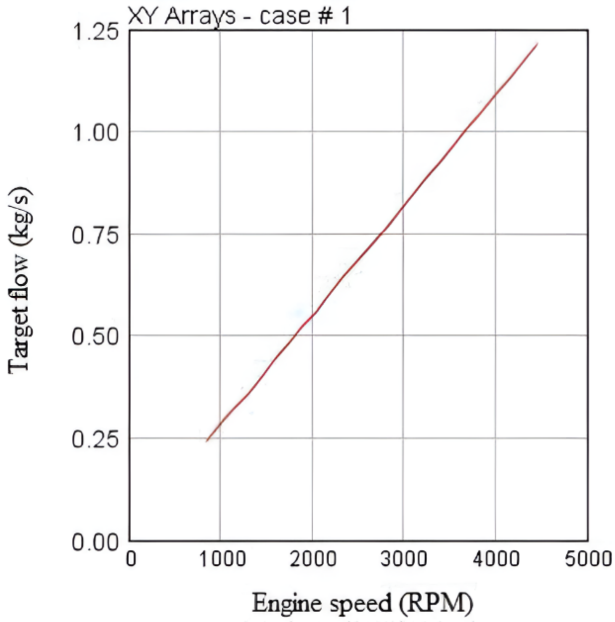

Figure 5: Target Flow by the Pump Controller

Figure 6 illustrates that the target flow is regulated by the pump controller based on the head flow rate. Furthermore, the PI controller, or proportional-integral controller, operates based on the target flow set by the pump. A PI controller is a widely used control loop feedback mechanism in industrial control systems and various applications requiring continuous and precise modulation of system parameters. In this context, the X-axis represents the engine speed (RPM), while the Y-axis corresponds to the target coolant flow. The split cooling system employs an electric water pump to dynamically control the flow, with the target flow strategy being directly influenced by the head flow rate. As highlighted in previous research, the primary purpose of regulating pump speed is to control coolant flow, as coolant flow directly impacts the temperature differential within the engine [14]. This precise control enhances engine thermal management, improving performance and efficiency while mitigating risks of overheating or overcooling.

The interval of 1,000 rpm to 5,000 rpm was selected for engine speed to represent the normal operating ranges of internal combustion engines, including idling and high-performance conditions. The 1,000 rpm mark captures conditions close to idling, where the engine operates under low load and requires precise thermal management during cold starts. At 5,000 rpm, the cooling system experiences increased loads, resulting in greater heat generation, which tests the system's ability to withstand thermal stress. This range allows for comprehensive testing of the cooling system's efficiency, ensuring it remains effective at both low and high engine speeds. It facilitates a proper comparison between split cooling systems and conventional cooling systems, particularly in terms of warm-up time, temperature distribution, and fuel consumption. Overall, this range accurately reflects real-world driving conditions, providing valuable insights into the cooling system's performance and efficiency.

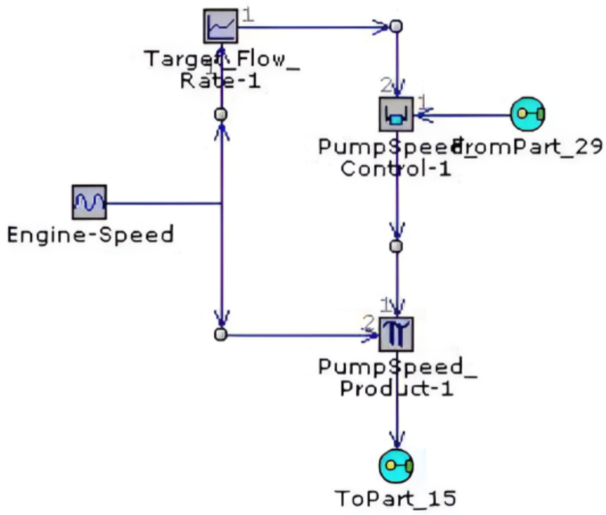

Figure 6: GT-Suite layout of pump controller

Figure 7 illustrates the block valve lift in the engine, which is regulated by the temperature of the cylinder wall, number 4. The number 4 cylinder is situated near the coolant outlet and valve and must be precisely synchronised with the block valve for optimal performance. The X-axis in the figure represents temperature in Kelvin, and the Y-axis indicates valve lift in millimeters. The valve is shut to restrict coolant flow from the block until the number 4 cylinder wall temperature is 167°C. The temperature control system regulates the cylinder block temperature, providing quicker warm-up of the engine compared to conventional cooling systems. Jawad et al. [15] noted that active management of coolant using electronic valves and pumps can significantly reduce coolant warm-up time during cold engine starts, resulting in decreased toxic emissions and improved fuel economy.

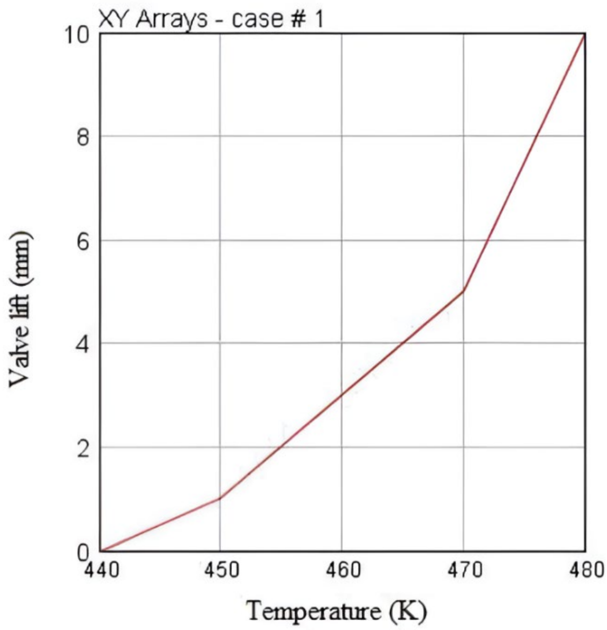

Figure 7: Temperature of the block valve lifting

2.5 Simulation load and boundary conditions

For this simulation, various load and boundary conditions were employed to replicate the actual operating conditions of an internal combustion engine (ICE). The engine speed range was specified from 1,000 rpm to 5,000 rpm, encompassing both idling conditions at 1,000 rpm and high-performance conditions at 5,000 rpm. This approach ensured that the cooling system was tested across a broad spectrum of engine operations, from low-speed idling (minimum load) to high-speed driving (maximum load), allowing for a comprehensive evaluation of the cooling system's performance under different thermal conditions. The coolant flow rate was dynamically controlled using a proportional-integral (PI) controller, which mimicked actual cooling behaviour as a function of engine speed and load. Flow boundaries were established at the inlet and outlet of key components, such as the radiator, water pump, and engine block, to facilitate effective coolant circulation throughout the system. These flow boundaries ensure adequate heat transfer and coolant distribution at varying engine speeds.

The differential cooling approach in the split cooling system was implemented by introducing thermal boundary conditions to critical components, such as the engine block and cylinder head. A higher thermal boundary, which requires more intensive cooling, was applied to the cylinder head, while a lower temperature was designated for the engine block to facilitate heat rejection. The thermostat boundary, which regulates coolant flow based on the engine's temperature, was also integrated into the system. The thermostat is calibrated to specific temperature thresholds, allowing it to open and close, enabling the system to respond to changing thermal conditions and maintain optimal engine temperatures during various stages of operation. Temperature sensors affixed to the engine block and cylinder head continuously monitor real-time temperature profiles, providing essential data to modulate coolant flow and ensuring the system operates within optimal thermal parameters.

By subjecting the simulation to these boundary and load conditions, both the split cooling system and conventional cooling systems were accurately modeled, demonstrating comparable thermal efficiency, warm-up times, and overall performance. The integration of thermal boundary conditions, coolant flow, and engine speed ensured that the simulation authentically represented actual engine operation, encompassing a comprehensive range of operating conditions from idle to high-load scenarios. These parameters enabled a thorough evaluation of the cooling system's ability to manage heat, maintain engine efficiency, and minimise emissions across varying engine speeds.

3.0 RESULTS AND DISCUSSION

The simulation results will be oriented towards three basic objectives: temperature distribution in the cylinder head and block, comparison of split versus normal cooling systems, monitoring of warm-up duration, and development of a 1D coolant flow model using a simulated circuit in GT-Suite software. The analyses have been performed on cylinders 2 and 3, as these cylinders are the hottest among all, being located in the middle, and there is also a small number of coolant passages. The three sections will explain the results: simulation layouts, temperature distribution, and warm-up duration.

Results drawn from the fact that the 1D simulation successfully modeled both the split and normal cooling systems showed large differences in temperature distribution and warm-up time. In the split cooling system, the strategic placement of the thermostat after the cylinder block outlet traps coolant, enhancing warm-up efficiency by improving thermal management and reducing engine friction. The results highlight the superior thermal performance of the split system, particularly for applications that require rapid engine warm-up.

3.1 Temperature Distribution: Cylinder Head, Cylinder, Port and Liner

Figure 8 illustrates the comparative head temperature distribution between the split cooling system and the normal cooling system. The split cooling system exhibits a higher maximum head temperature, reaching approximately 260°C, compared to about 250°C in the normal cooling system. This difference is attributed to the split cooling system's enhanced thermal management, which enables it to achieve optimal warm-up temperatures more rapidly than the conventional system. The temperature distribution over a 400-second simulation reveals specific regions with higher heat accumulation, indicating more efficient heat concentration in the split cooling system. Osman et al [16, 17] studies have shown that this efficiency is due to the system's design, which allows for targeted cooling flow control, resulting in improved engine performance and reduced warm-up time.

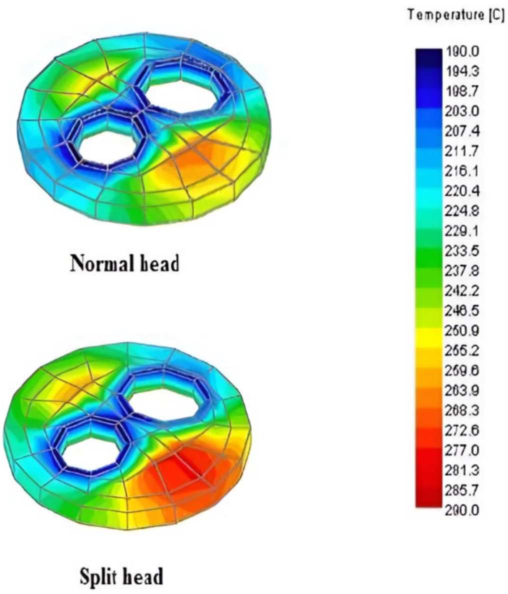

Figure 8: Differences in head temperature of split cooling and normal cooling systems

Figure 9 illustrates the variations in piston temperature between the split cooling system and the conventional cooling system. The data indicates that the piston in the split cooling engine attains higher temperatures, reaching approximately 210°C (represented by a red hue), compared to the piston in the normal cooling system, which reaches about 190°C (depicted by an orange hue). This colour differentiation signifies that the red areas are at a higher temperature than the orange regions. The accelerated warm-up in the split cooling system is facilitated by the strategic control of the thermostat valve at the cylinder block, which effectively reduces warm-up duration.

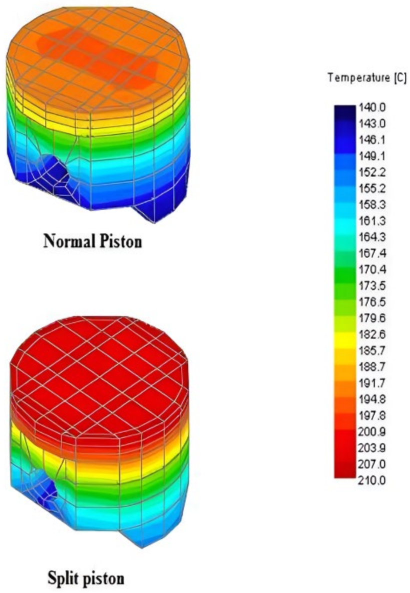

Figure 9: Differences between the liner temperature of split cooling and the normal cooling system

Figure 10 below compares the temperature distribution in the engine ports, using a Normal Port and a Split Port cooling system. In the 3D colour-coded diagram, the temperature gradient in both systems indicates similar characteristics, with higher temperatures around the lower region, represented by orange to red, and at the upper parts, represented by blue to green. That means the Split Port cooling system doesn't significantly reduce port temperatures compared to the Normal Port system. Both systems appear to capture approximately the same level of heat; this suggests that further modifications may be necessary to enhance cooling effectiveness and improve engine performance.

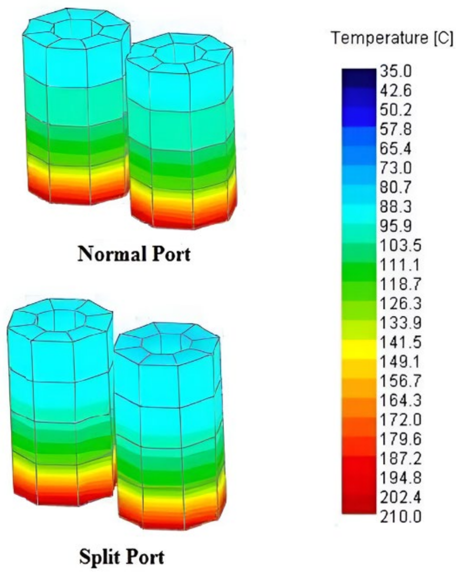

Figure 10: Differences in port temperature of split cooling and normal cooling systems

Figure 11 illustrates the difference in cylinder liner temperature between the split cooling system and the normal cooling system. From observation, the split cooling cylinder liner absorbs more heat in the cylinder block than the normal cooling system. The temperature distribution for the liner indicates that the upper part of the liner is coloured red. The red color shows that the areas are at a high temperature. Because the upper part of the liner is nearer to the combustion, the heat gained by the upper part of the liner is higher. The temperature of the cylinder liner of the split cooling system reaches about 230˚C and above. The normal cooling cylinder liner temperature is typically above 210˚C. The split cooling system reaches the warm-up temperature earlier than the normal cooling system. Because such a strategy provides control over coolant flow at the outlet of a cylinder block fitted with a thermostat [18], which by design blocks or restricts the flow of coolants, it is due to this that temperature will rise on one side thereby making the process of heat transfer from block to coolant not to be efficient for assisting in a faster warm up of the temperature of the engine.

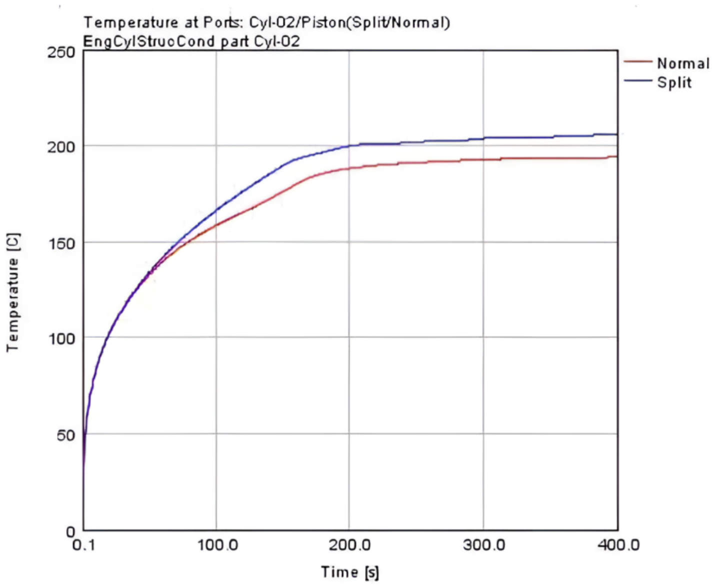

Figure 11: Differences between the liner temperature of split cooling and the normal cooling system

3.2 Warm-up Duration: Head Temperature, Piston Temperature, Cylinder Temperature

Figure 12 illustrates the temperature difference at the cylinder head during the warm-up phase for both split cooling and normal cooling systems. For 400 seconds, the split cooling system reaches 260°C, whereas the normal cooling system stabilizes at 250°C, indicating that the split system achieves a 10°C advantage in warm-up efficiency. [19, 20] suggests that the split cooling system facilitates a faster temperature rise, which is crucial for reducing engine friction and improving fuel efficiency in cold-start conditions.

The temperature difference between the two systems becomes noticeable at approximately 80 seconds into the simulation. This faster warm-up in the split cooling engine occurs because the block valve remains closed, trapping coolant within the engine block. As a result, the coolant temperature increases more rapidly, eventually opening the block valve, allowing the coolant to circulate. Additionally, some coolant entrapped in the block passes through passages in the water jacket to the cylinder head, further enhancing the temperature rise. Although the split cooling system shows a slightly higher final temperature, the difference remains moderate. These findings highlight the thermal efficiency benefits of split cooling in engine design, particularly for cold-start performance and emissions control.

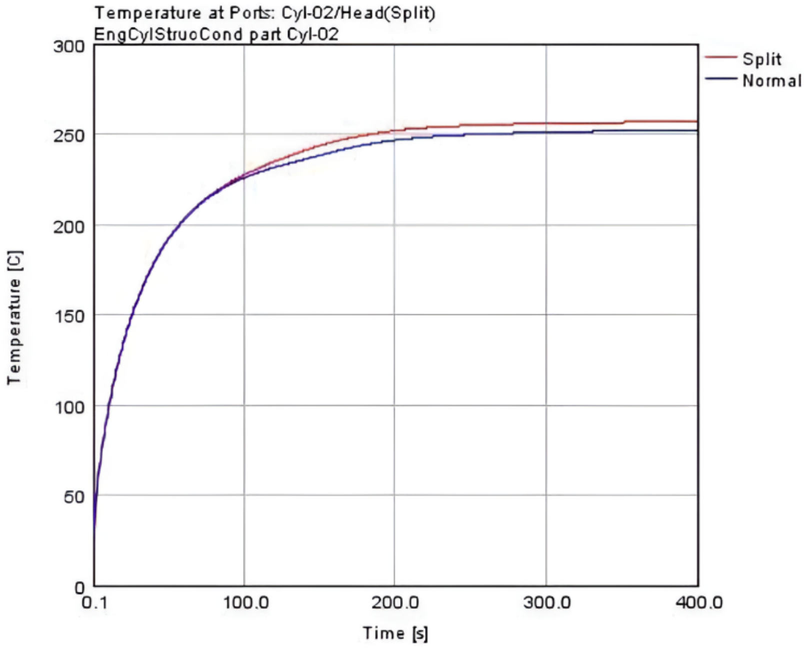

Figure 12: The temperature differences between head split cooling and the normal cooling system

Figure 13 illustrates the warm-up time of the piston for split cooling and conventional cooling systems. The graph shows that, in 400 seconds, the temperature of the piston in the split cooling system is approximately 210°C. In contrast, in the conventional cooling system, it is approximately 190°C, resulting in a 20°C difference. This demonstrates that the split cooling system contributes to faster piston warm-up, which is essential for reduced friction and improved fuel efficiency [21]. The difference in temperature between the two systems becomes apparent around 80 seconds into the simulation. The split cooling system heats up faster due to the strategic utilization of the block valve, which is initially utilized to restrict coolant flow out of the engine block. Such a design layout allows heat to be contained in the engine block, resulting in a faster buildup of temperature. The 3D temperature distribution plot and the temperature-time graph confirm that the split cooling system enhances warm-up efficiency by accelerating heat retention within the engine block and piston areas.

Additionally, the enhanced cylinder head coolant warm-up efficiency of the system can significantly benefit port fuel injector-equipped engines, resulting in improvements in fuel consumption, emissions, and cold-start drivability [22]. These findings demonstrate the ability of split cooling systems to improve engine thermal efficiency, reduce emissions, and enhance cold-start capabilities.

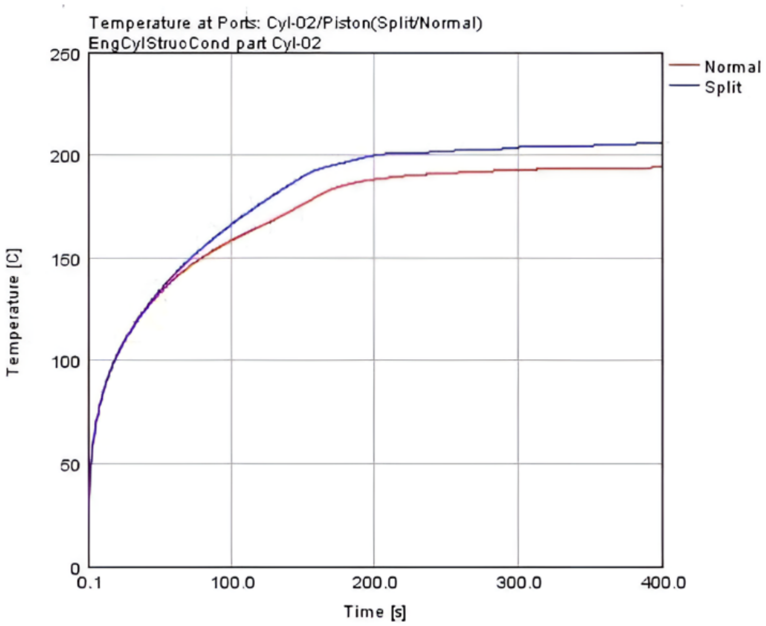

Figure 13: Temperature differences of piston split cooling and normal cooling system

Since the thermal performance of the cooling system is crucial to any engine, it optimises combustion efficiency, reduces fuel consumption, and minimises emissions. Comparing split cooling with conventional systems reveals distinct advantages in its primary features: warm-up efficiency and thermal management. The figure shows that 400 seconds after the engine started, the cylinder temperature achieved by the split cooling system reached approximately 230°C. In contrast, the normal cooling system stabilised at around 210°C, which is 20°C higher. The fast warming up significantly improves the combustion process and saves fuel during the engine's cold start.

The coolant flow control strategy is the main reason for the efficiency of the split cooling system. While conventional cooling circulates coolants in a uniformly split cooling system, it delays coolant flow in the engine block, allowing heat to build up and causing temperatures to rise rapidly. This mechanism is particularly effective during cold starts, as reduced friction losses and improved fuel vaporisation lead to better engine performance.

Advanced cooling systems, such as split cooling, utilise optimised heat sharing to maximise fuel efficiency while minimising it. Previous studies have emphasised that the utilisation of such systems provides increased thermal management, conserves energy, and improves overall engine efficiency. Additionally, studies by Lee et al. and Liu et al. [23, 24] have shown that synergistic advantages are available through active control of coolants, such as real-time dynamic adjustment of the coolant flow rate according to the current engine state, which also further optimize thermal efficiency.

In general, all these facts underline the promising potential of split cooling technology for modern internal combustion engines. Because it optimizes coolant distribution and reduces warm-up time, split cooling contributes to improving engine efficiency and meeting the increasingly stringent emission regulations, thereby making it one of the probable solutions for future automotive powertrain developments.

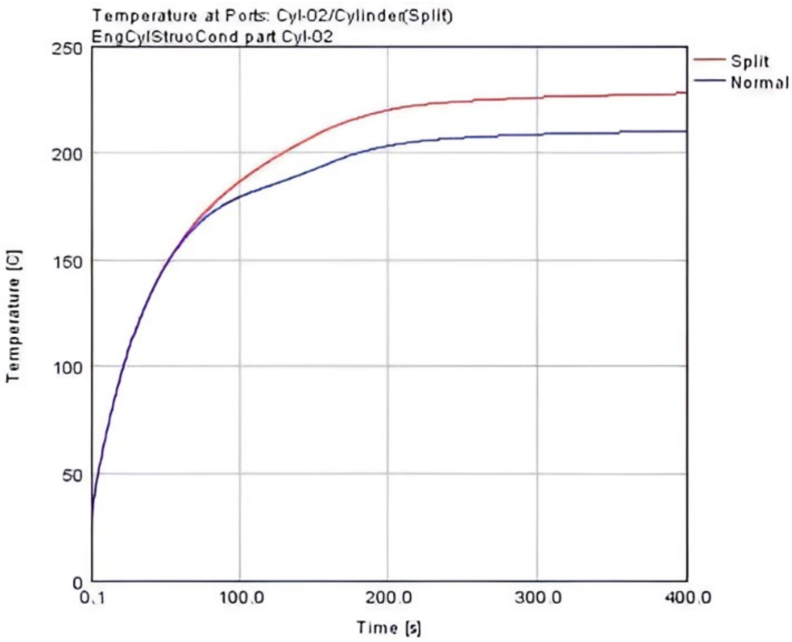

Figure 14: Split cooling and normal cooling system cylinder temperature difference

3.3 Effect on Cooling System Performance

Figure 16 illustrates the inlet temperature and the thermostat valve for both the split cooling system and the normal cooling system. In the obtained results, the main thermostat valve is activated earlier than the system, because the engine reaches its warm-up temperature quickly, and the rest of the system quickly increases in efficiency [25, 26]. As shown in Figure 15, the split cooling system achieves the thermostat opening temperature at 150 seconds, whereas the normal cooling system achieves it at 170 seconds. The thermostat of the split cooling block also starts to open at 207 seconds as the coolant reaches 87°C, allowing the controlled release of coolant. This delays coolant circulation within the block, thereby maintaining higher temperatures to allow coolants to reach their optimum operating temperature quickly.

Furthermore, because of the increased cylinder bore temperatures of the split cooling system, the viscosity of engine oil is reduced to decrease the friction between the bore surface and piston rings. Reduced rubbing friction would ensure improved fuel efficiency and longer engine life [27, 28]. These results demonstrate that split cooling technology provides effective performance in terms of engine warm-up efficiency and overall engine performance. With improved thermal management, the split cooling system contributes to reduced fuel consumption and lower emissions, making it particularly beneficial in modern automotive applications.

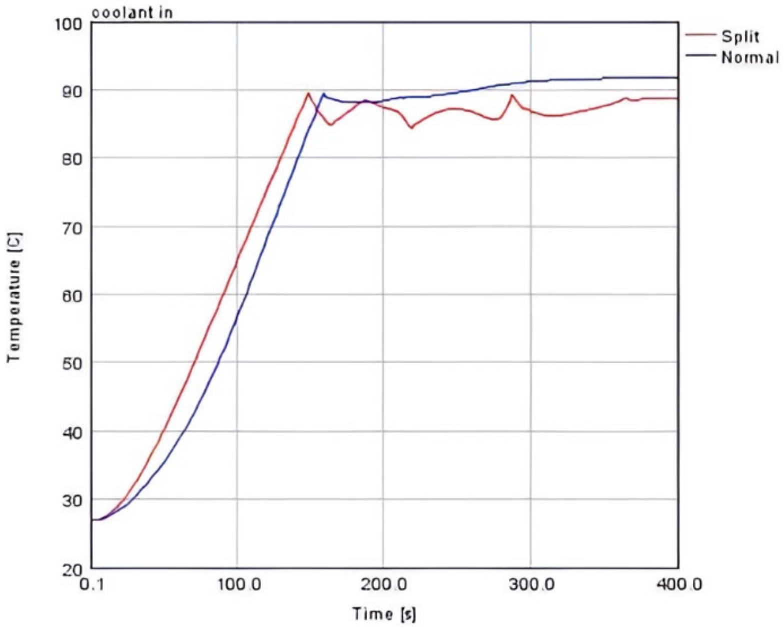

Figure 15: Temperature of coolant in the split and normal cooling systems

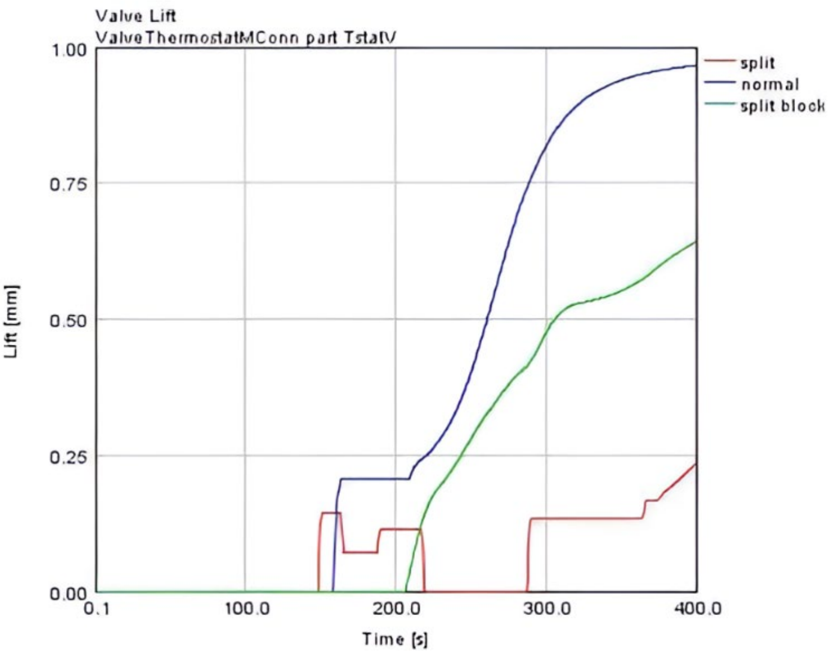

Figure 16: Thermostat valve lift for split cooling system and normal cooling system

Figure 17 illustrates the pump's speed in seconds. At the start of the engine, the split cooling pump speed increases from 1300 rpm while the normal cooling system pump speed increases from 1350 rpm. At 150 seconds during the engine running, both cooling system pump speeds are decreasing. This is because the main thermostat is opening, resulting in a pressure drop in the coolant circuit where the coolant flows to the radiator for cooling. At 200 seconds of engine running, the pump speed of the split cooling system increases again. This is due to the block thermostat starting to open, and the pump needs to increase the power consumption to raise the coolant flow rate.

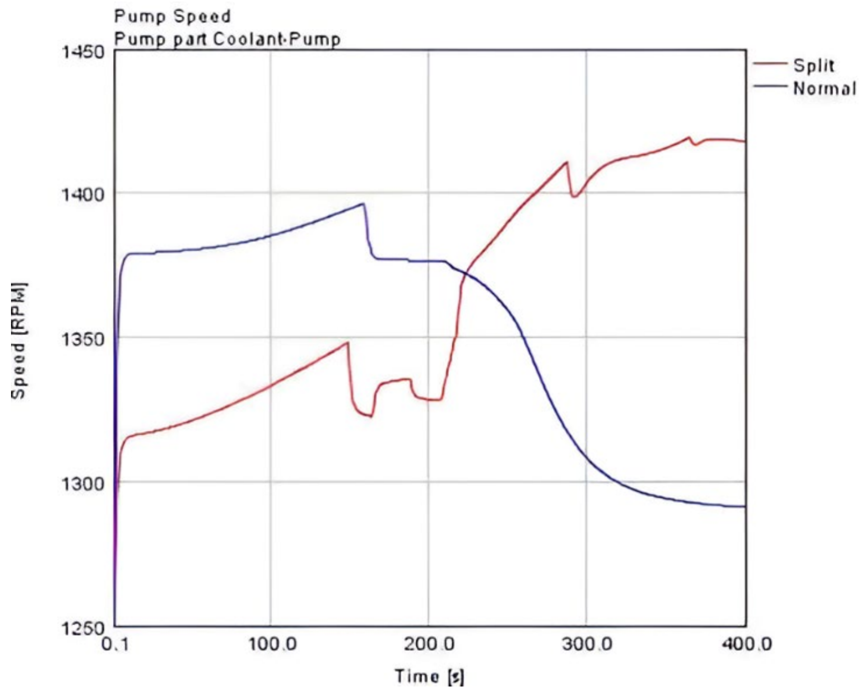

Figure 17: Pump speed of the split cooling and normal cooling systems

Figure 18 shows the mass flow rate deviation between the split cooling system and the normal cooling system. The plot figure also shows that, after the block thermostat is open, the mass flow increases because more power is required from the pump to compensate for the lost coolant pressure throughout the entire circuit. The normal cooling system mass flow rate remains at 0.68 kg/s throughout the 400-second simulation. Simultaneously, the cylinder block mass flow rate remains very small, only 0.065 kg/s, as the block valve is closed, impeding any coolant flow in the block itself.

At the same operating conditions, the split cooling system has a greater head mass flow rate of 0.68 kg/s, as it pumps a larger volume of coolant directly to the cylinder head. In contrast, the opening of the block valve at around 207 sec increases the block mass flow rate in the setup. The cooling demand is raised concurrently by the split cooling pump, while the block valve opens during this period because the pump needs to increase its capacity in providing coolant to both the cylinder head and the cylinder block, unlike the normal cooling pump that maintains a constant flow rate.

According to [29, 30], these results indicate that split cooling systems offer advantages in engine thermal management, including optimised coolant distribution and reduced warm-up time. An increased mass flow rate in the cylinder head contributes to a more uniform temperature distribution, which enhances engine efficiency and reduces emissions.

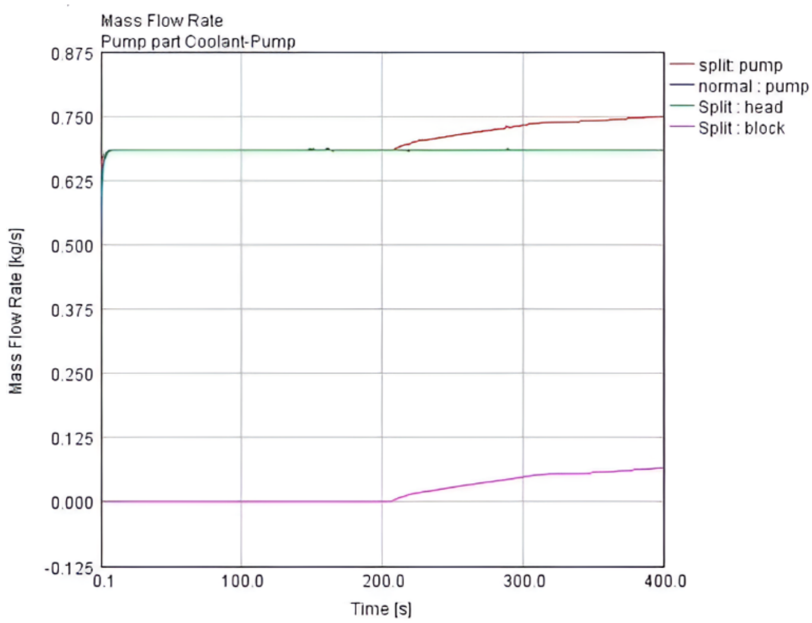

Figure 18: Mass flow rate of split cooling

4.0 CONCLUSION

These simulation findings confirm that the split cooling system provides several key advantages over a standard cooling system and is therefore promising as an approach to improving engine thermal management.

Quicker Warm-Up: The Split cooling system warms up faster, thanks to the block thermostat that traps coolant in the block and reduces thermal losses. The result of all this is that the temperature gradient for large engine components is in the range of 10°C to 20°C, which means quicker achievement of operating conditions, thereby reducing frictional losses. This is surely a boon to fuel economy and reduces engine wear during cold starts.

Better Temperature Distribution: The split cooling system provides improved thermal control by maintaining a higher temperature locally in the critical regions of the cylinder liner and cylinder head. It leads to improved combustion efficiency and optimal heat rejection, resulting in enhanced engine performance and a reduction in emissions. Additionally, the higher operating temperature of the combustion chamber could lead to more complete fuel combustion, thereby contributing to lower hydrocarbon emissions and improved engine durability overall.

Better Coolant Flow & System Complexity: This pump differs from typical systems in that it operates according to the concept of split cooling with variable pressure, ensuring improved coolant flow across various engine components. The additional complexity presents various challenges to the system under practical working conditions, particularly in terms of component wear and tear. Optimisation of tooling concepts leads to greater engine dependability and extended maintenance intervals, resulting in lower maintenance expenses throughout their lifespan.

Although this study focuses on simulation results, the long-term durability and reliability of split cooling systems in practical applications are critical considerations. The system's higher thermal efficiency may lead to increased thermal cycling, particularly at the cylinder block and head, which could impose stress on gaskets and sealing interfaces. Research by Cipollone et al. also indicates that frequent expansion and contraction in split-cooled blocks can lead to fatigue over extended lifecycles, necessitating the use of more heat-resistant materials. In terms of maintenance, the added complexity, such as electronically controlled valves and variable-speed pumps, introduces components that may require periodic diagnostics, calibration, or eventual replacement. Additionally, sustained long-term operation at elevated temperatures may lead to coolant degradation and promote the buildup of scaling and deposits, particularly in areas with hard water or in cases of inadequate maintenance. Real-world implementations, such as those reported by Osman et al., have demonstrated encouraging reliability when regular maintenance schedules are followed, effectively mitigating most operational risks. Therefore, while split cooling systems offer significant thermal advantages, their long-term reliability depends on the selection of robust materials, consistent maintenance, and well-designed control strategies.

It is also certain that the split cooling system has a thermal efficiency benefit, although this can be offset by increased complexity and uncertain durability. It also comes before such applications in both the automobile and industrial sectors, where warming-up time will be reduced, and where split cooling technology will be beneficial. It requires optimisation of the operating parameters, specifically block valve control, which will be explored during fuel consumption and emissions investigations in real driving situations. The long-term effects of knowledge will determine the business viability of the split cooling technology. Experimental model validation and field tests in different climatic conditions can provide further insight into the real performance of a split cooling system.

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