

Design and analysis of a cooling control system of a diesel engine, to reduce emissions and fuel consumption.

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Abstract. *The diesel engine technology has been driven by increasingly stringent laws. To comply with these laws the emissions control systems are rapidly developing in the market aimed at providing products that meet future emissions standards, but savings in fuel consumption and greater durability and competitiveness in international markets, improving cost-benefit ratio. In this context, it is performed a design and analysis of a control system for cooling the diesel engine, aiming to control the engine water temperature accurately, to save fuel and reduce emissions. So, the present work has as objective to design a mechatronic system is substitution to the traditional cooling system of the diesel engine commonly used in the market today. The system under study consists of an electric water pump, an electrically driven fan, an electronically controlled thermostatic valve and a control algorithm. This system is intended to provide precise control in water temperature of the diesel engine, thereby reducing pollutant emissions and fuel consumption, allowing also a rapid response to heating in cold start. Controller tuning was performed by algorithmic approach, through optimization and co-simulation using two distinct computational softwares, GT-Cool and Matlab/Simulink.*

Key Words: System Temperature Coolant Control, Diesel Engines, Engine Control Co-Simulation

1 - INTRODUCTION

Diesel aims to produce mechanical energy from chemical energy stored in fuels. The engine uses a conventional arrangement of cylinders and pistons found in other types of internal combustion engines, as gasoline engines. Conceptually, the diesel engine achieves high performance and excellent fuel consumption by compressing the air contained within the cylinder at high pressure and injecting a small amount of fuel into highly compressed air. The temperature generated during the compression of the air makes this small amount of pulverized fuel evaporates. Mixture of pulverized fuel to the existing hot air into the combustion chamber causes the vaporized fuel to reach its auto-ignition temperature and burn, thus freeing the energy stored before. With the burning of fuel, energy in the form of heat is released increasing the pressure inside the cylinder. This energy released raises the pressure in the cylinder that is applied to the surface of the piston, causing it to return to the PMI (bottom dead center) as in Figure 1. This cycle is known as a boom cycle, power cycle or duty cycle because this cycle is that the expansion of gases produces work by applying pressure to the piston surface.

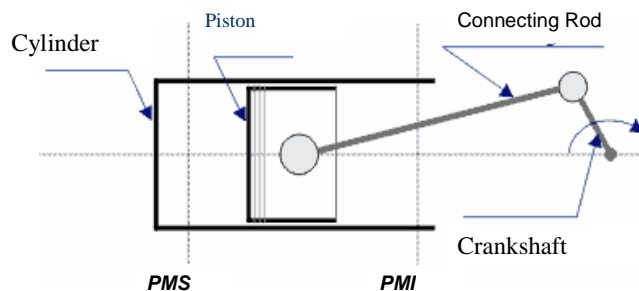


Figure 1. Schematic of an internal combustion engine piston and cylinder arrangement.

The Figure 2 shows that some of the heat produced by the energy stored in fuel is transformed into mechanical energy, part is radiated to the environment, one part is lost by mechanical friction, part is eliminated by the exhaust gases and part of the heat generated is transferred for the cooling system. The high degree of efficiency of the diesel engine is closely related to the pollutants created during the combustion process, in which fuel is introduced into the chamber for a short period. The rapid combustion near TDC (top dead center), and in combination with the high coefficient of intake air leads to greater efficiency of diesel engine. The rapid combustion of fuel is also associated with high local peak combustion temperature, which in turn cause the

formation of nitrogen oxides (NO and NO₂, usually joined and referred to as NO_x). The formation of nitric oxide (NO), according to (Heywood, 1988), occurs throughout the range of high-temperature exhaust gases behind the flame and through chemical reactions involving nitrogen, oxygen atoms and molecules who have not reached chemical equilibrium. Thus, in one form or another all the chemical pollutants are linked to the combustion process.

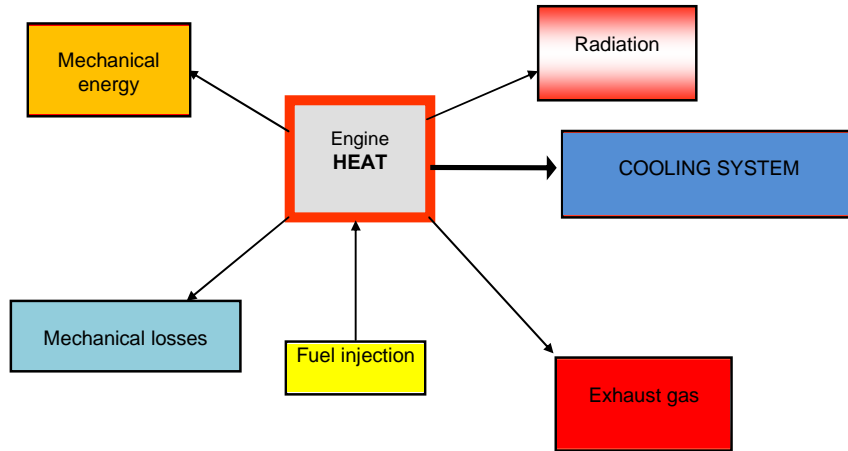


Figure 2: The heat generated by burning fuel is converted into mechanical energy.

The cooling system of a diesel engine has conventionally been regarded as an auxiliary system of lesser importance to engine performance, while necessary for its operation. Conventional systems for cooling the engine are simply designed to keep the engine temperature acceptable for a wide range of operation and operating conditions. With the introduction of mechatronic technology conventional mechanical systems are being replaced by electronically controlled systems. A cooling system of electronically controlled diesel engine should provide improvements in performance through their effects on the engine, improved friction loss, improvement in fuel economy, reduced emissions and increased durability. The basic design of automotive cooling system has remained essentially unchanged for a long time; for example, drive the pump water from the cooling system of the motor is accomplished by rotating the engine. Thus, the coolant flow rate is determined by engine speed, which is not ideal for most cases. A conventional, mechanically driven water pump can cause unnecessary and parasitic losses. A water pump with electronic control would control the flow of water from the cooling system regardless of engine speed, providing a further reduction of parasitic losses. Another potential advantage of the electric pump is the possibility of reducing the size of the radiator, which is an important issue in the development of engine cooling systems. Increasing control possibilities provides a better choice of operating points of the diesel engine. Results of research in advanced cooling systems have been published over the past year, with main focus on temperature control of the motor based on simulated studies, for example, in (Xu et al 1984) and (Luptowski, 2005). Some works, such as (Lehner et al, 2001) indicate that in an electronically controlled cooling system there is benefit in fuel economy and in reducing emissions of greenhouse gases. Other studies, such as (Pang et al, 2004) show that there is a potential reduction of NO_x with temperature control by cooling the diesel engine. Most previous work in the control of the temperature of the engine cooling system focuses on the benefits of fuel economy and reducing emissions of greenhouse gases through the reduction of friction losses and reduced energy demands of auxiliary components. Government policies around the world have acted as control agents in order to impose the reduction of air pollution. As an example, Figure 3 shows the evolution of acceptable levels of NO_x and particulate matter since 1992 as the European standard (EURO V). It can be seen in Figure 3, that current requirements almost precludes null pollutants. For diesel engines law limits for NO_x emissions are more restrictive. Knowing that temperature directly influences the rate of formation of NO (nitric oxide), a method of controlling emissions involves the efficient control of combustion temperature. The use of an electronically controlled system offers an opportunity to change the calibration of engine parameters for a better relationship among fuel economy and emissions of NO_x (nitrous oxide), CO (carbon monoxide) and HC (Hydrocarbon).

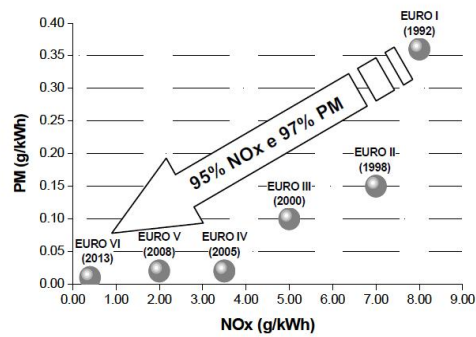


Figure 3: Emission levels of NOx and Particulate Material (PM).

2. OBJECTIVE

The objective of this his work is the design and analysis of a mechatronic control system for the cooling system of a diesel engine, aiming a precise control of engine temperature considering that this will provide fuel economy and reduced emissions.

3. MATERIAL AND METHODS

In this section it is presented information regarding the equipment considered in this work: a reference diesel engine, cooling system as proposed, water pump electrically controlled, electronically controlled thermostatic valve etc.

3.1 Engine systems

The engine used as a reference for testing and analysis is a diesel engine MaxxForce 7.2-liters EURO V equipped with Bosch electronic fuel injection and maximum output of 330CV @ 2200rpm.

The internal combustion engines can be divided into the following systems:

- Structural (block, head, media,...);
- Power (crankshaft, connecting rods, pistons, rings,...);
- Lubrication (oil pump, oil ejectors,...);
- Management of air (turbo, intercooler, EGR valves, intake manifolds and exhaust,...);
- Cooling (heat exchangers, water pump, thermostat, coolant, fan,...);
- Electric (ECM, battery, sensors, actuators, electrical harness, ...);
- Fuel (fuel injection pump, feeding pump, nozzles, filters,...);
- Auxiliary (air compressor, alternator, hydraulic pump,...);
- Distribution and timing (intake and exhaust valves, camshafts, rocker arms, gears,...).

The system in focus is the cooling system and the proposal of this work is illustrated in Figure 4. The main components of the cooling system are then:

1. Water Pump - to circulate the liquid throughout the cooling system;
2. Coolant - to raise the boiling point, lubricate and protect against corrosion;
3. Radiator – for lowering the temperature of the liquid that comes out of the engine;
4. Hoses - interconnect engine with radiator;
5. Thermostatic Valve - control the flow of coolant and engine temperature;
6. Thermal switch - on and off the fan;
7. Fan - cools the liquid in the radiator;
8. Temperature Sensor - indicate the temperature on the dashboard and for the engine electronics module (ECM).
9. Electronic Control Module Engine (ECM).

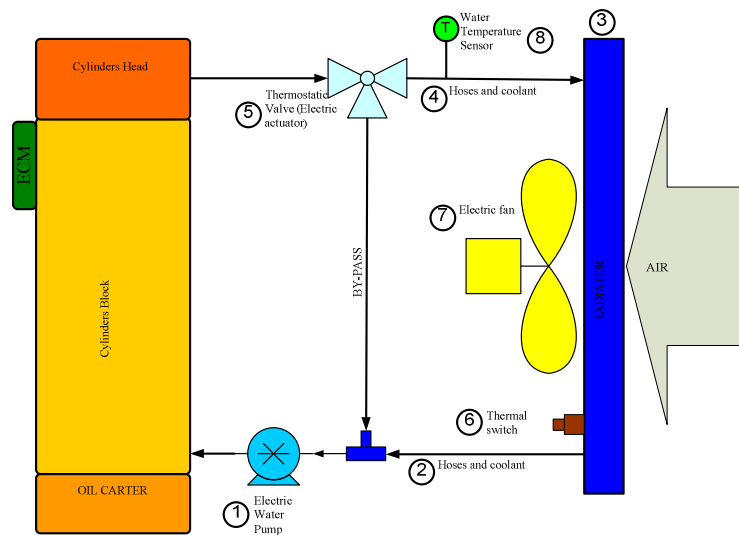


Figure 4: The cooling system proposed.

The ECM is an electronic module and a computerized control algorithm highly sophisticated; it is the state of art in open and close loop control that are essential to meet the demand functions for the correct functioning of the internal combustion engine, its safety, environmental compatibility (emissions), performance and comfort. This electronic module is associated with a wide range of automotive subsystems installed in modern vehicles. The sensors are monitored by the engine electronic control module (ECM), and this module also converts the signals necessary to adjust the final control elements and actuators of the engine. As illustrated in Figure 5 the input signals can be: analog (e.g. temperature and pressure sensors voltages), digital (e.g. position of the ignition key) or pulse shape (signal of engine rotation and vehicle speed).

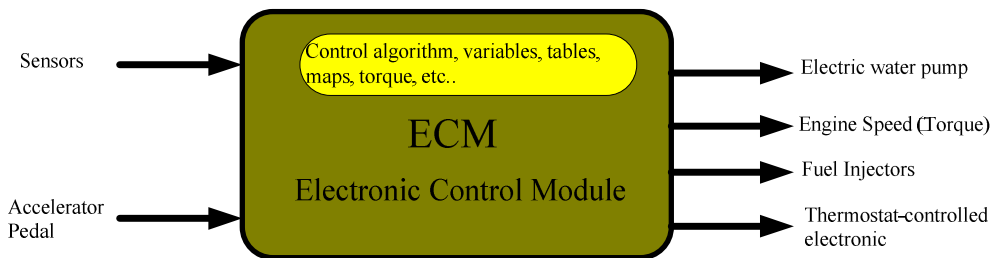


Figure 5: Illustration of functional electronic engine control module (ECM).

3.2 Plant components

3.2.1 Electric water pump

The electric pump unit is composed of an electric motor and a water pump connected to the same axis, and a speed control device. The variation of rotation is determined by the electronic module which receives a PWM (pulse width modulation). The percentage variation of PWM is directly related to the the variable speed electric pump motor. Thus, it can be considered from stopped engine up to full speed. The main feature of the electric water pump is to have control independent of rotation of the combustion engine (Ribeiro et al, 2007).

3.2.2 Fan

This device is responsible for the forced circulation of air through the radiator fins. Typically, when the vehicle is in motion, the natural ventilation caused by the displacement of the vehicle would be sufficient to cool the coolant that goes through the radiator, but this is not always feasible when the vehicle is in low speed. In

vehicles, the fan pulls air front to back, like a hood. The fan can be belt driven by an electromagnet, an electric motor or by means of hydraulic devices (viscous fan).

3.2.3 Thermostatic valve electronically controlled

The temperature of the coolant and with it the engine must be adjusted so it remains approximately constant within a narrow range. An efficient way to compensate for different working conditions is to install an electronically controlled thermostat, and incorporating an element of control that will regulate the temperature regardless of pressure variations in the cooling system. An electronically controlled thermostat differs from conventional thermostats. The controller receives information from the ECM and sends a PWM (pulse width modulation) to a solenoid valve. The solenoid valves open and close the internal mechanism of the thermostat, controlling the flow of coolant liquid that goes through the radiator. This increases the range of work for different climatic conditions and with large fluctuations in load factors and help in reducing engine emissions while reducing engine wear.

3.2.4 Thermal switch

The thermal switch shown in Figure 6 is a component used to connect and disconnect a circuit as a function of temperature. In the car, it is often used to drive the electro fan cooling system. The thermal switch is installed in the radiator or engine, and is in contact with the most heated part of the cooling system. Internally it has a bimetallic strip responsible for detecting the temperature.

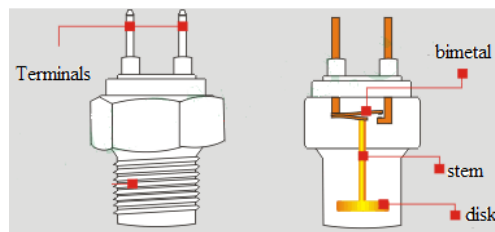


Figure 6: Electric diagram of switch bi-metallic.

3.2.5 Water Temperature Sensor

The water temperature sensor comprises a thermistor NTC (Negative Temperature Coefficient) which reduces the value of its resistance with increasing temperature, so the higher the temperature the lower the electrical resistance of the element. The sensor reports the temperature of the coolant from the engine to the fuel injection module (ECM) and/or temperature indicators (dashboard of the vehicle).

3.2.6 Radiator and Coolant

The radiator is the component responsible for making the exchange of heat from the engine coolant to the air passing by flippers as shown in Figure 7. The nuclei of the radiators are almost always made of aluminum, a pipe through which circulates the cooling liquid. Heat exchange is accomplished by forcing air through the fins that are welded on aluminum tubes. Regardless of operating conditions and ambient temperature, the radiator must continue to provide efficient heat transfer, making the exchange of heat from the engine cooling fluid with the external environment. The liquid cooling system removes heat from the combustion chamber, cylinder head, engine block and others. Until the engine reaches its normal working temperature, the fluid flows only through the galleries of the engine; when the working temperature of the engine is reached (85 ° C to 95 ° C) the fluid begins to circulate around the cooling system, goes through the radiator, which together the fan, cool the engine.

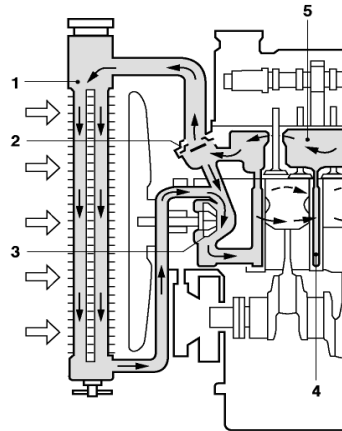


Figure 7: Cooling system showing the circuit passing through the liquid:

- 1-Radiator, 2 - Thermostatic valve, 3 - Water pump, 4 - Galleries of the cylinder block, 5 - Galleries of the cylinder head.

3.2.7 Model for transfer of heat from the engine

As shown in Figure 8, the transfer of heat generated in the combustion chamber inside the internal combustion engine is rated at forced convection heat or radiation. The objective of the control system is to ensure that the cooling temperature of the outer wall of the cylinder is below 132 ° C such that the temperature of the inner wall of the cylinder is below 177°C (Lehner et al 2001).

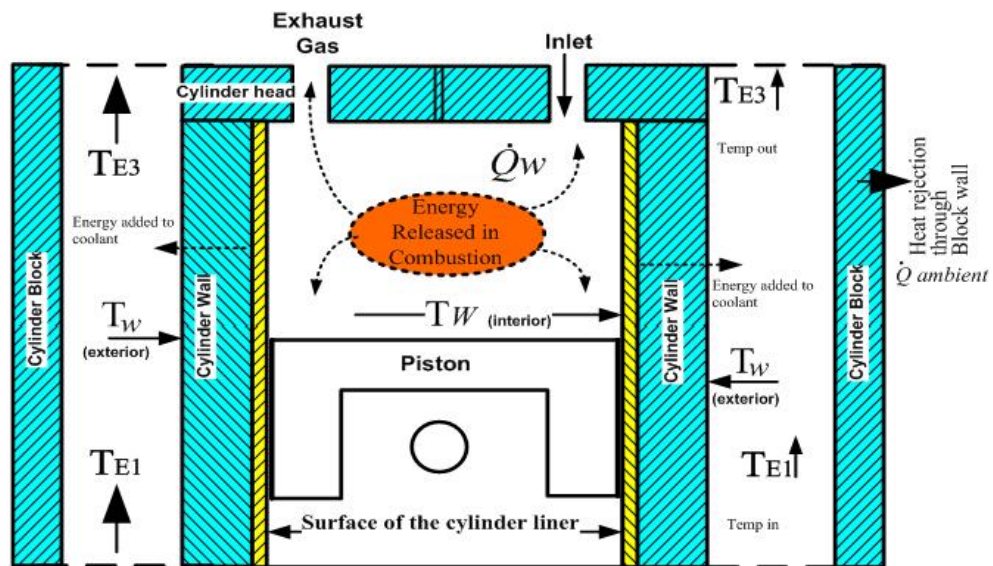


Figure 8: Engine cylinder block with the release of energy during the combustion and coolant circuit.

4. CONTROL SYSTEM

4.1 A proposed control system for engine cooling

The Figure 9 shows the diagram of generalized engine cooling control system as focused in this work.

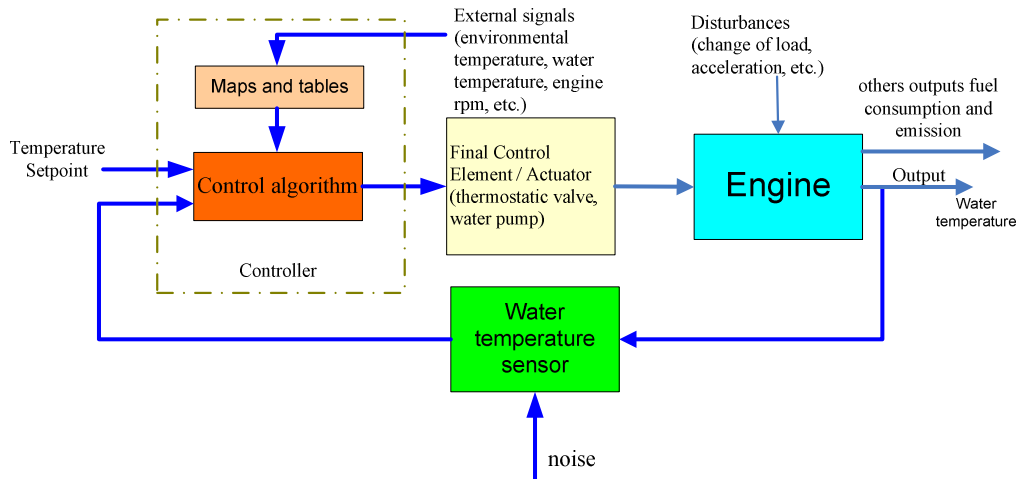


Figure 9: Block diagram of control system.

Figure 12 shows the control system in greater detail, consisting of two control loops: the water pump and thermostatic valve respectively. This configuration was proposed in (Lehner, C. et al, 2001) and adopted in this work, taking into account aspects such as feasibility of the proposed system. The variables required to implement this strategy are: ($TE1$) inlet temperature of coolant, ($TE3$) the outlet temperature of the liquid cooling, (N) engine speed, ($Tamb$) ambient temperature, (\dot{m}_f) flow fuel and (\dot{m}_c) the mass flow of coolant. In conjunction with the specific parameters of the system, the control system determines the flow of the electric water pump and the correct positioning of the thermostatic valve actuator (flow rate of liquid coolant that passes through the radiator) to maintain a desired temperature on the outer wall ($Twext$) of the cylinder, as shown in Figure 9. Three input parameters are needed to calculate the feed-forward control component: flow rate of fuel (\dot{m}_f), inlet temperature coolant ($TE1$) and outlet temperature of the engine coolant ($TE3$) (see figure 9). The thermostatic valve control also uses a feed-forward component and a feedback component, to achieve the desired output temperature of the cooling, and minimizing the activation of the fan. The desired inlet temperature of the coolant temperature is derived from the outer wall of the cylinder ($Twdes$), and output coolant temperature ($TE3des$). In this work, it is assumed that the output temperature of the coolant radiator is approximately equal to the temperature of liquid entering the engine block. The portion of the feedback control will compensate for any error associated with differences in temperatures.

4.2 Co-Simulation Models

GT-Suite is an integrated set of tools for computer-aided engineering (CAE) developed by Gamma Technologies, Inc. to handle engine and power train design. It is composed of six tools (GT-POWER, GT-COOL, GT-FUEL, DRIVE-GT, GT-and GT-CRANK VTrain), and an interface for building models (GT-ISE, Interactive Simulation Environment). The simulation of the engine cooling system is done in GT-Power/GT-Cool while the control system is modeled in Simulink. For a full sync in the simulation, both models are dynamically interconnected (Luptowski et al, (2005)). This is possible by the component “wiring harness” of the GT-Power, which allows signals to be sent and received between the engine model and cooling controller in running the models. The engine model requires several boundary conditions to be defined. Cooling system modeled values can be “triggered” or updated simultaneously. As shown in Figure 10, the inputs and outputs to the model of the engine cooling system will be generated on GT-Cool model and the engine is controlled by means of SIMULINK, the environment in which it is designed and simulated the control system.

Figure 11 shows the cooling system and engine GT-cool simulation model.

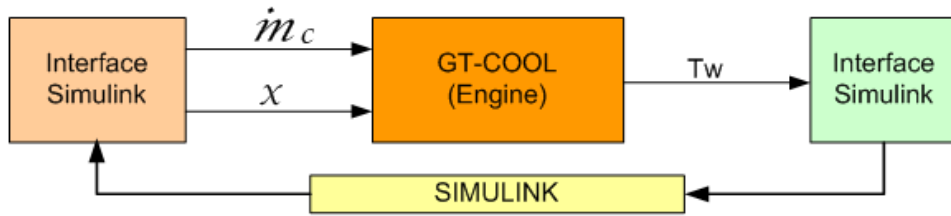


Figure 10: Block diagram of the co-simulation model GT-COOL/SIMULINK

4.3 Controller Design

The models and their parameters needed to make the design of the controllers as shown in Figures 11-14 were determined by tests, information from manufacturers and the technical literature. We decided for an algorithmic process in designing the controllers, since it will allow taking in account more complete and detailed models of the system. Figure 11-14 illustrates the configuration and the environments used in the algorithmic design of controllers. The engine was simulated in the GT-Cool (see Figure 11), more suited to this type of application and analysis. Another positive aspect in the use of GT-Cool is that the temperature of the external wall of the cylinder (T_w in Figures 8 and 13) and other elements (see box marked in Figure 13) are information provided by GT-Cool engine simulation, for example, removing the need of an estimator, as shown in Figure 13, to this level of the control tuning. The components (actuators, sensors, etc) and the control actions of the controllers were implemented in Matlab / Simulink, since these models and the algorithmic design process itself are in this environment.

The tuning of PID and Feed-Forward controllers has the goal to obtain performance as defined in respect the response to step disturbances. Figure 14 shows the Simulink model for algorithmic controllers tuning.

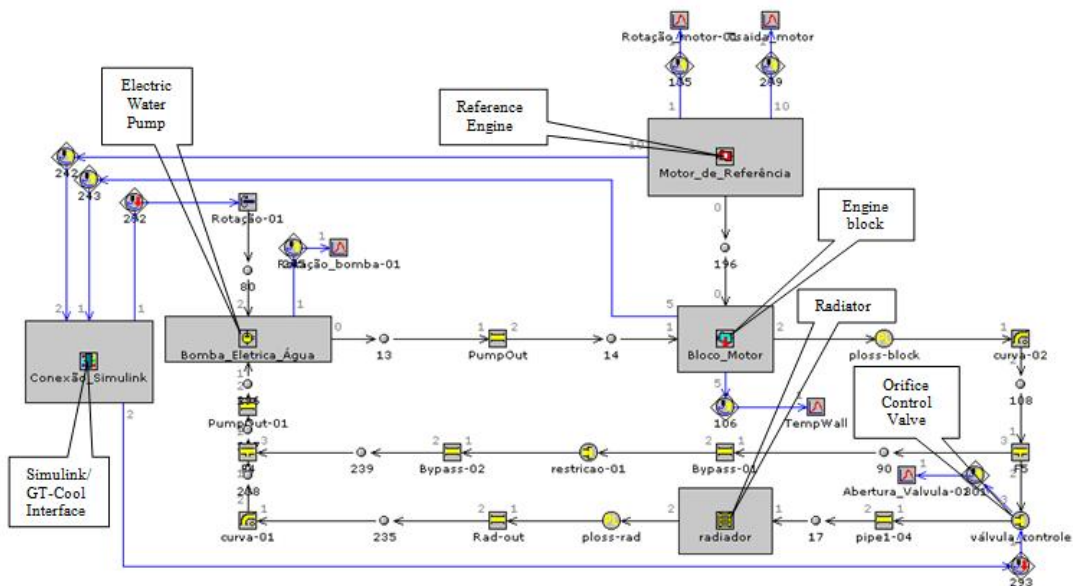


Figure 11: Block diagram of simulation model GT-COOL

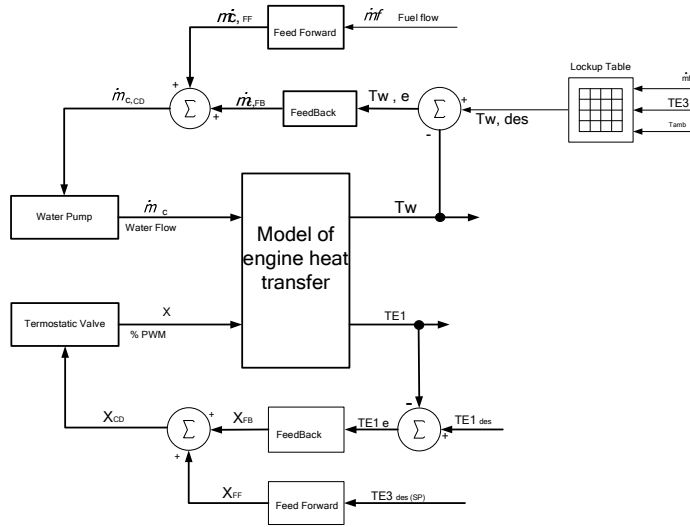


Figure 12: Thermostatic valve and water pump control system configuration (Lehner, et al, 2001).

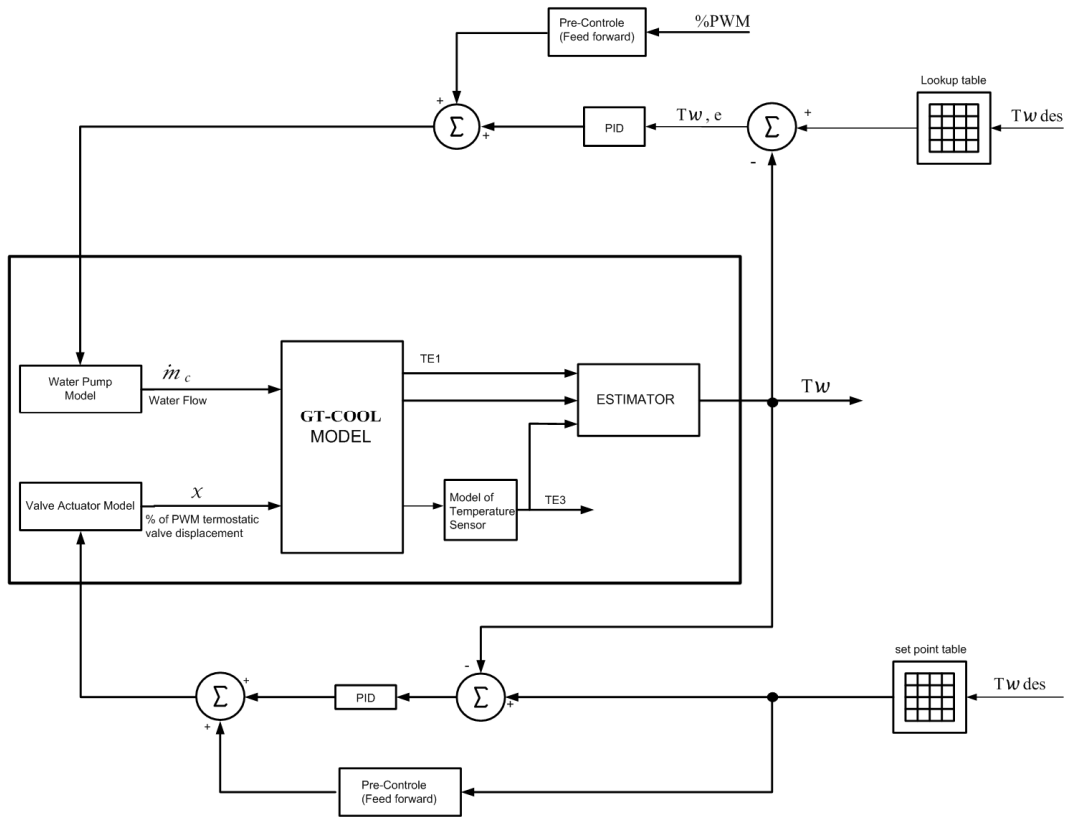


Figure 13: Control strategy of engine cooling system.

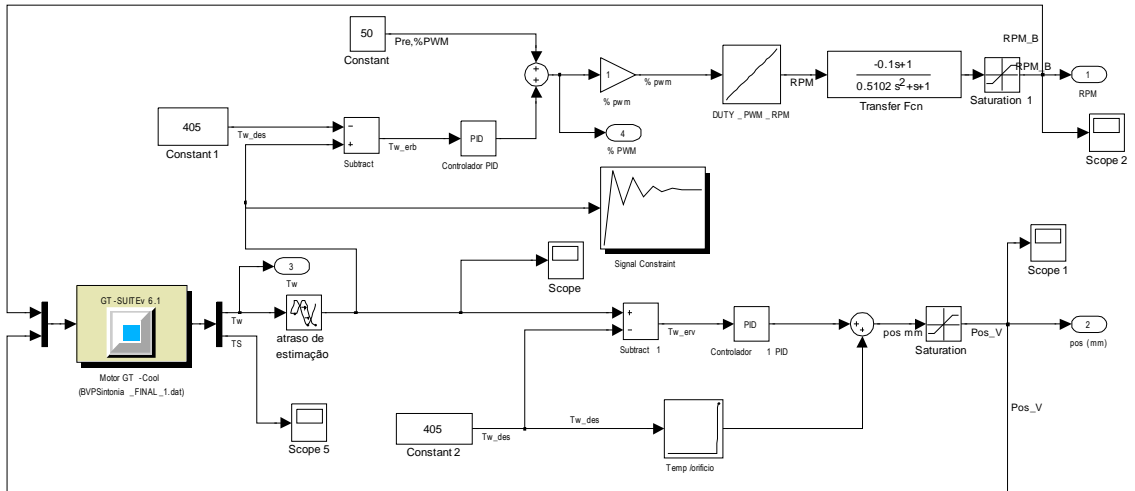


Figure 14: Model strategy of control engine cooling system Matlab/Simulink.

5. CONCLUSION

The results described in the specialized technical literature, as well as experience in the MWM International Motores and tests made in the context of this work, allow us to predict that the use of a cooling system with electronically controlled engine, tends to reduce both energy consumption, the temperature of the cylinder wall and the temperature fluctuations in order to reduce the thermal stresses and stabilizing the temperature of the oil film that reduces friction in the sliding components. The improvement in fuel economy is also obtained by reducing the power supplied to engine accessories. Moreover, experimental results found in literature and observed in tests already conducted, show that NOx can be reduced by controlling the temperature of engine coolant, and which additionally show a reduction of CO and HC. More investigation about this control system is in course and will be reported later.

6. REFERENCES

- Brian J Luptowski, 2005. "Development of the Enhanced Vehicle and Engine Cooling System Simulation and Application to Active Cooling Control" Technical Paper 2005-01-0697.
- Chad Lehner, et al., 2001. "Design and Development of a Model Based Feedback Controlled Cooling System for Heavy Duty Diesel Truck Applications Using a Vehicle Engine Cooling System Simulation" Technical Paper 2001-01-0336.
- EURO V "Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007".
- Heywood, John B., 1988 "Internal combustion engine fundamentals", McGraw-Hill, 62 p.
- H. H. Pang., 2004. "Potential of a Controllable Engine Cooling System to Reduce Nox Emissions in Diesel Engines", Technical Paper 2004-01-0054.
- Magdi, K. Khair, 2001. "Diesel Engines Fundamentals", <<http://www.dieselnet.com>>.
- Ribeiro, E., et al. 2007. "Electric Water Pump for Engine Cooling" Technical Paper 2007-01-2785.
- Xu, Z., Johnson, J. H., and Chiang, E. C., 1984, "A Simulation Study of a Computer Controlled Cooling System for a Diesel Powered Truck", SAE paper 841711.
- Xu, Z., Johnson, J. H., and Chiang, E. C., 1984, "The Design and Testing of a Computer Controlled Cooling System for a Diesel Powered Truck", SAE paper 841712.

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