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INTERNATIONAL JOURNAL OF RECENT TECHNOLOGY SCIENCE & MANAGEMENT “THERMAL MANAGEMENT OPTIMIZATION OF HEAVY-DUTY C.I. ENGINES USING AN ADVANCED DUAL-STAGE TEMPERATURE REGULATION SYSTEM”

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ABSTRACT

The increasing demand for improved fuel efficiency, reduced exhaust emissions, and reliable operation of heavy-duty Compression Ignition (C.I.) engines has created a need for improved engine thermal management systems. Engine performance is strongly influenced by operating temperature, and maintaining the coolant within an appropriate temperature range is essential for efficient combustion, lubrication, component durability, and emission control. Conventional cooling systems generally use a single mechanical thermostat to regulate coolant flow between the engine and radiator. However, a single thermostat may provide limited coolant-flow control under varying engine speed and load conditions and may not provide adequate cooling during high thermal-load operation. In the present study, an advanced dual-stage temperature regulation system is proposed for improving the thermal management of a heavy-duty C.I. engine. The proposed system incorporates an additional thermostat and modification of the existing mechanical thermostat to improve coolant-flow regulation and provide an additional stage of temperature control. The dual-stage arrangement is intended to maintain the engine within the desired operating temperature range during different operating conditions while providing increased coolant circulation when the engine thermal load rises. The modified thermostat arrangement also provides an additional level of protection in the event of malfunction of one temperature-regulation stage. The performance of the proposed system can be evaluated through CFD and experimental analysis using parameters such as coolant temperature, velocity, pressure distribution, heat-transfer rate, and temperature distribution. The proposed approach provides a potential method for improving cooling-system response, maintaining thermal stability, reducing overheating risk, and supporting improved overall performance and reliability of heavy-duty C.I. engines.

Key Words: Heat Transfer, Thermal Performance, Engine Cooling, Coolant, Ethylene Glycol, Propylene Glycol, Heat Transfer Coefficient.

I. INTRODUCTION

Heavy-duty Compression Ignition (C.I.) engines are widely used in commercial vehicles, agricultural machinery, construction equipment, power-generation units, and industrial applications because of their high torque, durability, reliability, and good fuel economy. During engine operation, a considerable amount of heat is generated inside the combustion chamber due to the burning of fuel. Only a part of the chemical energy of the fuel is converted into useful mechanical work, while the remaining energy is released as heat through exhaust gases, cooling systems, and other components. Proper thermal management is therefore essential for maintaining engine components within their safe and desirable operating temperature range.

Engine operating temperature has a significant influence on combustion efficiency, fuel consumption, lubrication, emissions, and component durability. An engine operating below its optimum temperature may experience incomplete

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combustion, increased frictional losses, poor lubrication conditions, and higher fuel consumption. On the other hand, excessive engine temperature can cause overheating, lubricant degradation, thermal stresses, component deformation, and premature failure. Therefore, the cooling system must maintain the engine temperature within an appropriate operating range under different engine speed and load conditions.

The conventional engine cooling system mainly consists of a radiator, coolant pump, cooling passages, fan, and thermostat. Coolant absorbs heat from the engine components and transfers it to the radiator, where the heat is rejected to the surrounding atmosphere. The cooled coolant is then circulated back into the engine through the water pump. The thermostat plays an important role in this process because it regulates coolant flow according to coolant temperature. During cold starting, the thermostat remains closed or partially closed, allowing the engine to reach its operating temperature more quickly. As the coolant temperature increases, the thermostat opens and permits greater coolant flow through the radiator.

Although conventional single-stage thermostats are simple, economical, and reliable, their temperature-control capability is limited. Heavy-duty C.I. engines operate under widely varying conditions, including changes in engine speed, load, ambient temperature, and operating duration. Under high-load conditions, the heat generated inside the engine increases significantly, requiring a greater rate of heat removal. A conventional thermostat may not provide sufficiently flexible coolant-flow regulation for these changing thermal conditions. Similarly, excessive coolant circulation during low-load or warm-up conditions may result in unnecessary heat loss and delayed attainment of the desired operating temperature.

Maintaining the coolant temperature within an optimum range is therefore important for achieving better engine performance. Appropriate temperature regulation can support improved combustion, reduced frictional losses, effective lubrication, controlled thermal stresses, and improved component life. It can also contribute to controlling harmful exhaust emissions. Consequently, the development of an improved temperature regulation system is an important requirement for modern heavy-duty C.I. engines.

The thermostat is one of the most important components responsible for controlling the operating temperature of an engine. Its opening characteristics directly influence coolant circulation and heat rejection. A conventional mechanical thermostat generally operates according to a predetermined temperature range. However, its response may not be sufficient when the engine experiences rapid changes in thermal load. Modifying the thermostat arrangement can provide an opportunity to improve coolant-flow characteristics and thermal response. In the present study, an advanced dual-stage temperature regulation system is proposed for a heavy-duty C.I. engine. The proposed system incorporates an additional thermostat along with modification of the existing mechanical thermostat. The objective of this arrangement is to provide improved coolant-flow control under different operating conditions. During normal engine operation, the first stage can regulate coolant circulation within the desired temperature range, while the second stage can provide additional coolant flow when the engine temperature increases due to higher thermal loading. The proposed dual-stage arrangement can also provide an additional level of safety in the cooling system. If one temperature-regulation stage experiences a malfunction or becomes less effective, the second stage can provide an additional path for coolant regulation. This arrangement can potentially reduce the risk of excessive engine temperature and improve the reliability of the cooling system. The modification of the existing thermostat diameter can further influence coolant-flow characteristics and heat-transfer performance. The performance of the proposed system can be investigated using Computational Fluid Dynamics (CFD) and experimental methods. CFD analysis can provide detailed information about coolant velocity, pressure distribution, temperature distribution, and heat-transfer behaviour inside the cooling passages. Experimental investigation can then be used to validate the numerical results and evaluate the actual performance of the modified cooling system. A comparison between the conventional and proposed dual-stage systems can be performed to determine the improvement in thermal behaviour. The present research therefore focuses on the thermal management optimization of a heavy-duty C.I. engine using an advanced dual-stage temperature regulation system. The study aims to improve coolant-flow regulation, maintain suitable engine operating temperature, enhance cooling response under high thermal loads, and reduce the risk of overheating. The proposed system is expected to provide a simple and practical approach for improving the thermal management, reliability, and operating performance of heavy-duty C.I. engines.

II. PROBLEM IDENTIFICATION

Heavy-duty C.I. engines generate a large amount of heat during combustion, particularly under high-load and high-speed conditions. Effective cooling is therefore required to maintain the engine within its suitable operating temperature range. Excessive temperature can cause overheating, thermal stresses, lubricant degradation, component damage, and reduced engine life. Conventional cooling systems generally use a single mechanical thermostat to regulate coolant flow between the engine and radiator. Although this system is simple and reliable, it has limited capability to respond to rapid changes in engine speed, load, and heat generation. During low-load conditions, excessive cooling may delay engine warm-up, while during high-load operation, insufficient coolant flow may result in excessive temperature rise. The thermostat is a critical component because its opening characteristics directly control coolant circulation. Failure, delayed opening, or restricted flow through a single thermostat can reduce cooling performance and increase the risk of overheating. Therefore, improving coolant-flow capacity and providing an additional temperature-regulation stage can enhance the reliability of the cooling system. In the present study, an advanced dual-stage temperature regulation system is proposed by adding a second thermostat and modifying the diameter of the existing mechanical thermostat. The proposed arrangement is intended to increase coolant flow when higher cooling capacity is required and provide an additional level of fail-safe operation. The major problem addressed in this study is the limited temperature-control capability and coolant-flow regulation of conventional single-stage thermostat systems under varying operating conditions. The proposed dual-stage system is therefore investigated to improve temperature stability, cooling response, heat transfer, and overall thermal management of heavy-duty C.I. engines.

III. RESEARCH OBJECTIVE

The specific objectives of the present research work are as follows:

1. To develop the CAD model of the existing engine cooling system, including coolant passages and thermostat arrangement.
2. To perform CFD analysis of the existing cooling system under different thermostat conditions:
 - (a) Thermostat closed condition.
 - (b) Thermostat open condition.
3. To identify the limitations of the existing single-thermostat system and modify its design by incorporating a twin-thermostat arrangement with suitable operating levels and geometric configurations.
4. To perform CFD analysis of the modified cooling system and evaluate its coolant flow, temperature distribution, pressure, and heat-transfer characteristics.
5. To compare the existing and modified cooling systems in terms of coolant flow behaviour, temperature distribution, heat transfer, and cooling effectiveness.
6. To validate the CFD results of the modified system with available experimental or reference results and assess the effectiveness of the proposed dual-stage temperature regulation system.

IV. METHODOLOGY

The methodology of the present research work begins with a detailed study of the existing cooling system of the heavy-duty C.I. engine. The construction, coolant flow path, thermostat arrangement, and major cooling-system components are studied to understand the existing temperature regulation process. The required dimensions and operating conditions of the cooling system are collected for further analysis. A three-dimensional CAD model of the existing engine cooling system is developed using Creo Parametric 2.0. The model includes the important coolant passages and thermostat arrangement. The developed model represents the existing cooling system and is used as the base model for further CFD investigation. The existing cooling system is analyzed for different thermostat operating conditions, mainly the closed and open conditions. The CAD model is imported into ANSYS Fluent, where the computational domain is prepared and an appropriate mesh is generated for the coolant flow passages. Suitable boundary conditions and coolant properties are applied according to the selected operating conditions. CFD analysis is then performed to study the flow and thermal behaviour of the existing cooling system. Important parameters such as coolant velocity, pressure distribution, temperature distribution, and heat-transfer characteristics are obtained from the analysis. The

results are examined to identify the limitations of the conventional single-thermostat arrangement. Based on the identified limitations, the existing thermostat arrangement is modified by incorporating an additional thermostat and suitable changes in the existing thermostat geometry. The proposed arrangement provides two stages of coolant-flow regulation and is intended to improve coolant circulation during higher thermal-load conditions. A CAD model of the modified dual-stage cooling system is developed and analyzed using ANSYS Fluent under suitable operating conditions. The same important parameters, including coolant velocity, pressure, temperature distribution, and heat transfer, are evaluated for the modified system. Finally, the results obtained from the existing and modified cooling systems are compared. The comparison is made in terms of coolant flow behaviour, temperature distribution, pressure variation, heat transfer, and overall cooling effectiveness. The CFD results of the modified system are also compared with available experimental or reference results to assess the effectiveness of the proposed dual-stage temperature regulation system.

V. RESULT AND DISCUSSION

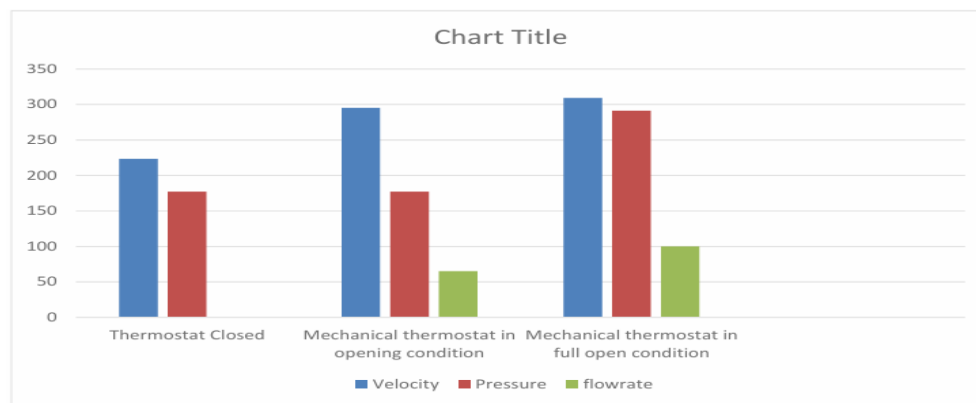


Chart 5.1 Single thermostats Pressure, velocity and flow rate comparison

The above chart presents a comparison of coolant velocity, pressure, and flow rate for the conventional engine cooling system using a single mechanical thermostat. Three different operating conditions were considered in the analysis: (1) thermostat in the closed condition, (2) thermostat at the initial opening condition, and (3) thermostat in the fully open condition. It can be observed from the comparison that the coolant flow rate increases as the thermostat progressively opens. Correspondingly, changes in coolant velocity and pressure are observed under the different operating conditions. As the coolant temperature increases, the thermostat opening increases, allowing a greater amount of coolant to circulate through the cooling system. The increase in coolant temperature also causes thermal expansion and changes in the flow characteristics of the coolant, resulting in variations in pressure and velocity within the cooling passages.

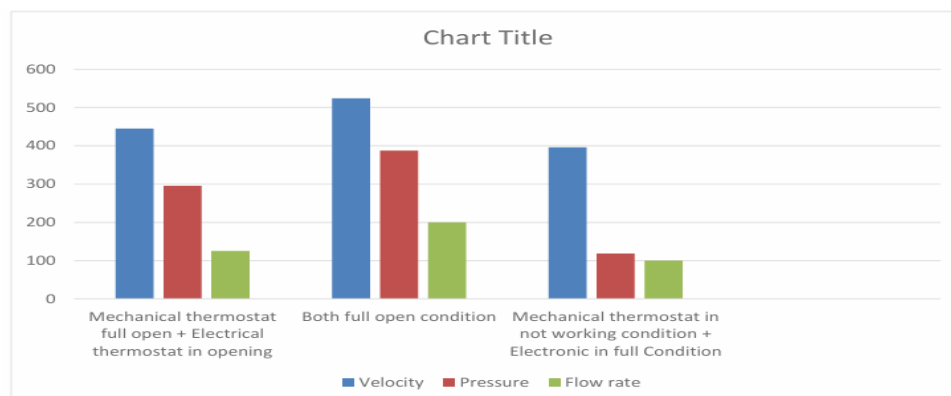


Chart 5.2 Twin thermostats Pressure, velocity and flow rate comparison

The second condition represents the operating condition in which both thermostats are allowed to operate according to the changes in coolant temperature. From the chart, it can be observed that the coolant flow rate is maximum when both thermostats are in the open condition. When both thermostats reach the fully open condition, the maximum coolant

flow rate is achieved, along with the corresponding maximum values of coolant velocity and pressure as compared with the other operating conditions. From these results, it can be concluded that the use of two thermostats provides an additional flow passage for coolant circulation, resulting in a higher coolant flow rate to the radiator. The increased coolant circulation enhances the heat removal capability of the cooling system and consequently improves its cooling effectiveness. Furthermore, the comparison of the CFD results with the validation results provides additional confirmation of the effectiveness of the proposed dual-thermostat cooling system. The validation results also indicate a reduction in NO_x emissions compared with the conventional cooling system. This reduction can be attributed to improved control of the engine operating temperature and enhanced heat removal provided by the proposed cooling arrangement.

Table.5.1 Results Comparison

Temperature	Case	Velocity (m/s)	pressure (KPa)	Density(Kg/m ³)	Flow rate (%)
Below 84 C	Close thermostat condition	2.23	177	1110	NA
Above 84 C	Mechanical thermostat in opening condition	2.95	177	1110	65
Above 94 C	Mechanical thermostat in full open condition	3.09	291	1110	100
Above 94 C	Mechanical thermostat in not working condition	2.73	266	1110	0
Above 94 C	Mechanical thermostat full open + Electrical thermostat in opening	4.45	295	1110	100 + 25
Above 98 C	Both full open condition	5.24	387	1110	100 + 100
Above 98 C	Mechanical thermostat in not working condition + Electronic in full Condition	3.96	118	1110	0+100

VI. CONCLUSION

The present research focused on improving the thermal management of a heavy-duty C.I. engine through better coolant-flow regulation. CFD analysis of the conventional cooling system showed limitations in coolant flow and heat removal under different operating conditions. The existing system was modified by incorporating an additional electronic thermostat along with the mechanical thermostat. The mechanical thermostat starts opening at approximately 84 °C and becomes fully open at approximately 94 °C, while the electronic thermostat operates above 94 °C and provides an additional coolant flow passage through a 35 mm outlet. The dual-stage arrangement increases coolant circulation when engine temperature rises beyond the desired operating range. The modified system showed improved coolant velocity, pressure variation, and flow rate, particularly when both thermostats were open. Increased coolant circulation improves heat removal and helps maintain the engine within the desired temperature range. The additional thermostat also provides an alternative coolant flow path, improving the reliability and fail-safe capability of the cooling system. Overall, the proposed dual-stage temperature regulation system provides improved thermal

management and cooling performance compared with the conventional single-thermostat system.

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