

Modeling of Phase Change within a Wax Element Thermostat Embedded in an Automotive Cooling System

Chiranth Srinivasan, Chonglin Zhang, Haiyang Gao, and De Ming Wang
Simerics Inc

Jody Slike
Ford Motor Company

ABSTRACT

In an automotive cooling circuit, the wax melting process determines the net and time history of the energy transfer between the engine and its environment. A numerical process that gives insight into the mixing process outside the wax chamber, the wax melting process inside the wax chamber, and the effect on the poppet valve displacement will be advantageous to both the engine and automotive system design. A fully three dimensional, transient, system level simulation of an inlet controlled thermostat inside an automotive cooling circuit is undertaken in this paper. A proprietary CFD algorithm, Simerics-Sys®/PumpLinx®, is used to solve this complex problem. A two-phase model is developed in PumpLinx® to simulate the wax melting process. The hysteresis effect of the wax melting process is also considered in the simulation. The physics captured in the simulation includes the turbulent flow out of the coolant pump, turbulent mixing, heat transport, and rigorous treatment of Fluid Structure Interaction (FSI) of the circuit with the dynamic valves in the system. Two different operating sets of data are used for the analysis, case A, lower engine speed and case B, higher engine speed. The details of the model setup and the comparisons of the simulation results with experimental data are discussed in the paper.

CITATION: Srinivasan, C., Zhang, C., Gao, H., Wang, D. et al., "Modeling of Phase Change within a Wax Element Thermostat Embedded in an Automotive Cooling System," *SAE Int. J. Engines* 10(2):2017, doi:10.4271/2017-01-0131.

INTRODUCTION

The automotive cooling system is a critical structure to the operation of any automobile. A typical internal combustion engine in the automobile produces large quantities of heat. Even small quantities of heat generated can result in engine failure if the engine is not cooled down appropriately. The maintenance of the engine temperature also plays a pivotal role in controlling the fuel economy and automotive emissions of the automobile. The cooling system is essential in controlling the temperatures of the engine. In this paper, we will concentrate on the liquid cooled cooling system. As shown in [Figure 1](#), a typical cooling system consists of a water pump that circulates the liquid coolant inside the circuit, the water jackets that encompass the engine block and head, generating heat in the system. Additionally, the thermostat assembly containing poppet and bypass control valves. A radiator, that acts as a heat rejecting component. Heater system (consisting of a heater core, another heat rejecting component) that is used to warm up the vehicle's interior on a cold day along with oil cooler and some plumbing consisting of interconnecting hoses to transfer the coolant between the above components in [Figure 1](#) [1].

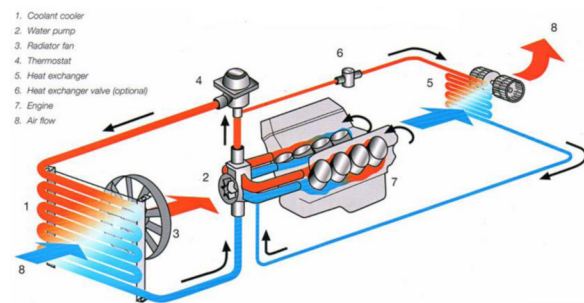


Figure 1. Pictorial representation of an engine cooling circuit [1].

The operation of an engine cooling system is based on the flow and heat equilibrium in the circuit. Three branches operating in parallel constitute the main flow circuits of the cooling system. The purpose of these circuits is to effectively dissipate the heat generated in the engine. The circuit contains some heat rejecting components like heater core and radiator, and the circuits add themselves into the system based on the pressure loads on each of them. The capacity of the system is engineered for the type and size of the engine and the

work load that it is expected to undergo. On a large vehicle, the radiator is larger with many more tubes for the coolant to flow through. The radiator is also wider and taller to capture more air flow entering the vehicle from the front grille.

The coolant should have the ability to withstand temperature limits such that it does not freeze or does not flash boil. It should also have rust inhibitors and be a lubricant. Vehicles contain a mixture of ethylene glycol and water as the coolant.

As with any automotive system design, information available a priori about the viability of certain designs, effects of design on the working and efficiency of the system, could be valuable in determining the cost effectiveness and output of the system. Flow bench testing of the vehicle cooling circuit can be used to determine the pressure restrictions and flow rates through the different branches. But, the tested flow bench is applicable for that tested radiator loop restriction and for the given circuit. Further testing is necessitated for different flow restrictions or for a different circuit design. Also, according to some test procedure, in the flow bench data, the thermostat is mechanically set at various positions. These data sets are then of limited value when trying to understand actual transient operating conditions.

The alternative is to run a 1D thermo-hydraulic system analysis of the whole coolant circuit. Valuable information is obtainable but the reality of the 3D transient and geometric effects can be hard to replicate.

The above limitations of flow bench testing and 1D analysis then provides 3D CAE as a valuable alternative in closing the existing gaps available between testing and computational studies. The ability of 3D Computational Fluid Dynamics (CFD) to evaluate within a transient environment the prediction of the thermostat behavior in the cooling circuit is a major addition to the existing approaches. The challenges are plentiful, namely, the transient movements of the main-poppet valve, bypass valves, the modeling of the coolant pump, the transient behavior of the phase change of the wax element, and the loop pressure restriction and flow predictions of the different circuits inside the cooling system. Also the accurate prediction of the hot/cold cooling mixing temperatures surrounding the wax element which determine the melting/freezing is a major challenge. To compound the above challenges, since the cooling circuit system changes happen over a period of few minutes in real time, the simulations should be able to span over these timeframes while keeping the physical time consumed for simulations relatively short. The current paper is aimed at handling these challenges using the commercial CFD code Simerics-Sys/PumpLinx®. An engine inlet, controlled thermostat of Ford Motor Company is used for this current paper to implement the wax melting model, and predict the behavior of the cooling circuit.

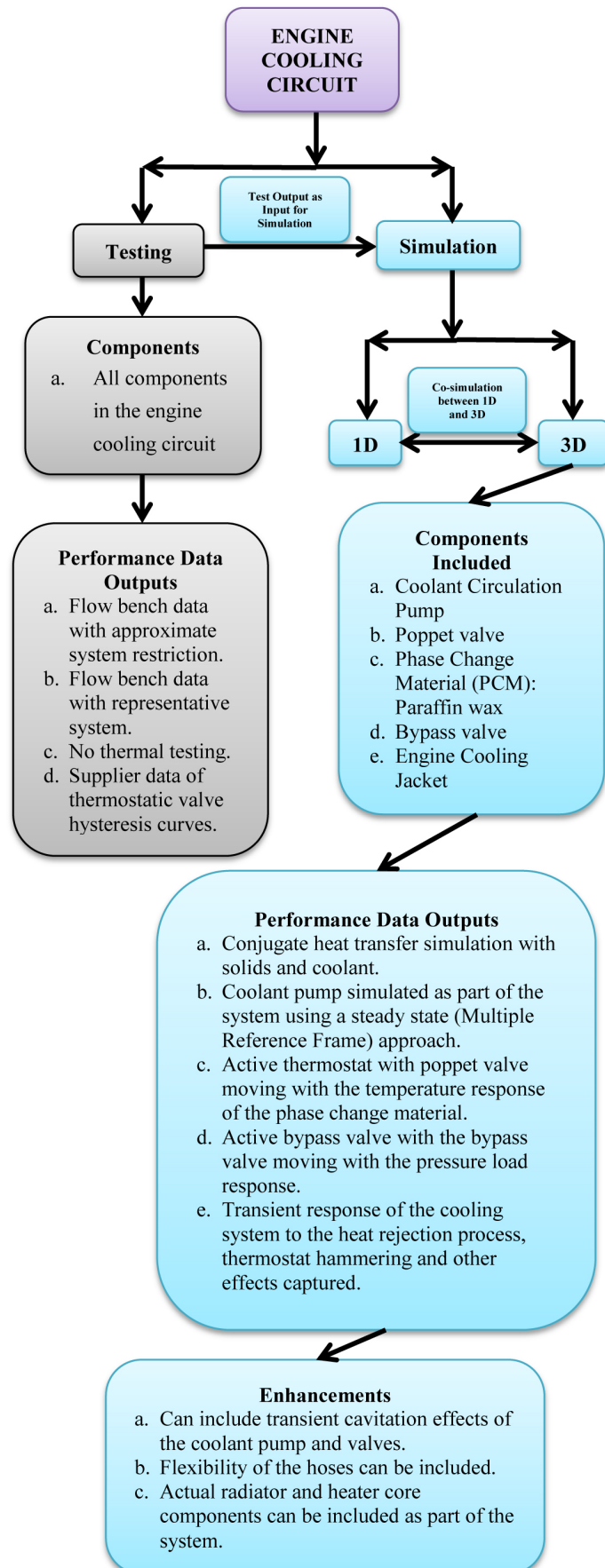
BACKGROUND AND MOTIVATION

The internal combustion engine is the main driving component of an automobile. Some aspects of the performance of an automobile like low fuel consumption, efficiency, cost effectiveness is inherently associated with the working of the engine. Regulating the temperature of the engine is a key aspect in the design of an automobile. The temperatures inside the combustion chamber could exceed, in some cases, the material limit of the metal enclosures. The engine cooling system has to make sure that the coolant operates within its optimal temperature limits. An inefficient cooling system could affect the fuel consumption and life of engine through abnormal combustion events such as knock and pre-ignition. Thus, it is very important to control the temperatures. On the other side of the spectrum, if the engine is cooled excessively, it causes the incomplete vaporization of the fuel and causes the reduction in efficiency of the system. A good cooling system can help in reducing the engine starting and warming up time [2]. The increase in demands of heavy duty vehicles, that require increased engine output whilst maintaining the sizes of the cooling inlets and other auxiliary cooling components due to space limitations have increased the demands on the engine cooling system of automobiles. Thus, efficient design of the cooling circuit has become a vital part in the efficient workings of an automobile.

Advances in numerical computation have enabled a new avenue into the study of cooling system using computers. Through numerical simulations, insights into the local flow characteristics of the cooling system, the local heating and cooling effects in the different domains of the system is achievable. The dynamic response of the valves, the effect of the paraffin wax properties on the stability of the system, and the pressure pulsations based on the valve responses, can all be understood beforehand, leading to a design of a more reliable and robust cooling systems. The numerical simulations can also offer in depth analysis into areas of the cooling system that are inaccessible by experimental tests, and also help identify local regions of hot spots and stagnation zones.

Current computational fluid dynamic (CFD) analyses of the engine cooling system are simulated at two levels. The first option is the study of external cooling circuit (refer Fig. 3) using 1D code while the second option is the detailed simulations of the local flows within components, like the radiator, water jacket, thermostat and others using 3D CFD software. 1D simulations [3,4,5,6,7,8] are useful in getting the overall flow rate behaviors, temperatures and pressure losses while the 3D analysis [9,10,11] is vital for engine designers to obtain detailed heat transfer rates, temperatures and velocities. 3D CFD simulations of engine cooling system are still limited to only component-level analysis. The authors are not aware of any work having reported on 3D modeling at the system-level of the complete engine cooling system, the subject of this paper. The current simulation is an attempt to handle the multi-level complexity in a single model. The Table 1 shows a flow chart summarizing the motivations behind the paper and the further enhancements that can be added to the current implementation of solving this problem.

Table 1. Insights into the complexities handled by this current paper and the possibilities for the near future.



INLET CONTROLLED THERMOSTAT COOLING SYSTEM

The thermostat modeled in this paper is an inlet controlled thermostat. Some of the main components inside the thermostat are highlighted in Figure 2. In the Figure, the dark green solid is the pin which is made of solid steel and wedged to the top of the thermostat. In the normal operation of the thermostat, this pin is pushed to the top from the inside volume expansion and remains stationary. The lighter and darker blue solids in the Figure are the poppet valve solids, which are all made of copper. The void region in the poppet valve solid is filled with paraffin wax element. The brown solid in the bottom is the bypass solid which is also made of steel material. The mechanism that controls the thermostat operation is predicated on the wax melting of the element inside the thermostat. As the coolant gets heated up, circulation of it through the thermostat component heats up the wax element. This increase in temperature of the wax element then causes the melting of this element (changing phase from solid to liquid) beyond a certain temperature based on the properties of the paraffin wax being used. This causes a volume expansion and the poppet valve is pushed down in order to account for this volume expansion of wax.

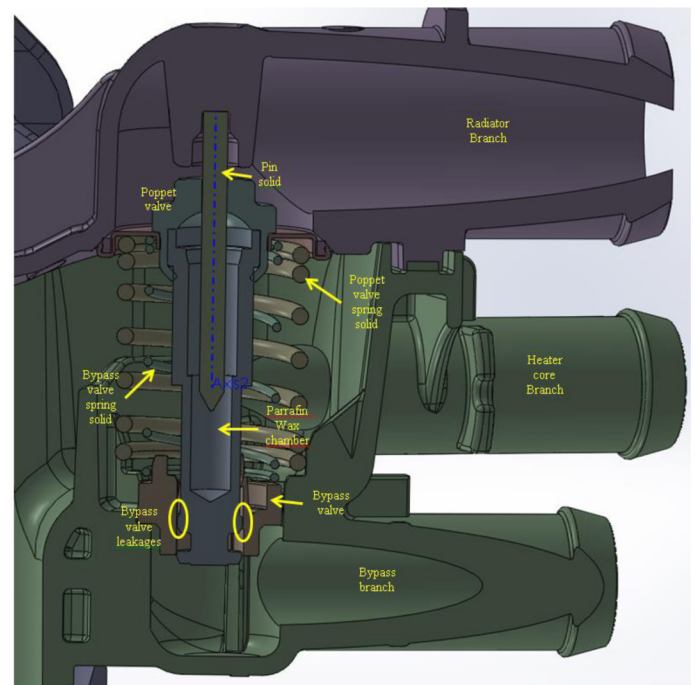


Figure 2. Section cut through the inlet-controlled thermostat modeled in this paper, depicting the different valve components inside.

The mechanics of melting of wax element inside the thermostat in turn controls the working of the cooling system. As the Figure 3 shows, the hot coolant exiting the engine cooling jacket has three possible branches it can take back to the thermostat assembly. The radiator branch that connects to the top part, the heater core branch that connects to the middle and the bypass branch that connects to the bottom (also represented in Figure 2).

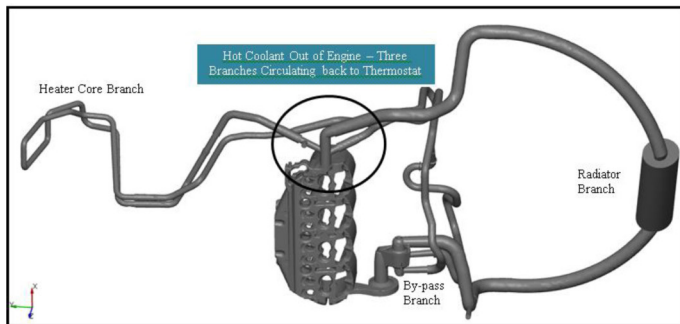


Figure 3. Three divisions of flow from the cooling jacket exit to the thermostat assembly*.

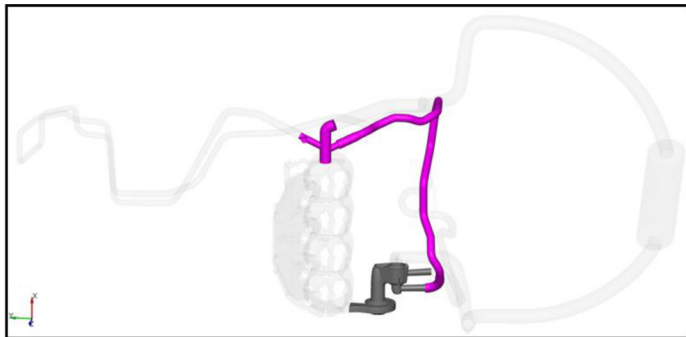


Figure 4. First partition, bypass branch, from cooling jacket exit to bottom of thermostat assembly.

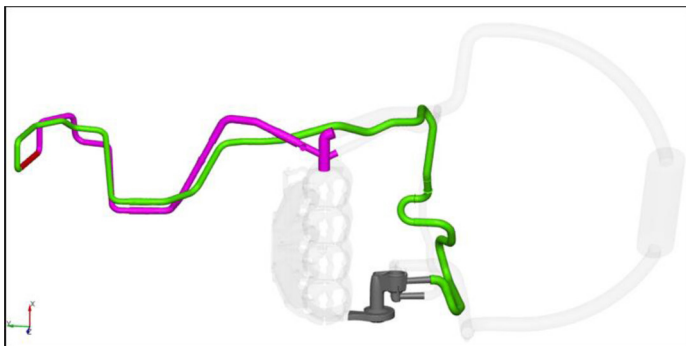


Figure 5. Second partition, heater core branch, from cooling jacket exit to middle of thermostat assembly.

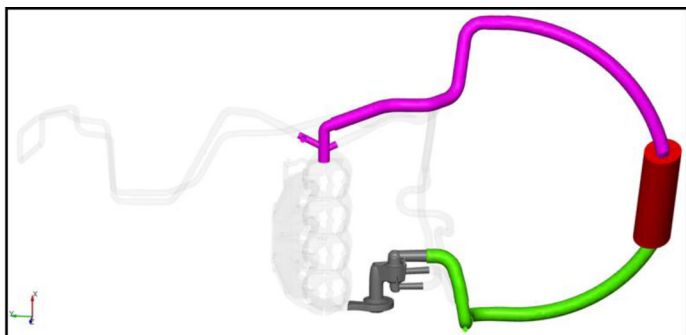


Figure 6. Third partition, radiator branch, from cooling jacket exit to top of thermostat assembly.

The first branch depicted in Figure 4 is the bypass branch. This branch connects the engine cooling jacket outlet to the thermostat assembly through a bypass valve. The bypass valve is controlled by the pressure force-spring force dynamic and will open only if the fluid pressure can overcome the spring load. So, at closed operation of the bypass valve, the flow resistances in this branch is high, and only leakage flow from engine cooling jacket outlet finds its way back to the thermostat. As shown in Figure 2, there are leakage gaps present in the bypass valve. The coolant flow that enters the thermostat through this bypass branch, however, carries the entire heat, as there is no heat rejecting component in this circuit. As the Figure 4 shows, the exit of the cooling jacket is directly connected through pipes to the bypass inlet of the thermostat. The second branch of flow from the cooling jacket outlet is the heater core branch. Figure 5 shows a picture highlighting this branch. The component in red is the model equivalent of the heater core. The heater core acts as one of the heat rejecting component in this system. The heat absorbed by the heater core is in turn used to heat up the passenger cabin. It is important to note that at certain operating conditions of the engine, the net heat generated in the engine can be rejected just by the heater core. In this case, the poppet valve will not open and the radiator branch will never be included in the system. It should be noted here that similarly, the oil cooler in this heater core branch of the circuit can add or remove heat from the coolant depending upon the instantaneous oil and coolant temperatures. The third branch of the system is the radiator branch shown in Figure 6. The component highlighted in red is the model equivalent of the radiator in the system. This branch connects the engine cooling jacket outlet to the top of the thermostat through the radiator. If the heat in the system exceeds a certain threshold, which happens to the melting temperature of the paraffin wax element in the thermostat, then the poppet valve opens including this radiator branch in the system. The radiator acts as the other heat rejecting component in the system. The heat generated in the engine needs to be rejected by the combination of heater core and radiator.

When the wax element gets heated up, the phase change from solid to liquid of the paraffin wax causes volume expansion pushing on the pin solid, the force exerted due to this process pushes on the spring and opens up the poppet valve. This opening of the poppet valve causes part of the coolant flow from the engine outlet to be taken through this radiator branch and enter the thermostat assembly. The heat generated by the engine added into the cooling circuit is rejected by the radiator and heater core. Sometimes, based on the operating conditions of the engine, the heater core is sufficient to reject the heat added by the engine into the system. But, if more heat keeps getting added to the system, the poppet valve opens and the radiator is also added into the circuit for rejecting the heat. On the other side of the operation, when the system is rejecting more heat causing the coolant to drop its temperature, then the decrease of temperature is felt by the wax element causing it to revert back to the solid phase. This causes reduction in the volume, and the force on the spring is relieved, causing it to shut off the poppet valve. This causes the radiator branch of the flow to be shut down, hence, making heater core the only heat

rejecting component in the circuit. In order to simulate the wax melting and freezing process, there is a hysteresis of the paraffin wax element that needs to be accounted into the simulation. This means that when the wax gets heated up and melts, the change in enthalpy with the temperature of the paraffin wax is at a higher range compared to when the wax freezes. The freezing process has the enthalpy change with temperature at a slightly lower range as shown in the Figure 7.

The hysteresis effect of the wax is modeled using a simplistic approach associated with the heat flux. The heat flux that enter or exits the wax chamber surfaces are monitored. Based on the direction of heat flux, the corresponding path, melting or freezing, is adopted.

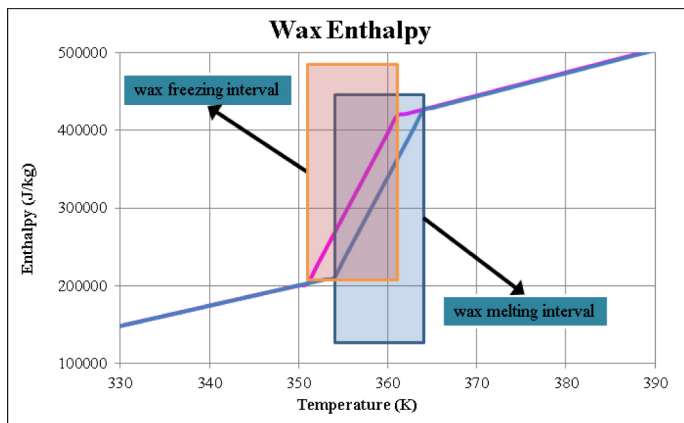


Figure 7. Enthalpy change of wax with temperature, hysteresis effect is seen when the wax melts and freezes again.

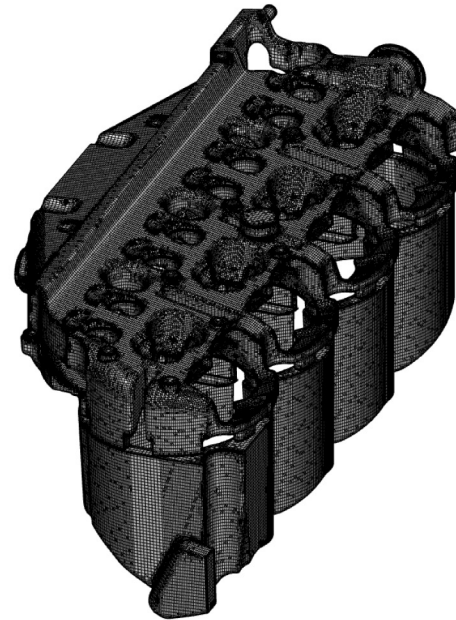
MESHING

Simetrics-Sys® and PumpLinX®, which are the same base codes with some template options available in the latter, both have the automated binary-tree meshing capabilities to provide a fast and effective means of mesh generation without sacrificing accuracy. The mesh for majority of the components will be generated as body fitted binary-tree meshes. This type of grid belongs to the family of unstructured body-fitted Cartesian grids. In this type of meshing, an overlaid cubic grid is refined by factors of two as it approaches regions requiring higher geometric resolution. The important point to note here is the marching of the mesh from finer to coarser is always from the surface, hence the surface meshes are always at least half the size of the inside mesh. Figure 8 shows the mesh for engine cooling jacket and the thermostat.

The mesh created for the coolant pump, and a z-section cut through the axis of the pump are shown in Figure 9. At the boundary, the grid is cut to conform to the surfaces defining the fluid domain. As we can see from the figures, the mesh is predominantly hexahedral cells with the cells cut to fit the surface architecture. The advantages that the binary tree mesh offers are multifold and are discussed in detail by Ding et al. [12]. In order to create the mesh, the user just selects the

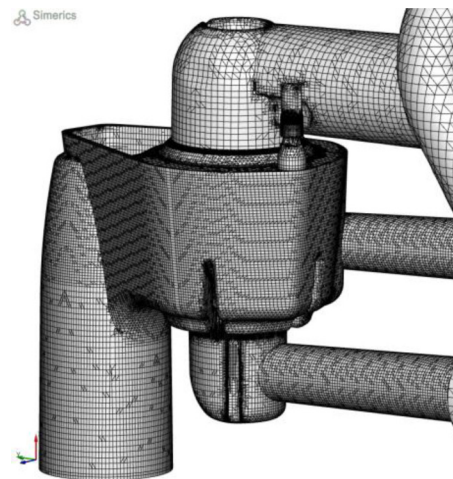
surfaces that define a closed fluid region, and clicks on a button to create a high quality grid. In the inner region, the faces of the binary tree cells are perfectly perpendicular to each other, and at the boundary of the grid, orthogonality ranges between 45 and 135 deg. For the first simulation at low engine speed, the mesh with the cooling jacket is utilized. This mesh size is around 3.5 million cells. In the second set of simulation with high engine speed, the actual cooling jacket is replaced by a simplistic model and the mesh size is around 2.7 million cells.

Simetrics



A.

Simetrics



B.

Figure 8. Mesh of the engine cooling jacket and thermostat.