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ENGINE HEAT TRANSFER IN MECHANICAL ENGINEERING CURRICULUM

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Abstract. *It is the purpose of the present work to show the methodology followed to study the thermal behavior of a Diesel engine, to illustrate the advantages of modeling and simulation tools to enhance the learning and research processes in engineering curricula. Heat flow rates dissipated through the combustion chamber walls of a high speed direct injection Diesel engine were used in the modeling and simulation studies of the engine cooling system design. The engine cooling system model is tuned by comparing its time response under engine constant load and speed; then the model is used to observe the behavior of the thermal-hydraulic parameters of the system under the transient schedule of a NEDC driving cycle. Results of the simulation are presented and the relevance in the use of the applied computational tool for the analysis and development of a mechanical system is demonstrated.*

Keywords: *engine cooling system, modeling, simulation*

1. INTRODUCTION

Internal combustion engine is a unique machine in which all the disciplines of industrial engineering are present. As a machine it comprises, in general, two universal crankshaft-slider and camshaft-follower mechanisms thoroughly studied in the courses of machine mechanics and machine design; intake and exhaust gas exchange fluid dynamic systems are the subject of study in courses such as compressible flow dynamics; cooling and lubrication systems are thermo-hydrodynamic systems designed under the laws and criteria studied in the courses of hydrodynamics, heat transfer and fluid power. The basic theory of the engine itself relies on the thermodynamics fundamentals and the modern theories of combustion related phenomena.

The use of commercial software with capabilities to model and simulate modern complex mechanical and thermo-hydraulic systems such engine cooling systems can help students acquiring comprehensive and insightful knowledge about important engineering devices and learn about the interrelationships and constraints in complex engineering systems in which multiple operational parameters are interconnected by means of nonlinear relationships, studied in more than one of the classic industrial engineering disciplines.

The work presented here is intended to stimulate the student's curiosity, and engage them in the use of a commercial computational program as a tool for the mechanical systems design, where the effects of the change in system parameters on the performance of a system can be readily assessed.

In the first part of the paper a brief description of some theoretical basis related to engine heat transfer and cooling system layout is given. Then, the main steps to model a thermal-hydraulic system with the aid of commercial software are outlined, followed by a synopsis of the modeling process applied to a studied engine. The simulation was run in two stages: a fitting stage, during which some parameters of the model were tuned to validate the steady state thermal response of the engine under a constant condition; and a following application part, during which the adjusted model was used to study the response of the engine thermal system under a changing load pattern proper of a normalized vehicle driving cycle, such as the New European Driving Cycle. Finally, some of the results of the simulation are presented, and some of them compared to experimental values.

2. ENGINE HEAT TRANSFER

2.1. Engine heat transfer correlations and coolant heat transfer

There are two types of coolants used to remove the heat from the engine block and head: air, and water. With air as a coolant, the heat is removed through the use of fins attached to the cylinder wall. With water as a coolant, the heat is removed through the use of fluid filled internal cooling passages. At present, most automotive applications are water cooled, as water proved to be the better medium to transfer heat from critical areas subject to overheating such as the exhaust valves.

Traditional teaching tools used in internal combustion engine courses are real engines, engine models and textbooks. Real engines help students understand how an engine is built from its parts and components; the engine models are used to demonstrate the main mechanical motions of the engine, and the textbooks contain comprehensive knowledge and explanations for the working principle of different engines. A computer-based tool as Amesim becomes an additional tool to study the internal combustion engine.

For a cooling system, the thermo-hydraulic specifications, such as coolant capacity, hydraulic diameters, component thermal masses, are the input parameters. The engine and pump operation regime and a series of data tables related to system heat exchanger components are the input data. The physical and mathematical models embedded in Amesim use these inputs to simulate the cooling system operation. In addition to the output data, such as coolant temperatures and flows for the different branches and nodes of the system, a series of intermediate data, such as fluid pressure, heat exchanged in components, are also calculated.

2.2. Cooling system layout and components

The cooling system is responsible for regulating engine temperature within a prescribed range. Besides simply cooling, this system must help the engine reach the temperature quickly and evenly. Especially in cool weather, it is important the cooling system not over-perform because cold engines wear more rapidly, pullulate more, have inferior fuel economy, and in general produce less power. Under-performing systems are prone to catastrophic failures such as burst hoses and warped metal. Engines that run cool make the passengers to feel uncomfortable in cool weather, at the time that engines that run hot cause discomfort on warm days. But for a better combustion performance achieving a very consistent operating temperature is extremely helpful. Cooling system performance requirements are at least somewhat proportional to power output, so improving the engine requires increasing the capacity of the cooling system.

The engine cooling system layout is particular for each application and is mainly determined by the engine warm-up strategies as well as the position of heater core, oil cooler, and EGR cooler in the branches of the cooling system. The system to be studied in the present work does not include oil and EGR coolers. Its main components can be followed in the schematic of figure 1.

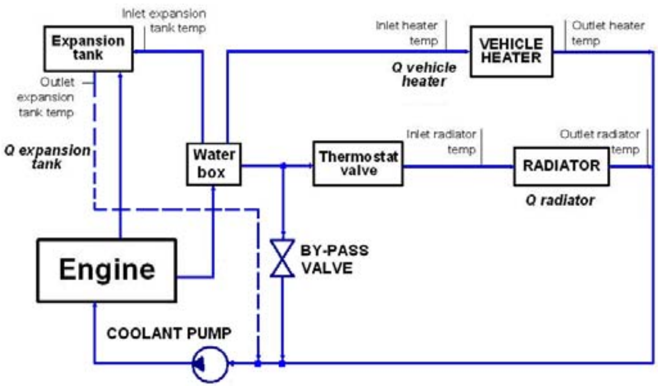

Figure 1. Schematic of the engine cooling system to be modeled

The coolant is driven to engine water jacket by the action of the coolant pump. At the exit of the engine the coolant is conveyed to the water box, from which the flow is diverted through four branches connected in parallel: to the radiator (as the thermostat opens with the coolant temperature increase), to the expansion tank, to the heater core, and to the bypass, which is the shortest way to the engine inlet. The thermostat has two main functions; on one hand, it restricts the coolant flow to the radiator at low operating temperatures, while on the other hand, it keeps coolant temperatures between pre-defined limits.

2.3. Theoretical basis

The work of the engine cooling system is based on the conservation of energy, mass and momentum laws. The energy conservation law for the system reduces to the heat balance between the heat flow sources and sinks. The momentum law is expressed through the relationship between the pressure drop in each system component and the respective coolant flow rate, $\Delta p = \frac{\rho}{2} \frac{Q_v^2}{A_{eq}^2}$. In the case of the coolant pump a series of similar equations are used for the different working speeds, i.e., the working map of the pump. Pressure loss characteristics for a particular branch in a network are obtained by adding up single component pressure losses at equal fluid flow rate values.

The momentum law is complemented by Kirchhoff's law, expressing the pressure balance in any closed loop in a hydrodynamic network as $\sum \Delta p_i = 0$. Mass conservation implies that the total mass flow rate into a node is equal to the total mass flow rate out of the node $\sum \dot{m}_i = 0$.

The coolant flow rate in the engine cooling system is determined by the simultaneous solution of the pump head coolant flow rate equation and the total system pressure drop-coolant flow rate equation (the flow rate is estimated by the intersection of the pump curve and the system resistive curve).

To characterize the heat exchange experimental tables are used. The experimental heat data (q_{exp}) are regrouped in data files whose format is specified in the parameter setting of the submodels. These experimental data are valid for a defined experimental temperature difference $dT_{\exp}$:

$$dT_{\exp} = T^{\exp}_{cool-in} - T^{\exp}_{air\_in} \tag{1}$$

Where $T^{\exp}_{cool-in}$ and $T^{\exp}_{air\_in}$ are respectively the coolant and air experimental temperatures at the radiator inlet. The real heat exchanged is computed as:

$$q_{real} = q_{\exp} \cdot \varepsilon_{rs} \cdot \left(T^{real}_{cool\_in} - T^{real}_{air\_in}\right) / dT_{\exp} \tag{2}$$

Where ε_{rs} is the radiator surface efficiency.

Previous to the modeling work, a process to obtain the required characteristics of each system component must be conducted. The components of the system must be tested individually. For the passenger heater, radiator and all heat exchangers the experimental heat exchanged for a set of coolant and air flows with a constant experimental temperature difference must be prepared. The obtained data is converted to dimensionless numbers and then extrapolated to the sizes used in the simulation model. The dimensionless numbers used are the resistance factor, Reynolds, Nusselt and Prandtl numbers.

When simulating the cooling system the modeling of the cooling air stream becomes especially important. However this part of the cooling system relies mostly on the experimental data and information found in literature in absence of more realistic information or information drawn from underflow CFD modeling.

3. MODELING METHODOLOGY

The modeling process starts with the collection of the submodels from the Amesim database that best suit the operation of the cooling system components, making use of the available thermal-hydraulic, hydraulic, electrical, cooling system and control systems libraries (use of the sketch and submodel modes). Then, the sketch of the network is built following the configuration of the real system and taking into account the connection compatibility of the different submodels. Sometimes in Amesim the component compatibility "rules" force the user to select submodels in a way convenient for the solution algorithms. An example of this is the decision of combining a thermal hydraulic restriction with a thermal hydraulic adiabatic pipe to model a hose, instead of using a single hose, to reach a faster solution. Certainly, Amesim allows the user a great number of submodels for the elastic hoses, but, in our experience the use of them slows down the solution without significant gains in the solution accuracy. When trying to adjust the model layout to the real connections, the parameters are set in accordance to the information requested in the submodel blanks (parameter mode) (every component in the system must be associated with a mathematical model. This is a collection of mathematical equations and their implementation as a piece of computer code).

The next step in the modeling process is the simulation mode, which starts with the analysis data setting (set the run parameters), where the solution tolerance, time step, simulation times, and also the possible solver options, as well as the simulation mode can be set. For the Cooling System models, the typical value of the *Tolerance* in the *Run Parameters* is 10^{-7}. Most of time, the default value of 10^{-5} is suitable, but in cases where small pressure drops occur in orifices, it may lead to slow runs. Reducing the Tolerance down to 10^{-7} can result in a significant increase in the speed of the simulation. Finally, the simulation can be launched (start a simulation) and the results can be analyzed and processed.

4. MODELING OF THE ENGINE COOLING SYSTEM

To model the thermal behavior of the vehicle engine during the warm-up operation under a NEDC driving cycle, it is necessary:

- to determine the heat dissipated to the combustion chamber walls by the combustion gases as a function of vehicle speed and driving pattern;
- to determine the coolant flows through the cooling circuit branches;

- to assess the thermal mass of the engine structure;
- to select the appropriate submodels for the main parts: the engine as a heat flow source with a thermal inertia represented by the coolant capacity and metal mass, and also a characteristic hydraulic resistance; the coolant pump with its hydrodynamic characteristics; the radiator and heater core with their heat dissipation and hydraulic characteristic on the coolant and air sides; the radiator fan and shutter characteristics; the thermostat with its thermal and hydrodynamic characteristics, and the expansion tank with its geometrical dimensions and thermal characteristics.

Given the availability of the *mep-speed* driving pattern of a HSDI Diesel engine, as well as its technical characteristics, it was decided to input the sequence of heat flows from reacting gases to combustion chamber walls, obtained with the aid of a prediction software, as the heat dissipated to the engine coolant during the engine warm-up. A test sequence of 1180 points corresponding to an approximated NEDC schedule (normalized New European Driving Cycle) was modeled with a prediction software. To model the heat flow during transitions, extreme values of the operating points were used. The figure 2 represents heat flow history to be input to the model in a commercial simulation software. The graphic also shows the engine and vehicle speed.

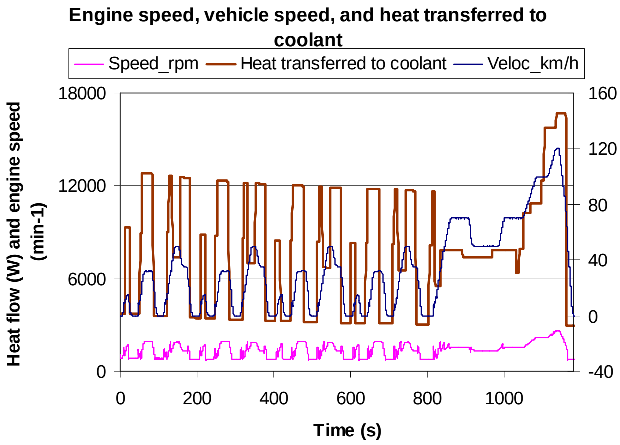

Figure 2. Vehicle and engine speed, and heat transferred to coolant as functions of the driving cycle pattern

The coolant flows through the cooling circuit branches are determined with the experimental data gathered during the engine testing. The graphic in the figure 3 describes the hydraulic system balance. The intersection between these two curves gives the total coolant flow and pressure loss.

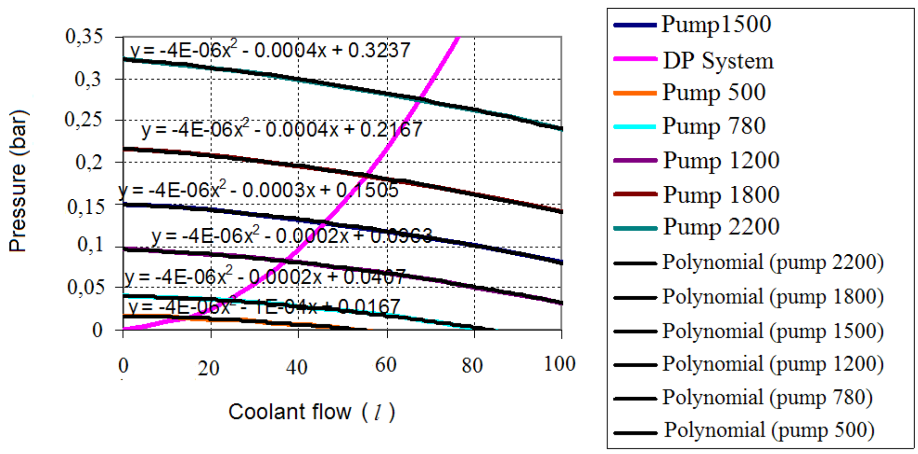

Figure 3. Hydraulic characteristics of the cooling system

The thermal mass of the engine structure is a parameter difficult to assess. Supposedly the coolant flows through the engine water jacket are correct and provided the characteristics of the system heat sinks are correct, it is practical to select the engine mass by setting the time required by the real engine under a known fixed operation point to reach a warmed condition corresponding to a coolant temperature of 80 ºC. The “Cooling system library” in some commercial simulation software of multi-domain systems provides the submodels for the combustion engine as a heat flow source.

For the purposes of our research work the modeling of the engine was performed with the discrete components integrated in the supercomponent *thermal-hydraulic vehicle engine*, *qv = f(earea,dp)*, with "solid thermal capacity".

The submodel "Characteristic data of the cooling system" from the cooling system library is a powerful submodel when using the complete cooling system library to model the engine cooling system in a complete vehicle. In our work we had to restrict ourselves to the manual calculation of the air stream velocity through the radiator. To simulate the passenger salon conditions in the model, the air mass flow and temperature through the heater core have been imposed at the inlet of the component by means of temperature and mass flow signal sources. After defining the submodels to be used in the model, the cooling system network is assembled as presented in Figure 4. Depending on the valve positions (valves 10 and 17) branches will be flowed through or disconnected. With the equations for the pressure balance and the mass balance for each node as well as the linear relationships between volumetric flow and pressure loss, a set of linear equations is established from which the volumetric flow distribution is calculated.

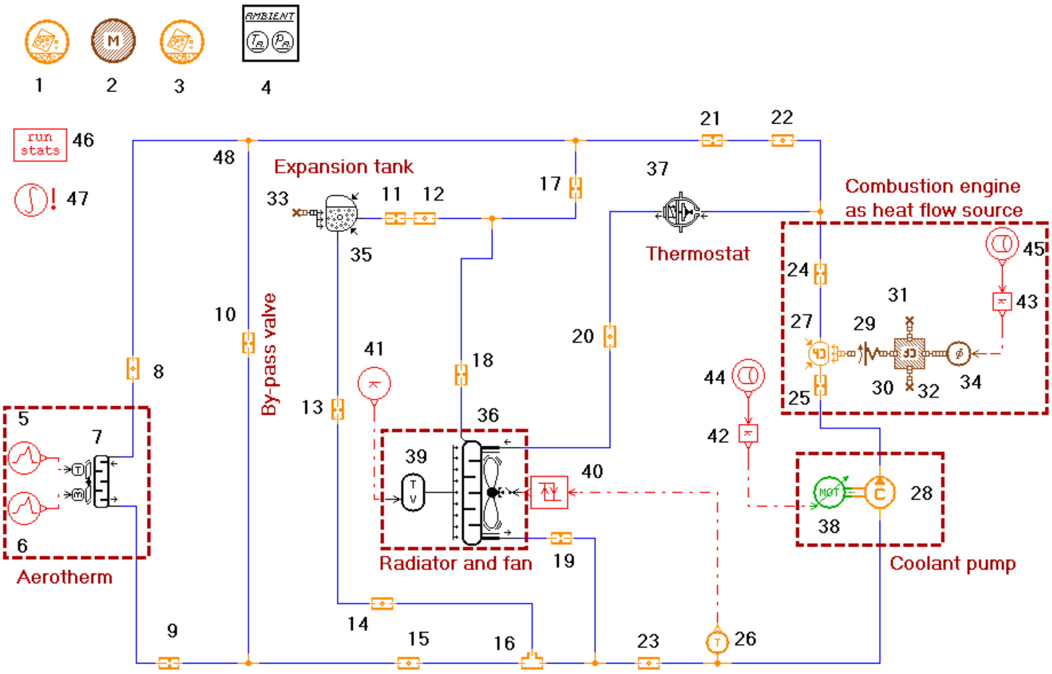

Figure 4. Layout of the engine cooling system network under some commercial simulation software

The circuit diagram in figure consists of 3 main circuits: engine cooling, ambient air and passenger salon. Within the engine, a heat defined by a file is produced and transferred to the coolant medium. Once the coolant temperature reaches a value of approximately 80ºC the thermostat will open, allowing thereby the coolant to go through the radiator. The heat is emitted to the ambient air. In the layout of the system it has been used an electrical pump.

5. SIMULATION RESULTS

5.1. Response of the system under constant engine load and speed

In order to assess the thermal mass of the engine, it was studied the temperature response of the coolant during the warm-up with the operation conditions corresponding to an engine torque of 60 N·m and an engine speed of 1500 rpm. The corresponding heat flow dissipated to the coolant is 7,56 kW. The thermal response of the system is judged by the coolant temperature. The temperature of the coolant at the engine exit is plotted in figure 5, for an engine thermal mass of 38 kg. In the same figure, for comparison it is plotted also the experimental coolant temperature at the exit of the engine.

The shape of the modeled curve shows a higher thermal inertia as compared to the experimental one, though they require the same time to reach the target temperature of 80 ºC. For modeling purposes this result is satisfactory, since many assumptions have been taken during the simulation. In the case that we had to adjust the model we would have to find more closed values for the coolant volume and engine mass. Once the model has been set for steady state conditions, the next step is the study of the system under a driving cycle schedule.

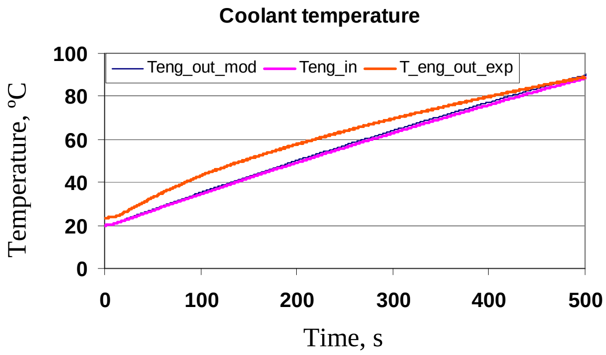

Figure 5. Coolant temperature during the warm-up of the engine under a constant load

5.2. Analysis of the model for the transient operation of the cooling system under the NEDC engine operation

To model the behavior of the designed engine cooling system under the New European Driving Cycle, the files for the engine coolant pump speed characteristic, and that for the heat dissipated to the coolant, were used. These files resulted from the simulation in a computational program for engine combustion prediction. In the following we are going to present some of the general results obtained during the simulation. We can access the evolution of the coolant mass flow rates in the engine, in the heater core and in the radiator as a function of time in figure 6. Little coolant flows through the thermostat. It should be noted that through radiator a small amount of the coolant has been diverted via the expansion tank valve 17; this flow is cooling down by the air encountered by the engine ram and modeled through the components 39 and 41 (these amounts have been decided by the designers and the underfloor design must provide it). This explains the delay in the opening of the thermostat valve.

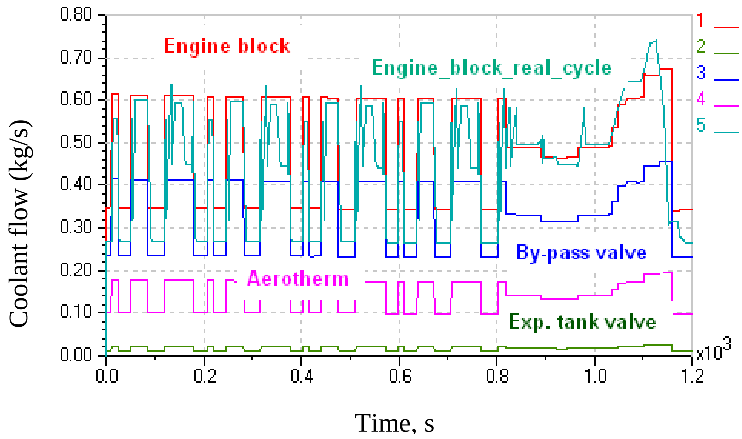

Figure 6. Coolant mass flow rates through the engine cooling system. It has been represented also the coolant flow through the engine water jacket for the case when the real speed of the engine mechanical pump is preserved

From the “Thermal capacity component”, 30 in figure 4, we can access the information related to the heat flow rates dissipated by the engine and the engine supplied to the coolant. Part of the energy balance in the cooling system can be followed in figure 7, where the dissipated through the combustion chamber walls heat flow rates and the heat transferred to the coolant are plotted. The difference between them must be attributed to the energy stored by the metallic parts.

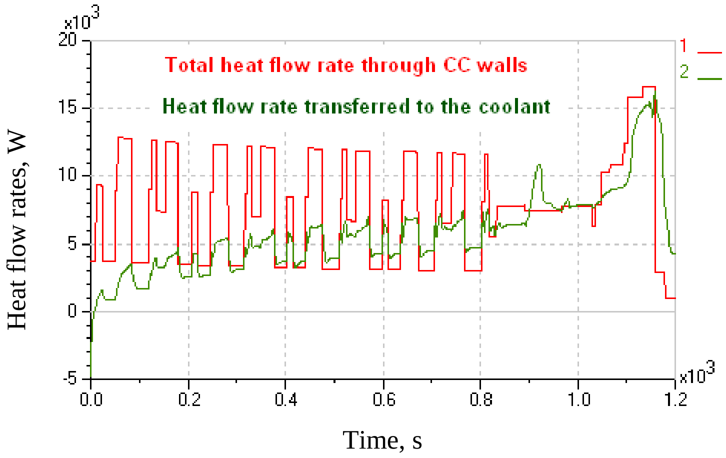

Figure 7. Heat flow rates through the engine cooling system. The difference in the curves corresponds to the stored energy by the metallic parts

Most of the heat produced by the engine is transported initially to the engine masses. As for the heat dissipated through aerotherm and radiator, it is seen from the low left graphic in the figure 7 that, as the engine warms-up, more heat is consumed by the aerotherm (improving the comfort for the passengers). If the aerotherm was not turned on, the radiator would start to dissipate sooner to dissipate the required heat flow. As the engine warms-up the heat transferred to the coolant increases. For the extra-urban part or the NEDC cycle the energy from the combustion chamber walls is almost entirely transferred to the coolant.

The traces of the inlet and outlet temperatures through the engine water jacket are those plotted in figure 8. The assessment of the coolant temperature is the main target in the analysis of the engine cooling system. In effect, as was commented on in the introduction, the main destination of the cooling system is to keep the coolant and metal temperatures between the recommended intervals.

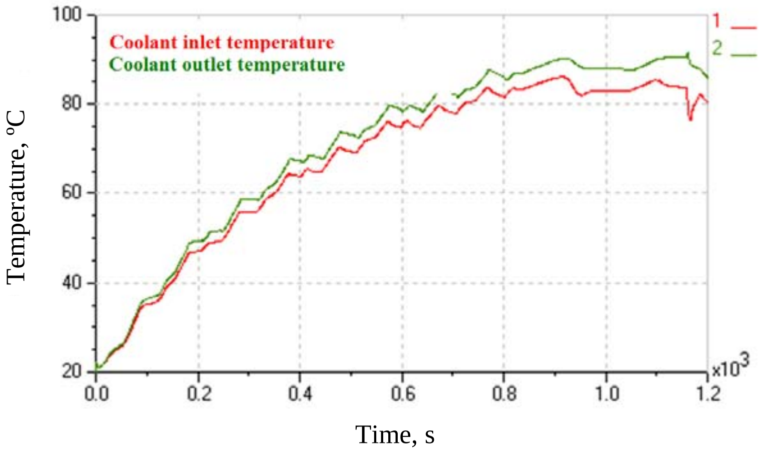

Figure 8. Coolant temperatures at the inlet and outlet of the engine water jacket.

From time t = 0 sec to 800 sec, the thermostat is closed because its opening temperature is set to 88,5 ºC in thermostat submodel. At time t = 800 sec, the wax temperature is equal to the thermostat opening temperature. As a result, the thermostat starts to open and the coolant begins to flow into the "cold loop" constituted by the pump, the engine, the thermostat and the radiator. From time t = 800 sec to 1180 sec, it is possible to observe temperature oscillations which are due to the consecutive closing and opening of the thermostat trying to reach an equilibrium opening. These oscillations are damped and the coolant reaches a steady-state temperature of around 83 ºC. Volumetric flow rates in the different branches.

To have an appraisal of the quality of the cooling system temperature response, modeled and experimental coolant temperatures in the water box of the cooling system of the studied engine are compared, as it is shown in figure 9.

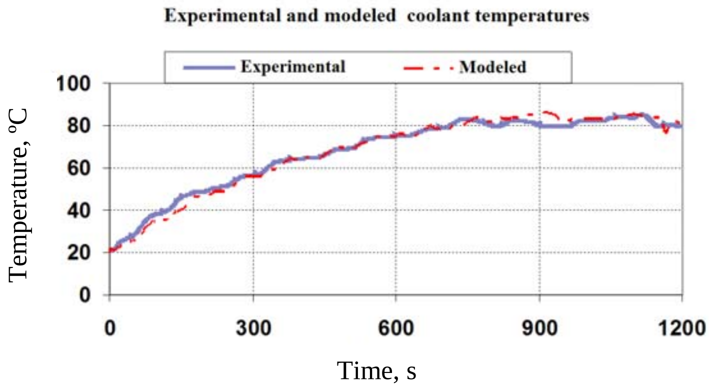

Figure 9. Comparison of experimental and modeled inlet temperature to engine water jacket

Figure 9 constitutes a figure of merit for the cooling system design; the response of the modeled system is very close to the real one. One would expect the studied engine to warm-up faster if a new engine cooling system is being developed, and the model in simulation softwares allows introducing and simulating design features to improve the thermal response of the new engine cooling designs.

6. CONCLUSIONS

This paper was intended to apply a research-based study of an engine cooling system to simulate available learning resources, such as computational programs, through which students can benefit and empower their knowledge. The main aim was to motivate, illustrate and evaluate how modeling and simulation can boost the development and analysis of engineering systems. To this end, it was used the commercial software to arrange the cooling system of a Diesel engine, yielding the opportunity to study its thermal response, and to realize parameter studies.

As for the cooling system studied, the results of the simulation were qualitatively analyzed, showing to be in good agreement with the available experimental data of a tested engine. By comparisons, the consistency of the hydraulic and thermal results under constant and changing engine loads was verified. The model allows conducting studies projected towards the optimization of new engine cooling systems provided the main cooling system components and their characteristics are known.

7. REFERENCES

Borman, G., Nishiwaki, K., 1987. “Internal Combustion Engine Heat Transfer”. *Progress in Energy Combustion Sciences*, Vol 13, p 1-46.

Chang, K. Babajimopoulos, A., Lavoie, G., Filipi, Z. et al., 2006. “Analysis of Load and Speed Transitions in an HCCI Engine Using 1-D Cycle Simulation and Thermal Networks”. *SAE Technical Paper Series* 2006-01-1087. doi: 10.4271/2006-01-1087.

Chang, J. Filipi, Z., D. Assanis et al., 2005. “Characterizing the Thermal Sensitivity of a Gasoline Homogeneous Charge Compression Ignitios Engine with Measurements of Instantaneous Wall Temperature and Heat Flux”. *Int. J. Engine Res*. Vol. 6, special issue paper 289. doi: 10.1243/146808705X30558.

Incropera, F., DeWitt, D.P., 1996. “Fundamentals of Heat and Mass Transfer”, fourth ed., John Wiley & Sons, New York.

Koch, F. W., Haubner, F. G., 2000. “Cooling System Development and Optimization for DI Engines”. *SAE Technical Paper Series* Nº 2000-01-0283. doi:10.4271/2000-01-0283.

Patton K, Nitschke R, Heywood J., 1989. “Development and Evaluation of a Friction Model for Spark-Ignition Engines”. *SAE Technical Paper Series* 890836. doi:10.4271/890836.

Yoo, I., Simpson, K., Bell, M., and Majkowski, S., 2000. “An Engine Coolant Temperature Model and Application for Cooling System Diagnosis”. *SAE Technical Paper Series* 2000-01-0939. doi:10.4271/2000-01-0939.