A Simulink Model for an Engine Cooling System and its Application for Fault Detection in Vehicles

by

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Abstract

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An engine cooling system is an integral part of the vehicle responsible for maintaining the engine at an optimum operating temperature. A faulty component of the cooling system will lead to engine overheating that can damage the engine and also increase vehicle emissions. On-Board Diagnostic (OBD) system is deployed in vehicles that stores information about the detected malfunction as Diagnostic Trouble Codes (DTCs) so that a technician can identify the possible faults inside the vehicle.

This project describes the development of a Simulink model for an engine cooling system and its application for fault detection in vehicles. Thermodynamics and physical laws are used to derive mathematical equations to represent an engine cooling system that is implemented in simulink. With specified input signals and engine cooling component data, the performance of the engine cooling system can be evaluated using the simulink model. A method for fault diagnosis of the engine cooling system is proposed. It is based on comparing the signals from a test vehicle to those generated by the simulink model. Appropriate diagnostic algorithm is written that compares data from a healthy and faulty system and indicates the presence of a faulty component if large deviations are found. Since data from a test vehicle was not available, the proposed method was tested using data generated by the developed simulink model using faulty component data. Results indicate that the proposed method has the potential to be used by car manufacturers to speed up fault detection and perform fault diagnosis without the use of expensive diagnostic tools.

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ARB	Air Resources Board
BLDC	Brushless DC Motor
CTS	Coolant Temperature Sensor
DTCs	Diagnostic Trouble Codes
ECM	Electronic Control Module
LHV	Lower Heating Value
NTC	Negative Temperature Coefficient
OBD	On Board Diagnostic
PID	Proportional Integral Derivative
PWM	Pulse Width Modulation
RPM	Revolutions per Minute

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Chapter 1. Introduction

1.1 Background

The engine cooling system of a vehicle is a system of parts and fluid that work together to control an engine's operating temperature for optimal performance. The system is made up of passages inside the engine block and heads and contains components as depicted in figure 1[1].

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).

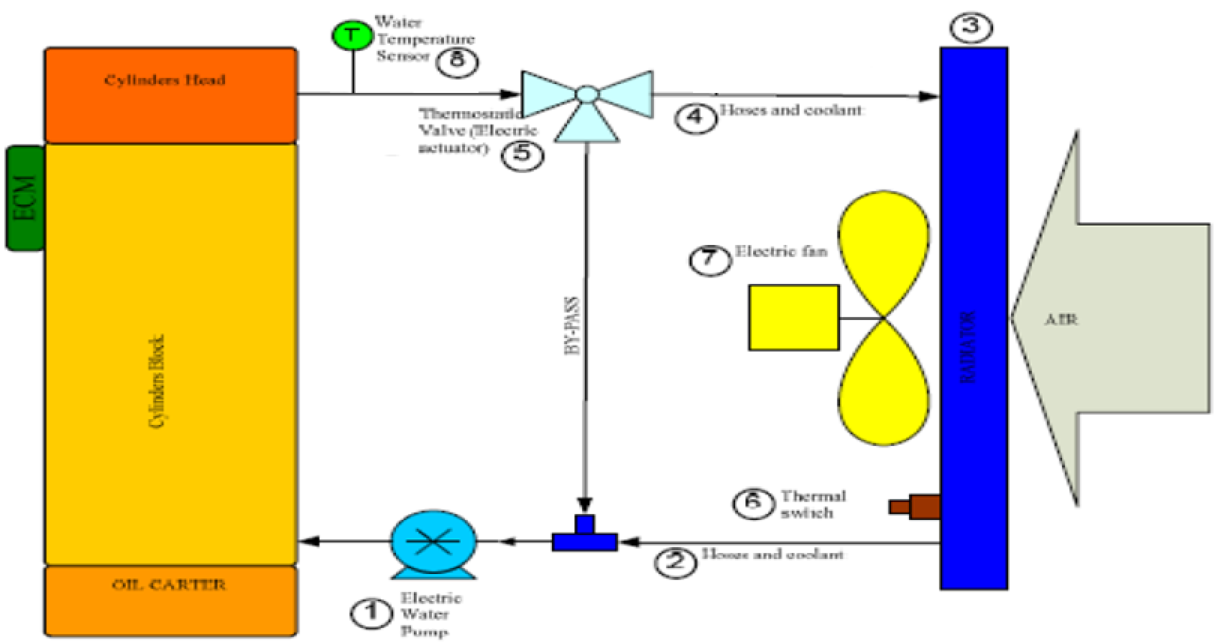


Figure 1: Engine Cooling System using Electric Water Pump [1]

The coolant is circulated through the engine block and cylinder head with the use of an electric water pump. As the coolant flows through these passages, it picks up heat from the engine. The heated fluid then makes its way through a rubber hose to the radiator in the front of the car. As it flows through the thin tubes in the radiator, the hot liquid is cooled by the air stream entering the engine compartment from the grill in front of the car. Once the fluid is cooled, it returns to the engine to absorb more heat and the process repeats.

A thermostat is placed between the engine and the radiator to make sure that the coolant stays above a certain preset temperature. If the coolant temperature falls below this temperature, the thermostat blocks the coolant flow to the radiator, forcing the fluid instead through a bypass directly back to the engine. The coolant will continue to circulate like this until it reaches the desired temperature, at which point, the thermostat will open a valve and allow the coolant back through the radiator [5].

Traditional cooling pumps were mechanical pumps driven by belts and hence their output was coupled to engine RPM. Nowadays, mechanical coolant pumps are becoming obsolete and are being replaced by electric pumps.

Electric pump offers complete flexibility over total coolant flow rate irrespective of engine operating conditions. Experimental studies have reported on the use of such devices [2], and numerical simulations have demonstrated the potential for reduced power consumption [3]. The problems with mechanical coolant pumps are well understood – they rotate in proportion to engine speed and not in proportion to heat rejection requirements [4]. Under the scenario of high-speed motorway cruising, the pump will be working unnecessarily hard even though the air-flow over the radiator will serve to aid cooling. This mode of operation can equate to the pump output only matching the required flow 5 per cent of the time [4].

Being able to vary the coolant flow has long been recognized as a means to reduce parasitic losses and therefore provide a potential fuel economy benefit as well as improve warm-up and cabin heater performance. Another advantage of electric water pump over mechanical ones is that there is no need to compromise hydraulic design as it is no longer linked to engine speed. Thus cavitation, a common problem in conventional arrangements can be avoided [3].

1.1.1 Faults inside Engine Cooling System and Need for Diagnosis

A failure is an event that occurs when a system does not behave according to its specification. Failures result from faults and errors. A fault is simply a latent defect or abnormal condition; a faulty component contains such a defect or is subject to such a condition. Faults can cause errors, which are anomalies in the internal state of a system [6].

It is important to regularly inspect the condition of engine cooling system. Soft hoses, cracked seal of the pump and hoses can have dire effects on the entire cooling system. Mineral deposits and sediments from corroded or malfunctioning parts accumulate in the cooling system and can affect the cooling efficiency of the cooling system. Moreover, there can be numerous faults associated with the components of the cooling system:

- Coolant temperature sensor reading may be 'erratic' or 'out of range' causing the coolant to be circulated through the radiator even when the engine is in its warming stage.
- The pump might be broken causing no circulation of the coolant.
- Faulty thermostat and radiator can affect the cooling efficiency of the cooling system.

Diagnosis of faults in engineering systems is the detection of a fault and determining where the fault is. Fault diagnosis is very important in vehicles as undetected faults may lead to several problems like:

- Engine overheating and its damage.
- Increased air emissions.
- Decreased fuel efficiency.
- Un-operational vehicle.
- High costs of repair.

1.2 Existing Methods of Vehicle Fault Diagnosis

Diagnostic or faultfinding is a fundamental part of an automotive technician's work. As vehicles continue to become more complicated, particularly in the area of electronics, the need for reliable vehicle diagnosis methods becomes even more important. Following are the Diagnostic methods most commonly used by the technicians at a workshop.

a. Use of Tools and Equipments

Diagnostic techniques are very much linked to the use of test equipment. In other words you must be able to interpret the results of tests. In most cases this involves comparing the result of a test to the reading given in a data book or other source of information [33]. Vehicle diagnosis at workshop may involve use of some of the following tools and equipments:

- Multi-meters
- Logic probe
- Pressure gauge and kit
- Ohm-meter
- Compression testers
- Engine analyzer
- Thermometer
- Gas analyzer

The reading shown by the above equipments are often compared to those given in a data book and a decision is made if the component under test is faulty or not. For example a coolant temperature sensor can be diagnosed by using an ohm-meter which is connected across the two terminals or, if only one, from this to earth. Most sensors have a negative temperature coefficient (NTC) in which the resistance falls as temperature rises. A resistance check should give sensor readings broadly as follows: 0°C = 4500Ω, 20°C = 1200Ω, 100°C = 200Ω [33]. A sensor which does not have these values of resistances corresponding to the mentioned temperature is considered to be faulty.

b. Oscilloscope Diagnostic Method

The oscilloscope is a graph-displaying device - it draws a graph of an electrical signal. In most applications the graph shows how signals change over time: the vertical (Y) axis represents voltage and the horizontal (X) axis represents time. The waveform displayed on the screen can be used to verify whether the component under test is faulty or not. For example a coolant temperature sensor can be diagnosed with an oscilloscope in the following way:

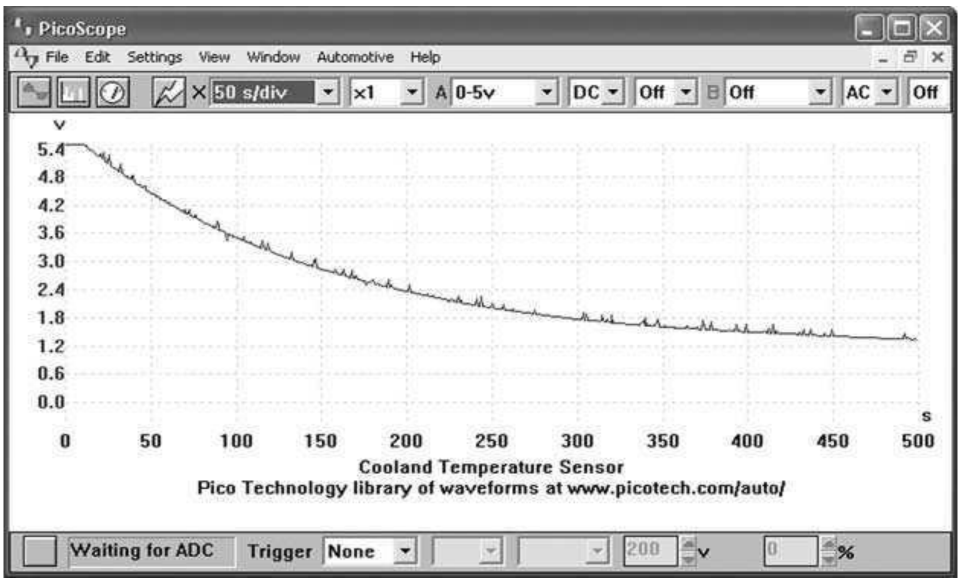


Figure 2: Decreasing voltage from the temperature sensor [33]

Most coolant temperature sensors are NTC thermistors; their resistance decreases as temperature increases. This can be measured on most systems as a reducing voltage signal. Figure 2 shows the graph of the voltage with time across a good working temperature sensor when the engine temperature is rising. As can be seen the voltage is decreasing linearly with temperature and any sensor which does not exhibit this linear rate of voltage change is considered to be faulty.

To perform this test on a vehicle, start its engine and connect an oscilloscope across the temperature sensor. In majority of the cases, the voltage will start in the region of 3 to 4 V and fall gradually depending on the temperature of the engine. If the sensor displays a fault at a certain temperature, the rate of voltage will be non-linear and the sensor may be considered to be faulty.

c. On-Board Diagnostic (OBD) System

To control emissions from overheating and other such issues, Air Resources Board (ARB) has developed On-Board Diagnostic (OBD) regulations which required automobile manufacturers to monitor emission control components on vehicles. Thus, all 1998 and newer light-duty vehicles are manufactured with an OBD system. The car manufacturers devised an electronic control system for the fuel supply and ignition devices, based on the standard [10], [11].

OBD systems are designed to monitor the performance of some of engine's major components including those responsible for controlling emissions. The OBD system detects the malfunctioning of vehicle components and illuminates dashboard "Check Engine" light if a fault is detected. By giving vehicle owners this early warning, OBD protects not only the environment but also consumers, identifying minor problems before they become major repair bills [34].

The OBD port can be found under the dashboard in the majority of current automobiles. It provides real-time access to a large number of vehicle status parameters. Furthermore, in case of malfunctions, Diagnostic Trouble Code (DTC) values are stored in the car ECM and can be later retrieved by maintenance technicians using proper hardware and software kits [12].

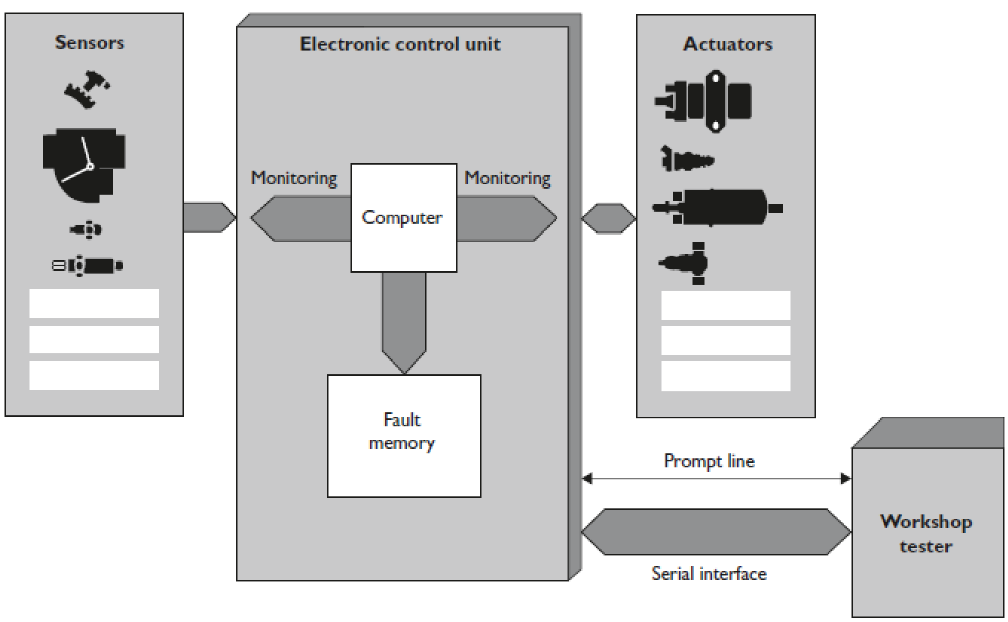


Figure 3: On Board Diagnostic (OBD) System for Fault Diagnosis [33]

OBD systems are intended to self-diagnose and report when the performance of the vehicle's emissions control systems or components have degraded. Figure 3 explains the setup of the OBD system having self diagnostic capability. When the fault occurs the system illuminates the MIL light and also stores a diagnostic trouble code (DTC) in its memory that can be used to trace and identify the fault. A service technician is able to connect a diagnostic scan tool that will communicate with the microprocessor and retrieve this information. This allows the technician to diagnose and rectify the fault. Example: A faulty coolant temperature sensor will have P0115 DTC code set with a description "Engine Coolant Temperature Circuit Malfunction" that will tell the technician that a coolant temperature sensor needs to be replaced. As vehicles and their systems become more complex, the functionality of OBD is being extended to cover vehicle systems and components that do not have anything to do with vehicle emissions control. Vehicle body, chassis and accessories such as air conditioning or door modules can now also be interrogated to determine their serviceability as an aid to fault diagnosis [33].

1.3 Objective and Motivation of the Project

The main objective of the project is to develop a simulink model of an engine cooling system for the purpose of detection of faulty components. Necessary mathematical equations are derived to represent an engine cooling system that is implemented in simulink. With specified input signals component data is collected from the simulink model of engine cooling system. The same input signals are used to collect faulty component data from the model and represent the faulty test vehicle. The two sets of data are compared to detect faulty component of engine cooling system.

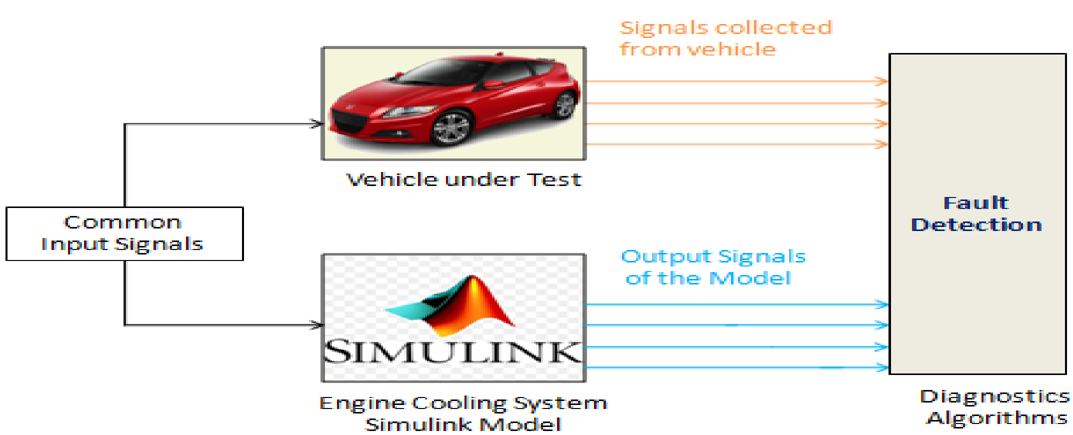


Figure 4: Methodology of the Proposed Method

Figure 4 shows the working of the proposed method for fault detection. With specified input signals, data from the engine cooling components i.e. sensor, pump and thermostat is collected from the vehicle under test. The same input signals are used for the Engine Cooling System Simulink model and simulation data are collected. Diagnostic algorithm compares the component's data from the vehicle to that generated by the simulink model and indicate a fault if large deviations are found.

The methods for doing fault detection and diagnosis on vehicles at a workshop may require several engineering hours of laboratory work and use of expensive tools and equipments. The process is so costly that no manufacturer builds on-board error detection software for all possible errors that can occur on a vehicle. Only the most important malfunctions are included in the on-board-Diagnostic tools. Also, the on-board computers are insufficient for running all Diagnostic tools [13]. Test engineers are always looking for cost effective and less time consuming methods for fault diagnosis. In this project report, another method of fault detection is discussed which has the following advantages over other methods:

1. Manual testing of vehicle using diagnostic tools is no longer required. Fault detection Algorithm can do that job.

2. Matlab generated graphs give a clear picture of the expected and actual behavior of engine cooling components, thereby enabling the detection of multiple faulty components.

3. Speeds up fault detection and isolation.

4. The purchases of cost intensive diagnostic tools and equipments are no longer necessary.

5. No knowledge of Diagnostic Trouble Codes (DTCs) for troubleshooting the vehicle problem is required.

6. The simulation results from many test data files can be used as records for any future use.

1.4 Outline of Project Report

The report can be divided into the following main parts:

In chapter 2, appropriate mathematical equations are derived that is used to build Simulink sub-models of engine cooling components (radiator, fan, electric pump and ECM). These sub-models are assembled together into an engine cooling system simulink model.

In chapter 3, the common faults that might occur in the components of engine cooling system are discussed. These faults lead to engine overheating resulting in higher vehicle emissions. Their effects on heat transfer rate and engine temperature are also talked about.

In chapter 4, a method for fault diagnosis of engine cooling components is proposed. It is based on comparing the signals from a test vehicle to those generated by the simulink model. Appropriate diagnostic algorithm is written that compares data from a healthy and faulty system and indicates the presence of a faulty component if large deviations are found. Since there are no test vehicles available, the signals from the test vehicle are generated using the simulink model with the faulty component.

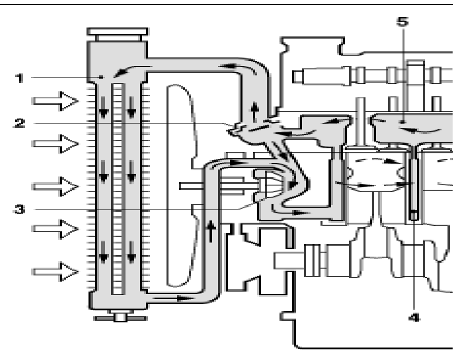
In chapter 5, the conclusion and the future work of the proposed method is presented.

Chapter 2. Engine Cooling System in Simulink

In Simulink, it is easy to symbolize and simulate a mathematical model representing a physical system. Models are presented graphically as block diagrams available in Simulink libraries. The mathematical equations governing an engine cooling system that serves as the basis for a Simulink model is derived from physical laws. Mathematical sub-models for each of the engine cooling system component (radiator, fan, pump and ECM) are designed and then assembled together into an engine cooling system model.

2.1 Representation of Radiator in Simulink

The radiator is the component responsible for making the exchange of heat from the engine coolant to the air passing by flippers and is shown in figure 5. 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.



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

Figure 5: Cooling system showing the circuit passing through the liquid [19].

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 pipes in the engine block; when the working temperature of the engine is reached (95° C - 100° C) the fluid begins to circulate, goes through the radiator which together with the fan, cool the engine.

2.1.1 Heat Transfer Equations inside Radiator

Heat transfer occurs whenever there is a temperature difference between two or more media. Three main mechanisms of heat transfer exist, conduction, convection, and radiation. The modes of conduction and convection are responsible for dispersing the buildup of heat produced during combustion through the engine. Similarly, it can be seen that through conduction and convection the heat is transferred to the cooling coolant. Finally these two processes explain the cooling effect of flowing ambient air and its interaction with the radiator core to redistribute generated heat from the system to the passing airflow [14]. The symbols used in the design of radiator model in simulink are given in table 1 below.

Symbol	**Description**	**Units**
c_p	Specific heat capacity	Jk/(gK)
m	Mass of coolant	kg
$\dot{m}$	Coolant mass flow rate	Kg/s
$\dot{Q}_{c-s}$	Convection heat transfer rate from the coolant to inner wall	W/s
$\dot{Q}_{s-s}$	Conduction heat transfer rate through the radiator wall	W/s
$\dot{Q}_{s-a}$	Conduction heat transfer rate from the radiator wall to the air	W/s
$\dot{Q}_{total}$	Total heat transfer rate from the coolant to the air	W/s
T_i	Engine coolant temperature	K
T_o	Coolant outlet temperature	K
T_s	Outside air temperature	K
U	Heat transfer coefficient	$W/(m^2K)$
A_t	Cross section area of radiator tube	m^2
A_r	Area of the radiator	m^2

Table 1: Symbols used in the design of Radiator Model

The heat loss via the radiator cooling system can be expressed as the temperature difference between the engine outlet and engine inlet points, where the engine outlet temperature is assumed to be the same as the engine coolant temperature. $\dot{Q}_{total}$ *is* $\frac{dQ}{dt}$ is the total heat transfer rate from the coolant to the air and is calculated by [15],

$$\dot{Q}_{total} = \dot{m}\, c_p (T_i - T_o), \tag{1}$$

where $\dot{m}$ is $\frac{dm}{dt}$ given by coolant mass flow rate, c_p is specific heat capacity, T_i is engine coolant temperature and T_o is radiator outlet temperature.

Heat energy transferred between a surface and moving fluid at different temperatures is known as convection. The heat transfer per unit surface through convection was first described by Newton and the relation is known as the Newton's Law of Cooling. $\dot{Q}_{c-s}$ is convection heat transfer rate from the coolant to inner wall and is given by,

$$\dot{Q}_{c-s} = U\, A_r\, (T_o - T_s), \tag{2}$$

where U is heat transfer coefficient, A_r is area of the radiator and T_s is outside air temperature.

Heat energy transferred between the two surfaces having different temperatures is known as conduction. The amount of heat transferred between the walls of the radiator tube is very small and therefore neglected. $\dot{Q}_{s-s}$ is heat loss rate by conduction through the radiator wall and is given by,

$$\dot{Q}_{s-s} \approx 0. \tag{3}$$

For the time interval dt, heat transferred out of radiator surface is equal to decrease in energy through the radiator surface. The relation between the heat transferred to outside air and the temperature decrease is given by,

$$dQ = m\, c_p\, dT_o, \text{ or } \frac{dQ}{dt} = m\, c_p \frac{dT_o}{dt},$$

where dT_o is the change in temperature of the coolant coming out of the radiator.

$\dot{Q}_{s-a}$ is conduction heat transfer rate from the radiator wall to the air and calculated by,

$$\dot{Q}_{s-a} = mc_p \frac{dT_o}{dt}. \quad (4)$$

Using the law of energy balance, the following equation is obtained,

$$\dot{Q}_{total} = \dot{Q}_{c-s} + \dot{Q}_{s-s} + \dot{Q}_{s-a}. \quad (5)$$

After putting equations (1), (2), (3) and (4) into equation (5) and solving we have,

$$\dot{m}c_p(T_i - T_o) = UA_r\,(T_o - T_s) + m\,c_p \frac{dT_o}{dt}. \quad (6)$$

Rearranging equation (6), we have [16],

$$mc_p \frac{dT_o}{dt} = \dot{m}c_p\,(T_i - T_o) + UA_r\,(T_s - T_o),$$

After rearranging further, we have,

$$\frac{dT_o}{dt} = \{\,\dot{m}c_p\,(T_i - T_o) + UA_r\,(T_s - T_o)\}/mc_p. \quad (7)$$

2.2 Representation of Fan in Simulink

Newton's Law of cooling states that the heat flow between an object and its surrounding environment can be characterized by a heat transfer coefficient h. $\dot{Q}_N$ is heat flow rate and is calculated by,

$$\dot{Q}_N = hA\,(T_s - T_o), \quad (8)$$

where h is heat transfer coefficient, $W/m^2\,K$, A is cross sectional area of surface, m^2, T_s is environment air temperature, °C and T_o is coolant temperature, °C at any given time.

According to first law of thermodynamics, the change in energy with the change in air temperature is given by $\dot{Q}_T$. It is net heat flow to the outside air, joules/s and given by,

$$\dot{Q}_T = \rho c_v V \frac{d(T_s - T_o)}{dt} , \qquad (9)$$

where ρ is air density (kg/m^3), c_v is specific heat of air (kJ/kgC) and V is air volume (m^3).

For the case where the net heat flow is zero, Newton's Law of Cooling and the First law of Thermodynamics, equations (8) and (9), can be equated and given by,

$$hA\,(T_s - T_o) = \rho c_v V \frac{d(T_s - T_o)}{dt}. \qquad (10)$$

The solution of the above equation is given by,

$$\ln\,(T_o - T_s) = -\frac{t}{\tau} + C , \qquad (11)$$

where ln(.) is the natural logarithm function and

$$\tau = (\rho c_v V)/\,(hA),$$

where τ is the time constant.

The constant C can be found by putting time t equal to 0 in equation (11),

$$C = \ln\,(T_i - T_s), \qquad (12)$$

where T_i is initial coolant temperature, i.e. when time t is 0.

Substituting equation (12) into (11), and simplifying, we have,

$$\frac{T_o - T_s}{T_i - T_s} = \exp\left(-\frac{t}{\tau}\right). \qquad (13)$$

After solving equation (13) for T, following equation is obtained,

$$T_o = T_s - (T_s - T_i)\,\{\exp\,[(-h*A)/\,(\dot{m}*c_v)]\}, \qquad (14)$$

where ṁ is air mass flow rate.

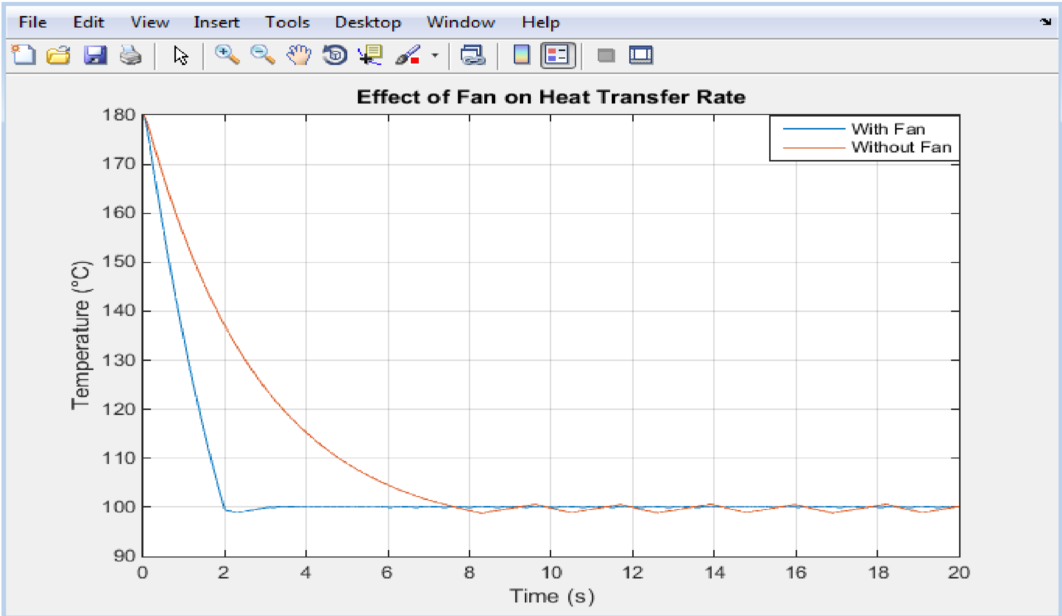


Figure 6: Effect of Fan on Heat Transfer Tate

Figure 6 shows the comparison of heat transfer rate inside the engine cooling system with and without the fan present. The coolant temperature which is the same as engine temperature is set to be at 180 °C. It can be seen that the presence of a fan improves the heat transfer rate and helps in achieving the desired temperature much quicker, set to be at 100 °C. The variable responsible for change is ṁ which the air mass flow rate.

2.3 Heat Generated by Combustion inside the Engine

The flow rate ($\dot{m}_t$) of air passing the throttle valve is calculated by [36],

$$\dot{m}_t = \mu_t\,(\theta_t)\ .\ A_t\,.\frac{P_a}{\sqrt{RT}}\,.\ \Phi\,(\frac{P_m}{P_a})\ , \tag{15}$$

where $\mu_t\,(\theta_t)$ is a flow coefficient at the throttle valve, A_t is an opening cross sectional area of the throttle valve, Θ_t is an opening angle of the throttle valve, P_a is a pressure of an atmosphere around the engine and $\Phi(\frac{P_m}{P_a})$ is a function using $\frac{P_m}{P_a}$ as a variable, R and T are gas constant and gas temperature respectively.

$\mu_t\ (\theta_t)$ is given by [37],

$$\mu_t\ (\theta_t) = 2.821 - 0.05231*\theta_t + 0.10299*\theta_t\text{^}2 - 0.00063*\theta_t\text{^}3, \quad (16)$$

P_a is constant atmospheric constant and is given by [37],

$$P_a = 1. \quad (17)$$

Pm is manifold pressure and is given by [37],

$$P_m = RT/V_m \int (\dot{m}_t - \dot{m}_{tc})\ dt, \quad (18)$$

where V_m is manifold volume, $\dot{m}_{tc}$ is mass flow rate of air out of the manifold given by [37],

$$\dot{m}_{tc} = -0.366 + 0.08979NP_m - 0.0337NP_m{}^2 + 0.0001N^2P_m\ , \quad (19)$$

where N is engine speed and P_m is manifold pressure.

A_t depends on the subtraction of Pm from Pa and based on this difference value [37],

$$\left.\begin{array}{l} A_t = 1;\ \text{if}\ (P_a - P_m) > 0, \\ A_t = -1;\ \text{if}\ (P_a - P_m) < 0, \\ A_t = 0;\ \text{if}\ (P_a - P_m) = 0. \end{array}\right\} \quad (20)$$

$\Phi(\frac{P_m}{P_a})$ is calculated by the following equation [37],

$$\Phi(\frac{P_m}{P_a}) = 2*\text{sqrt}(\frac{P_m}{P_a} - (\frac{P_m}{P_a})\text{^}2). \quad (21)$$

To calculate the total amount of heat from combustion Q_{cool} , Btu/s (1 Watt = $9.4*10^{-4}$ Btu/s), the following formula is used [38],

$$Q_{cool} = \dot{m}_t\ (LHV - H_{evap}), \quad (22)$$

where LHV is lower heating value of fuel, Btu/lb and H_{evap} is the evaporation heat of fuel, Btu/lb. Both are fuel characteristics and don't need to be measured by the ECM. They are calibration constants.

Equation (22) is solved using equations (15) to (21) to obtain Q_{cool}. Figure 7 (left) shows the amount of heat generated from combustion (Q_{cool}) for the flow rate passing through the throttle valve.

The equation for the heat flow to the coolant, T_{cool} is given by [38],

$$T_{cool} = T_s + \frac{1}{c_p} . Q_{cool} \ , \qquad (23)$$

where c_p is the heat capacity of the material.

After putting equation (22) into (23), T_{cool} is obtained and figure 7 (right) shows the heat flow to the coolant, T_{cool}.

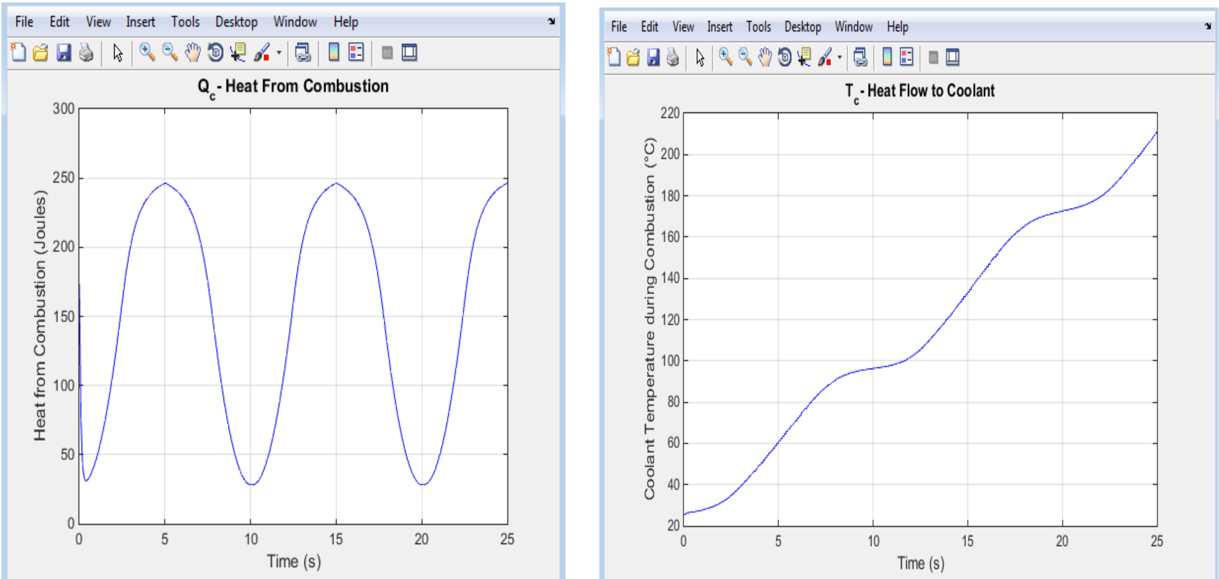


Figure 7: Heat from combustion (left) and Heat Flow to Coolant (right)

2.4 Representation of an Electric Water Pump in Simulink

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 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 [17].

Several motor concepts were considered to drive the water pump:

- Switched Reluctance Motor: The switched reluctance motor is a type of a stepper motor that runs by reluctance torque. This type of machine will have a lower construction cost and three -phase winding type would also provide a ‘limp home’ facility with one phase disabled [3].
- Brushless DC Motor: Brushless DC electric motor (BLDC motors) is synchronous motor that is capable of providing large amounts of torque over a vast speed range. A BLDC motor is highly reliable since it does not have any brushes to wear out and replace. Compared to switched reluctance, this type of machine runs quietly under all speed conditions, with improved response times due to high torque and low rotor inertia [3].

BLDC motor is used to rotate the coolant inside the cooling system. The velocity of flow of coolant is dependent on the angular velocity of rotation of pump’s impeller driven by dc motor. It is given by the relation w*r, where w is angular velocity of rotation of impeller and r is radius of impeller. For the design of the pump, its angular velocity and radius of impeller is set to be 350 rad/s and 0.001 m respectively. This gives velocity of the flow of coolant equal to 0.35 m/s.

2.4.1 Modeling DC Motor

Mathematical model is a description of the behavior of a system using mathematics [18]. A separately excited DC motor is used as a plant to the control system. There are two methods that can be used to control the speed of a separately excited DC motor. The famous method of armature voltage control has advantage to retain maximum torque capability while the other method of field flux control will reduce maximum torque capability [19]. Symbols used in the design of dc motor are given in table 2.

Symbol	**Description**	**Value**
k_m	Torque constant	0.0502 Nm/A
R_m	Terminal resistance	10.6 ohm
L_m	Terminal Inductance	0.82 mH
J_{eq}	Total moment of inertia	2.21 X 10^{-5} kg m^2

Table 2: Symbols used in the design of dc motor

The transfer function of dc motor is given by the equation [20],

$$G(s) = \frac{P_{dot}}{V(s)} = \frac{k_m}{L_m \; J_{eq} \; s^2 + R_m \; J_{eq} \; s + {k_m}^2} \;\; , \tag{24}$$

where k_m is torque constant, R_m is terminal resistance, L_m is terminal inductance and J_{eq} is total moment of inertia. After some approximations [20],

$$G(s) = \frac{{k_m}^{-1}}{(R_m \; J_{eq} \; {k_m}^{-2} \;)s + 1} \;\; . \tag{25}$$

This gives,

$$G(s) = \frac{K}{\tau s + 1} \;\; , \tag{26}$$

where K is ${k_m}^{-1}$ and τ is $R_m \; J_{eq} \; {k_m}^{-2}$.

By putting the parameter values from table 2 in equation (26), we have,

K= 19.9 rad/Vs, $\tau = \; 0.0929$ s .

Therefore, the transfer function of the DC Motor is given by [20],

$$G(s) = \frac{19.9}{0.0929s + 1} \;\; . \tag{27}$$

In designing the dc motor of the electric pump inside a car, it is assumed that the same dc motor is used as the one used in ELEC 360 labs at University of Victoria.

2.4.2 Modeling PI controller

Control objectives focus on the transient behavior of the system such as to produce a zero steady state error, a fast transient response to a step command, a short settling time and low overshoot. It is also desirable to make the system less sensitive to disturbance [19]. Proportional-Integral-Derivative (PID) control is the best-known controller in industries. This scheme offers simple structure as well as robust performance.

For DC motor drive purpose, the use of two term controller so called PI controller is sufficient for best performance [19]. According to [21] the use of derivative term for motor drive which equipped with DC/DC converter is unnecessary as some signals will have discontinuities or ripple that would result in spikes when differentiated.

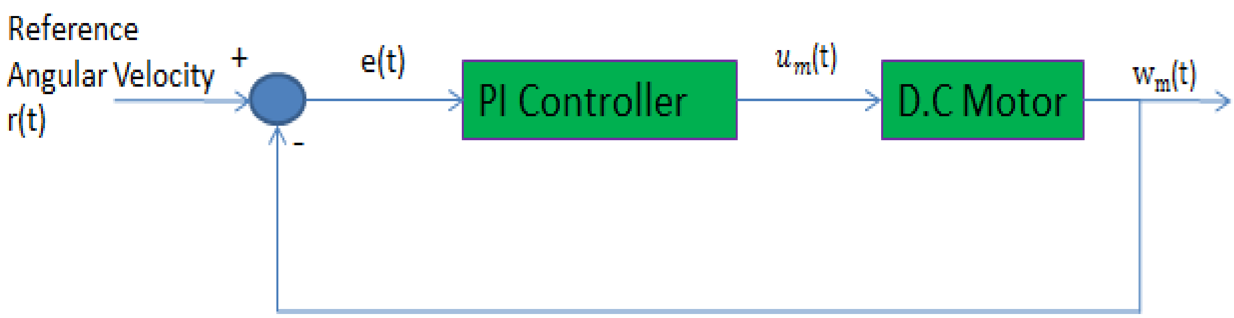


Figure 8: Speed Control of DC motor

From figure 8, the error signal is given by,

$$e(t)= r(t) – w_m(t). \tag{28}$$

The control signal is given by,

$$u_m(t) = k_p(r(t) - w_m(t)) + k_i \int_0^t (r(\tau) - w_m(\tau))d\tau \ , \tag{29}$$

where r(t) is reference signal, w_m (t) is output angular velocity, k_p is proportional gain and k_i is integral gain.

Ziegler and Nichols proposed rules for determining values of the proportional gain k_p, integral time T_i, and the derivative time T_d based on transient response characteristics of a given plant [22]. For the Ziegler-Nichols Frequency Response Method, the critical gain, k_{pc} and the critical period T_{pc} have to be determined first by setting the T_i and T_d equal to 0. Increase the value of k_p from 0 to a critical value at which the output first exhibits sustained oscillation [22]. The table3 below shows Ziegler Nichols controller gains obtained in ELEC 360 lab session at University of Victoria.

Description	Symbol	In – Lab Result	Units
Properties of PI Control			
Critical Proportional gain	k_{pc}	0.4	V.s /rad
Critical period of k_{pc}	T_{pc}	0.09	s
Ziegler – Nichols Design			
Proportional gain	k_p	0.16	V.s/rad
Integral gain	k_i	2.22	V/rad

Table 3: Ziegler - Nichols Controller Gains [20].

Therefore, the transfer function of the PI controller is given by [20],

$$G_{PI}\ (s) = 0.16 + (2.22/s). \quad (30)$$

2.5 Representation of ECM in Simulink

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 9 below 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) [1].

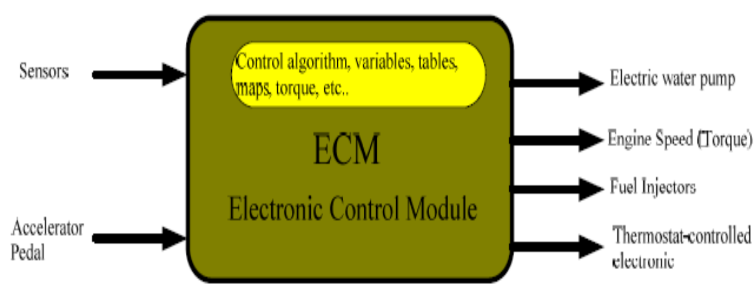


Figure 9: Illustration of functional electronic engine control module (ECM) [1].

Vehicle cooling systems typically have a coolant temperature sensor for providing coolant temperature information to the electronic engine controller and a thermostat for providing constant coolant temperature control [23]. Therefore, the Simulink model of ECM is designed which takes temperature information from the coolant temperature sensor and control the working of the thermostat, pump and the fan.

a) Water Temperature Sensor

The water temperature sensor comprises thermistors 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 [1].

The sensor reports the temperature of the engine to the ECM. Based on this input, the ECM controls the working of the electric pump, the thermostat and the electric fan.

b) Electric Pump

The water pump is considered the ‘heart’ of the cooling system. It is responsible for circulating the hot coolant from the engine to the radiator and the cooled coolant back to the engine. The water pump has fan-like blades on an impeller that spins, creating centrifugal force, moving the liquid outward. The motion of the electric pump is controlled by the ECM based on the engine temperature. When the engine temperature is low (<100°C), the ECM commands the pump to move at a lower speed. However, when the engine temperature is high (>100°C), the ECM commands the pump to move at full speed.

c) Thermostat

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. 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. [1].

The working of thermostat is controlled by the ECM based on the engine temperature. When the engine temperature is low (<100°C), the ECM closes the thermostat to enable the engine achieve its operating temperature quickly. However, when the engine temperature is high (>100°C), the ECM opens the thermostat fully to allow the hot coolant to reach the radiator.

d) Electric Fan

Electric fan 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) [1].

The working of electric fan is controlled by the ECM based on the engine temperature. When the engine temperature is low (<100°C), the ECM shuts off the fan as the coolant is not flowing through the radiator. However, when the engine temperature is high (>100°C), the ECM turn on the fan to intensify the heat transfer rate of the coolant flowing through the radiator.

2.6 Model of an Engine Cooling System in Simulink

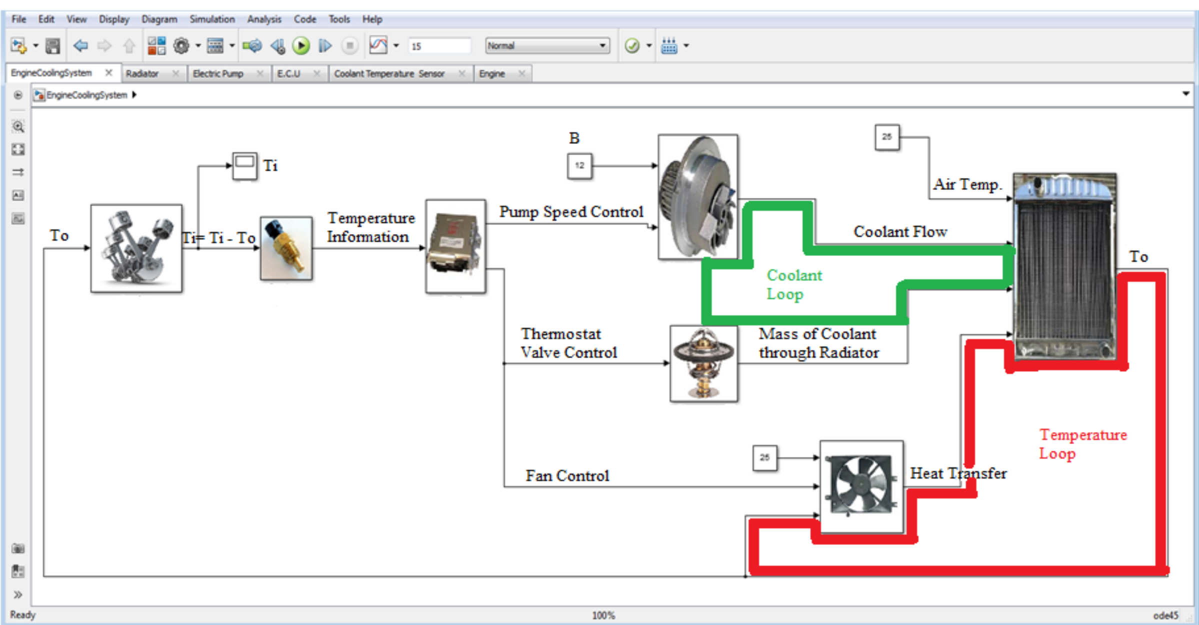
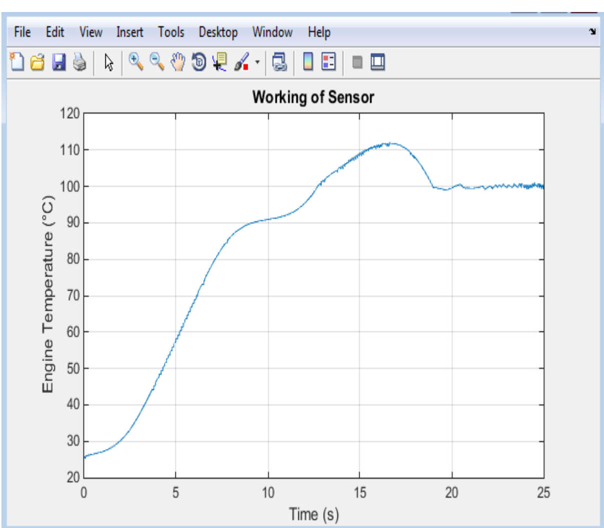
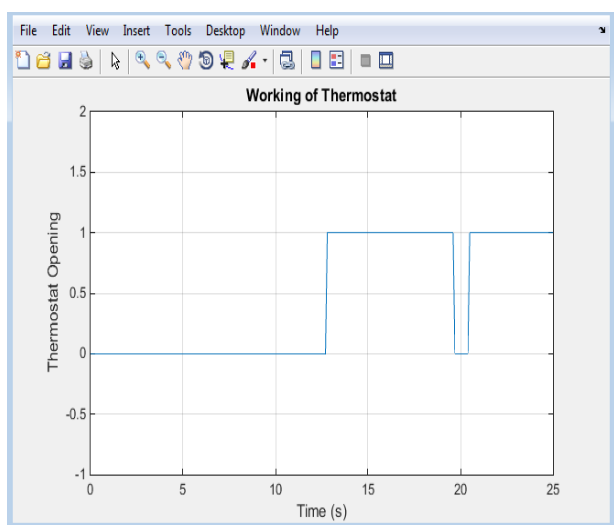


Figure 10: Engine Cooling System in Simulink

Figure 10 shows the model of an Engine Cooling System in Simulink. It contains an engine where the heat is generated and added to the coolant, a temperature sensor to record the engine temperature, ECM to control the cooling of the system, a water pump to circulate the coolant inside the engine cooling system, a thermostat to regulate the flow of the coolant to the radiator and a radiator with an electric fan to dissipate heat from the coolant. The black lines in the figure are the input and output signals of the components. The red line shows the coolant temperature loop (where the heat is dissipated) and the green line show the coolant flow loop (pump to radiator).

The model contains an ECM which controls the working of the pump, the thermostat and the fan based on the engine temperature. During engine warm up phase, the ECM closes the thermostat completely by-passing the coolant back again to the engine to help achieve its desired working temperature quickly. The ECM also makes the pump move at a slower speed to save energy consumption. However, when the engine temperature becomes high (more than 100°C), ECM opens the thermostat valve to its fullest, increases the speed of pump to its maximum value and switches on the electric fan. This control of the engine cooling by ECM helps in keeping a precise engine temperature and decreases air emissions.





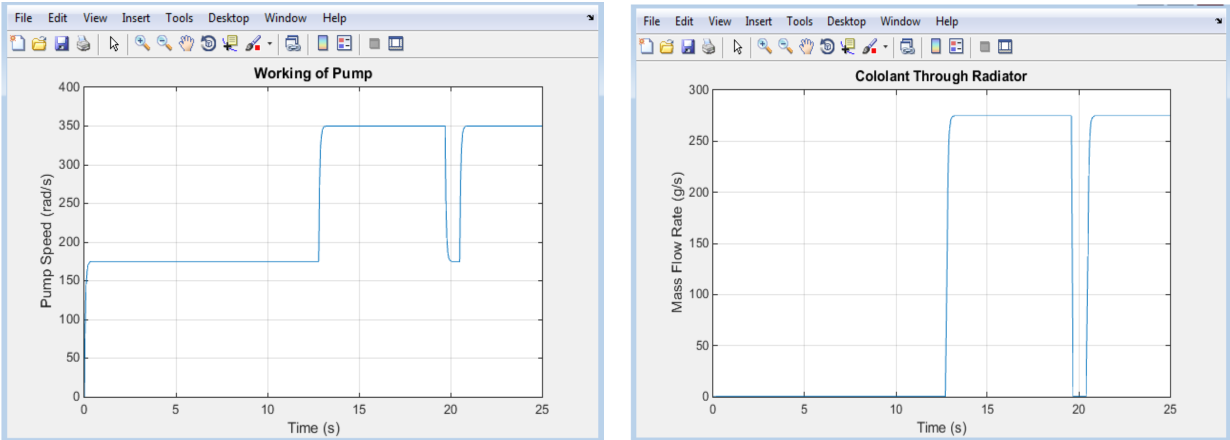


Figure 11: Working of Engine Cooling System in Simulink

Figure 11 shows the working of engine cooling components in simulink. The top-left graph shows the engine temperature kept at the desired temperature of 100°C by the cooling system. During engine warm-up phase the engine temperature is low, so the thermostat is closed to allow all the coolant to reach the engine block. This can be confirmed from the top-right graph which shows the thermostat opening to be zero until the engine temperature reaches 100°C. During this time the water pump is moving at half of its maximum speed (bottom-left graph) to circulate coolant inside the engine. As the engine begins to heat up, its temperature rises and when it becomes greater than 100°C, the ECM opens the thermostat to allow the coolant to go through the radiator. The pump begins to move at its full speed and the fan is turned on to maximize the engine cooling. Thermostat opening and pump speed increases the coolant flow rate through radiator (bottom-right graph). Every time the engine temperature falls below 100°C, the thermostat is closed and the pump speed is reduced to allow the engine to maintain the same operating temperature.

2.7 Conclusion

In this chapter, simulink models of engine cooling components i.e. radiator, fan, sensor are developed by using thermodynamic laws, Newton's law of cooling and other mathematical equations. These component models are assembled together to form an engine cooling system model. The designed model uses a coordinated control strategy to regulate the engine coolant temperature. The working of each of the engine cooling components and their ability to regulate and maintain the desired engine temperature is shown with the help of simulink graphs.

Chapter 3. Faults Causing Engine Overheating

3.1 Introduction

Overheating is a condition of an automotive engine in which the operating temperature of the engine is more than the normal typical range of operating temperature. [24] and [25] [26] identified causes of overheating as a result of improper operation or maintenance such as engine or parts specification inadequate to perform the job at the local climate, defective thermostat, defective water pump, defective radiator etc. This can result to seizure of piston movement in the engine, burning of head gaskets, damage to engine parts or complete knocking of the engine during operation.

Controlled removal of heat is necessary to maintain a definite temperature state of engine parts at different regimes and service conditions of the engine, thereby ensuring the attainment of maximum power, efficiency and longevity of the engine at all operating conditions [27] and [28]. Overheating can be caused by anything that decreases the cooling system's ability to absorb, transport and dissipate heat. A low or zero coolant level due to a coolant leak (through internal or external leaks), a defective thermostat that doesn't open or closes, an eroded or loose water pump impeller, defective coolant temperature sensor or radiator could be the possible causes of fault that may lead to engine overheating. In this project report, faults associated with the coolant temperature sensor, coolant pump and the thermostat are explored.

3.2 Faults in Coolant Temperature Sensor

The coolant temperature sensor is a device responsible for measuring the temperature of the internal combustion engine and sharing its data reading with the engine control module. If the sensor is faulty, one might notice that the water temperature needle:

a. Moves Up into the Red Area when driving [29]. (Temperature is always rising)
b. Indicates Overheating Just after Starting off [29]. (Temperature Increases as a Step function)
c. Position Fluctuates When Driving [29]. (Erratic Temperature Reading)
d. Never moves when driving and is always constant.

If the engine coolant temperature sensor is not indicating actual coolant temperature, emissions, fuel efficiency and driver satisfaction will be degraded [23]. Faults inside the coolant temperature sensor may arise due to wiring faults, loose or corroded connectors, a crack in the sensor, coolant leaks around the sensor, etc. Abnormally high engine temperatures can also damage the sensor. Without accurate input data, the ECM may not make the correct command decisions for driving the pump, the thermostat and the electric fan. This, in turn, can cause emissions, performance and drivability problems with a vehicle.

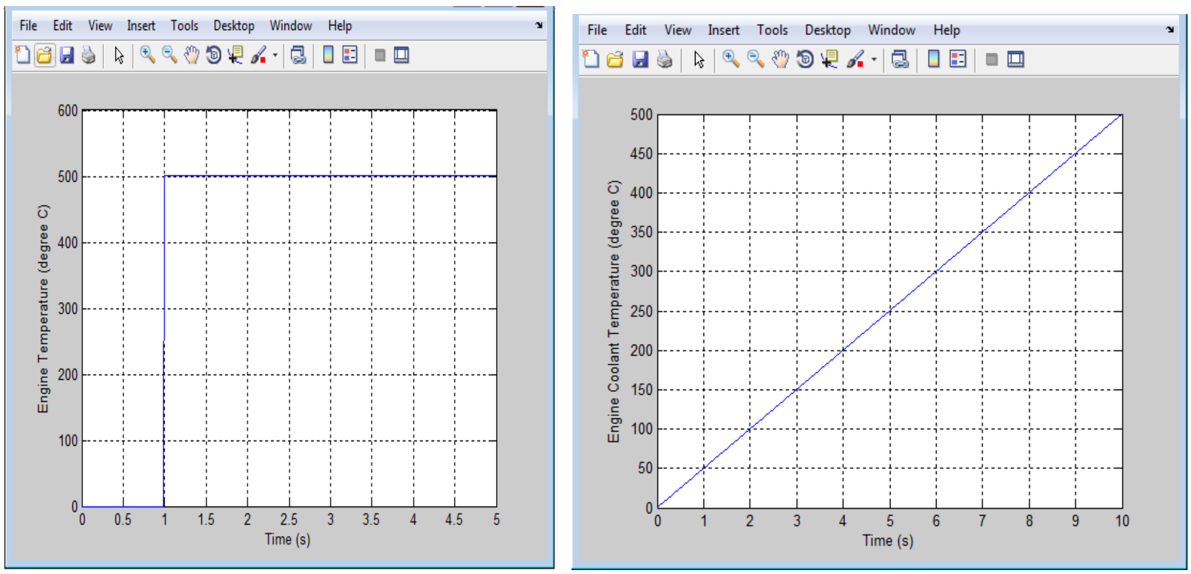


Figure 12: Faulty Sensor Curves - Temperature rises as step (left) and Temperature always increases (right) - Type of Fault- Reading out of Range

Figure 12 shows a faulty sensor when its reading rises to a very high value. This type of fault falls under the category 'reading out of range'. This fault type may cause the pump, the thermostat and the electric fan to be 'on' forever even when there is no requirement for cooling. The un-necessary working of engine cooling components will negatively impact the fuel economy of a vehicle as energy is wasted to drive these components. Moreover, the engine is working below its optimum range of temperature further decreasing fuel efficiency of a vehicle.

The other case of a faulty sensor is that when it always shows a 'zero reading'- even when the engine is running for a long time. This type of sensor fault might falsely keep the pump, thermostat and electric fan 'off' when there is a requirement of cooling. This may lead to engine overheating and damage the rings, pistons and/or rod bearings inside it.

Other possible faulty sensor is an 'erratic' type. An erratic sensor is a sensor whose reading changes continuously with time. Figure 13 shows the case of an erratic sensor. Here, the sensor reading is continuously varying between 0 and 200 °C.

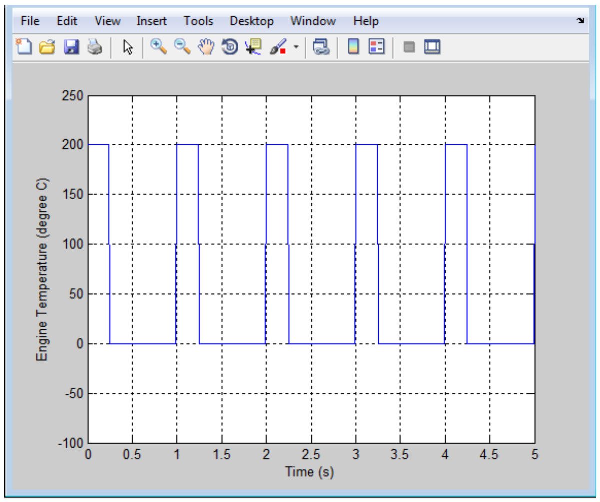


Figure 13: Faulty Sensor Curves- Erratic Temperature Reading

Figure 12 shows the temperature reading of the sensor when it is erratic. Since the thermostat is set at 100 °C, whenever the temperature rises above 100°C, the pump is turned full on and whenever it falls below 100°C, the pump speed is reduced. This leads to the situation where the pump is continuously varying its speed based on an erratic temperature reading. This may damage the pump and lead to higher consumption of energy. The similar effects could be noticed with the thermostat and the electric fan. Thus, an erratic coolant temperature sensor may also lead to frequent engine overheating and the damage of other components.

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3.3 Faults in Coolant Pump

The pump circulates the coolant between the engine and radiator to keep the engine from overheating. Inside the pump is a metal or plastic impeller with blades that pushes water through the pump. The impeller is mounted on a shaft that is supported by the pump housing with a bearing and seal assembly.

Following are the faults associated with the water pump:

a. The pump is severely damaged and thus does not move at all.
b. The impeller vanes are badly eroded due to corrosion or the impeller has come loose from the shaft. (Pump is working with low efficiency)

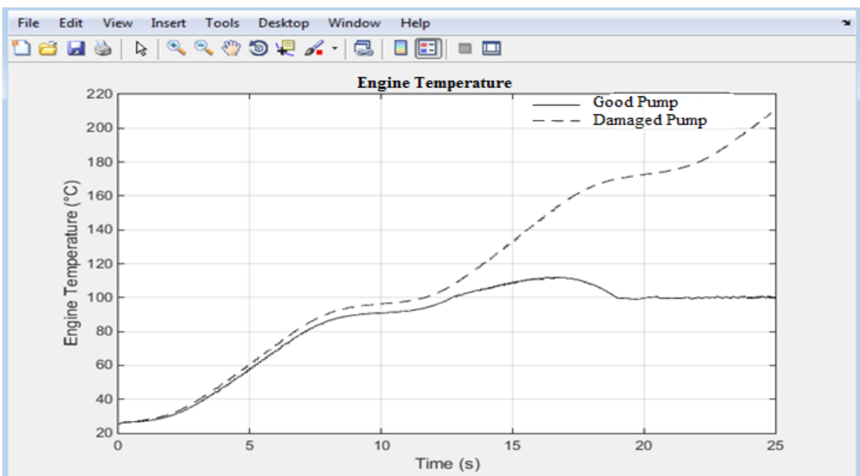


Figure 14: Effects of damaged pump on engine temperature

Figure 14 shows the engine temperature when the pump is damaged and does not move at all. Solid line is the engine temperature with a good pump in the cooling system and dashed line is engine temperature with a damaged pump in the cooling system. Since the pump does not move there is no circulation of coolant inside the engine cooling system and hence no heat dissipation. This causes the engine temperature to rise considerably and reach more than 200°C. Thus a damaged pump might lead to engine overheating causing engine damage and high vehicle emissions.

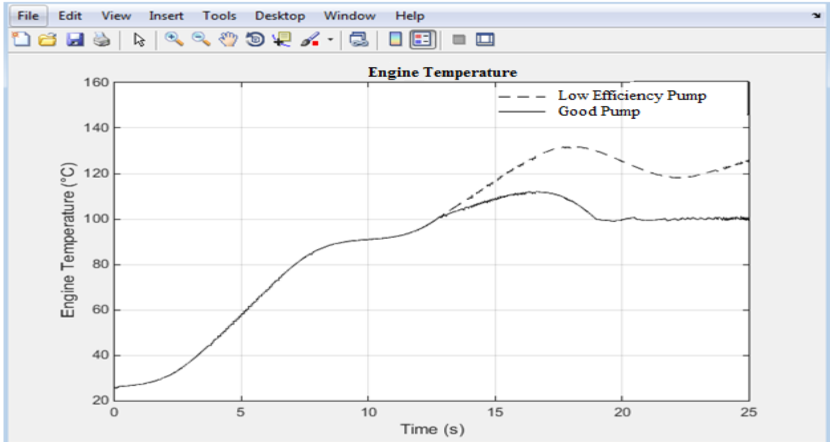


Figure 15: Effects of low efficiency pump on engine temperature

Figure 15 shows the engine temperature when the pump is working with a low efficiency. Solid line is the engine temperature with a good pump in the cooling system and dashed line is engine temperature with a damaged pump in the cooling system. A less efficient pump has very little impact on engine temperature during engine warm-up phase. However, when the engine temperature becomes higher, the less efficient pump fails to dissipate heat as desired and the engine temperature becomes more than 100°C. Thus, a low efficiency might lead to higher vehicle emissions as the engine is not working at its optimum working temperature.

3.4 Faults in Thermostat

The thermostat is responsible for controlling the operating temperature of the engine. When a cold engine is started, the thermostat remains closed until the coolant gets hot. Similarly, when the engine begins to overheat, the thermostat opens itself to allow hot coolant reach the radiator.

Following are the faults associated with thermostat:

a. The thermostat is stuck closed
b. The thermostat is stuck open

If the thermostat does not open once the coolant reaches a certain temperature, engine may overheat. Also, if the thermostat is stuck open, the engine will not heat up properly, a rich fuel-air mixture may be supplied longer than necessary, thus potentially degrading emissions and fuel efficiency [23].

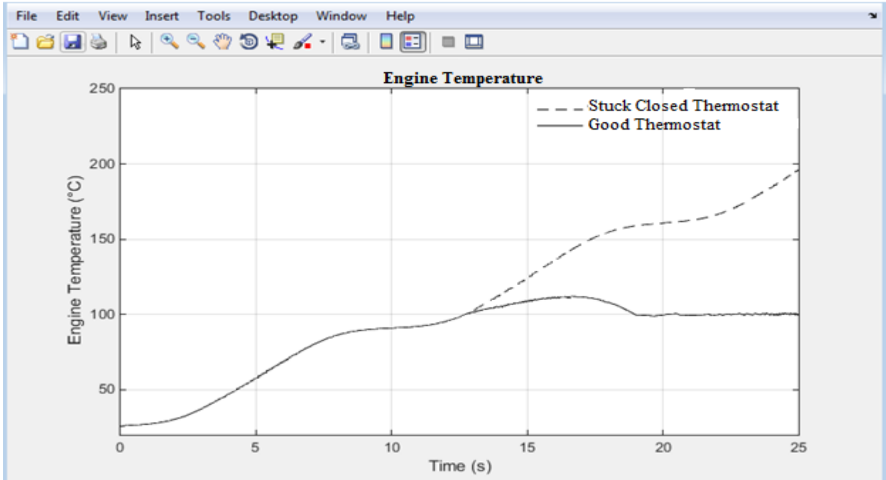


Figure 16: Effect of Stuck Closed Thermostat on Engine Temperature

Figure 16 shows the effect of a stuck closed thermostat on engine temperature. Since the thermostat is always closed, it blocks the flow of coolant to the radiator and thus no heat dissipation takes place. This leads to rapid heat build up inside the engine causing engine overheating and its damage.

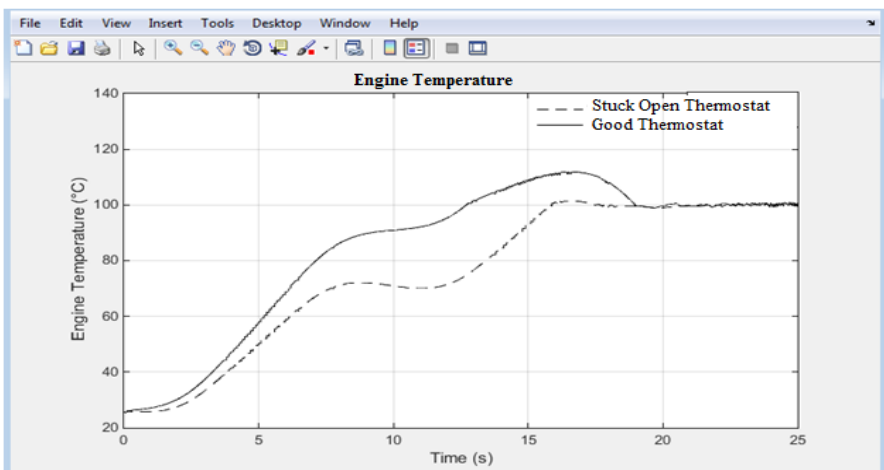


Figure 17: Effect of Stuck Open Thermostat on Engine Temperature

Figure 17 shows the effect of a stuck open thermostat on engine temperature. Since the thermostat is always opened, coolant is always flowing through the radiator. This causes excessive heat dissipation of the engine and delays the engine warm up time. This causes the engine to work at a temperature below its optimum range thereby degrading emissions and fuel efficiency.

3.5 Conclusion

This chapter explains different types of faults that might occur in the engine cooling components and their effect on the capacity of the system to dissipate heat. The faults inside the temperature sensor are ‘reading out of range’ and ‘erratic sensor’. The pump faults discussed are ‘damaged pump’ and ‘low efficiency pump’. The thermostat faults discussed are ‘stuck closed’ and ‘stuck open’. All component faults have adverse effect on engine cooling and it was concluded that fault diagnosis is necessary as a faulty component can lead to engine overheating and increased air emissions.

Chapter 4. Application of Simulink Model of Engine Cooling System to Fault Diagnosis

Diagnosis of faults in engineering systems is the process of detecting anomalous system behavior and then isolating the cause for the deviant behavior. Typically the cause is a faulty control setting or a faulty component in the system. In this project work, we limit ourselves to finding faulty engine cooling components that is the coolant temperature sensor, the thermostat and the pump.

4.1 Outline of the Proposed Method

Consider a situation where a fault occurs in the engine cooling system of a vehicle. This will decreaase engine efficiency, increase air emissions and thus the check engine light will turn on as required by the OBD requirements. Seeing the illuminated check engine light, the driver takes his vehicle to a workshop.

In order to find a fault in the vehicle under test, the technician will collect data from the vehicle under the input conditions given below:

a. Air temeperature is 25°C.
b. Drive cycle is 25 s.
c. Preesing of gas pedal of is shown in the figure 18 below:

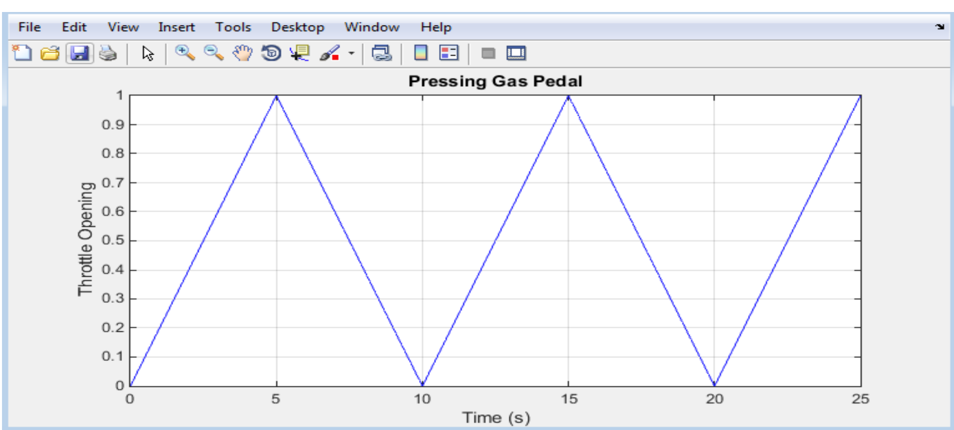


Figure 18: Pressing of Gas Pedal

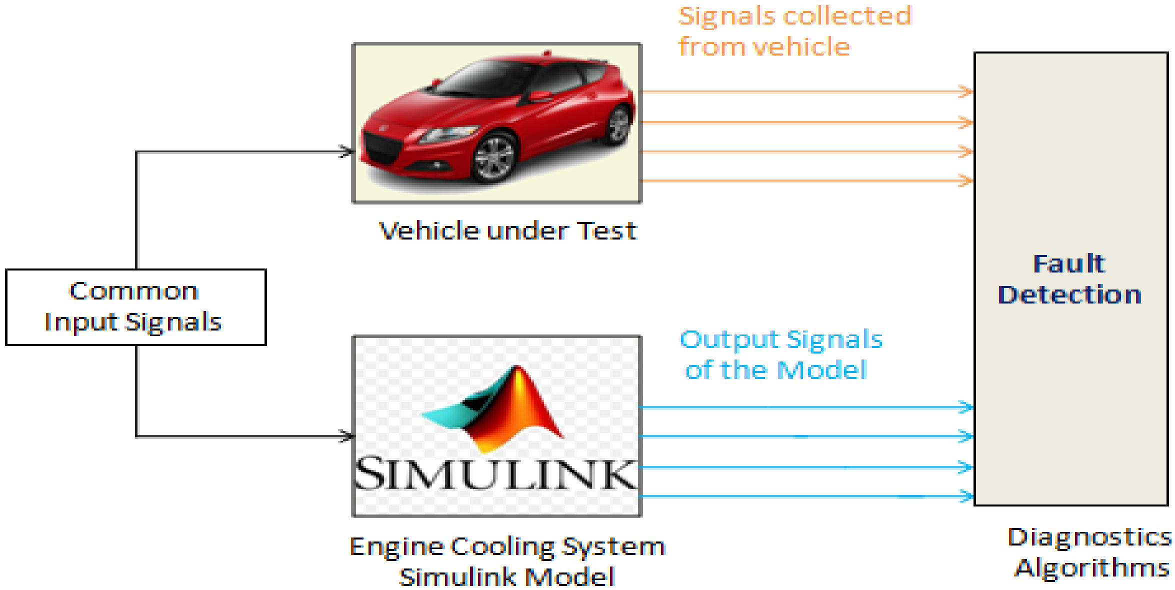


Figure 19: Fault Diagnosis using Proposed Method

Figure 19 shows the working of the proposed method for fault diagnosis. With specified input conditions, data from the engine cooling components (sensor, pump and thermostat) is collected from the ECM of the vehicle under test. The same input conditions are used for the Engine Cooling System Simulink model and simulation data are collected. These two sets of data are used to locate any faulty component in engine cooling system of the test vehicle. This is done by comparing the component's data from the vehicle to that generated by the simulink model and indicate a fault if large deviations are found.

4.2 Signals Used for Fault Diagnosis

The fault identification and isolation tasks require a model of the cooling system and a number of observable signals. To detect faults, the observed signal values and the system model can be employed to estimate parameters associated with each component. When a parameter deviates from the normal or expected value, the component associated with this parameter is considered to be faulty [31].

S.No	Signal	Signal Description	Associated Component
1.	Ti	Engine Temperature, $^\circ$ C	Temperature Sensor
2.	AngVel	Pump Angular Velocity, rad/s	Pump
3.	ThVal	Thermostat Valve Opening	Thermostat

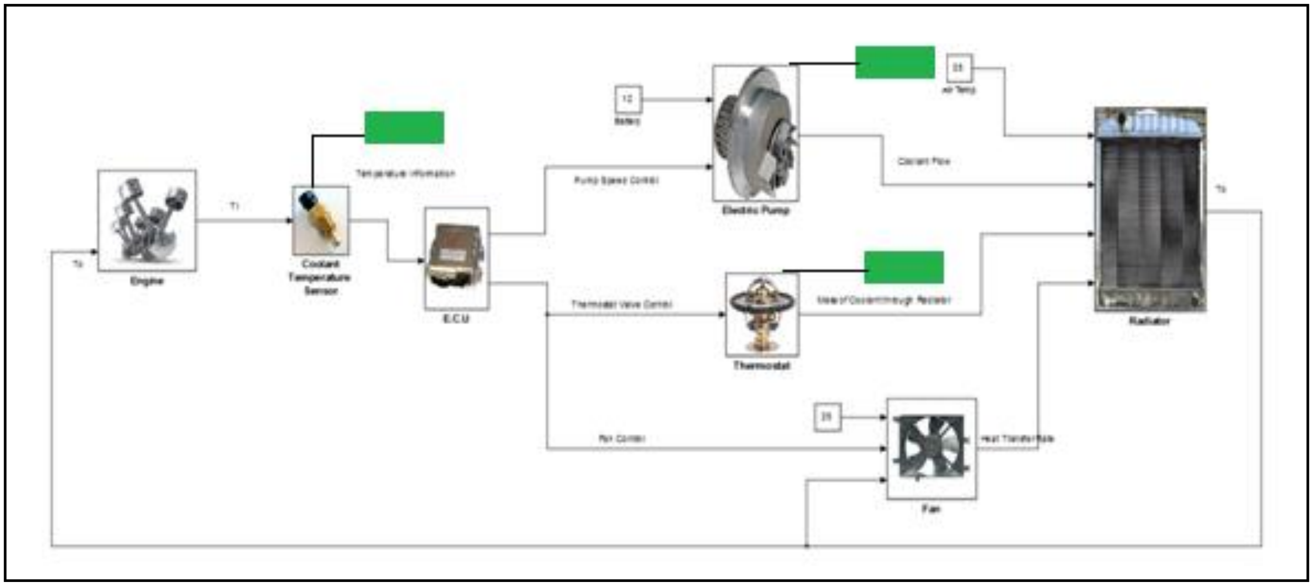
Table 4: Signals Observed for Fault Diagnosis

Table 4 lists the signals that are used for fault diagnosis. Each of these signals is collected from the vehicle and is compared to the ones simulated by the model. If large deviations between the two signal values are found, then the associated vehicle component is considered to be faulty.

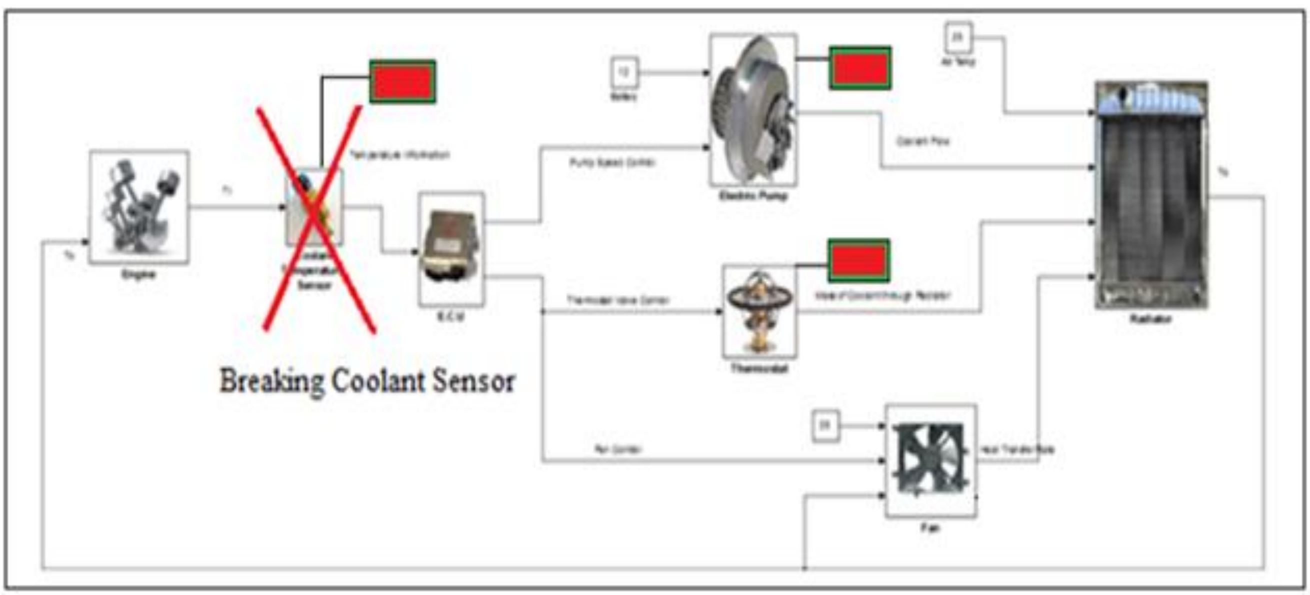
4.3 Collecting Data from the Simulink model and the Vehicle

For the purpose of fault diagnosis, data for the signals listed in Table 4 are first collected. This is done by connecting the associated components of designed simulink model, i.e. the sensor, the thermostat and the pump with the 'To Workspace' block shown as the green blocks in Figure 20a. After running the simulation, the required output signals are obtained and stored in Matlab workspace. To illustrate the proposed fault diagnosis system, two sets of data are generated using the simulink model. The first set is obtained using faulty component data and represents the faulty test vehicle. The second set is obtained using healthy component data and used for fault diagnosis by comparing it to the test vehicle data.

Faults are introduced into the engine cooling system by changing parameter values used in the design of the engine cooling components. After the fault is introduced, the model is simulated and the faulty data is collected in the Matlab workspace using 'To Workspace' block shown as red blocks in Figure 20b where the temperature sensor is faulty inside the engine cooling system.



a. Collecting Healthy Data from Model



b. Collecting Faulty Data from Vehicle

Figure 20: Collection of Data from Engine Cooling Components

4.4 Proposed Set-up for Fault Diagnosis and Diagnostic Algorithm

The vehicle and the Simulink model is first set up for testing. Both the model and the vehicle are subjected to the same input conditions, i.e. the outside air temperature, drive cycle, supply voltage and the pressing of gas pedal. Under these inputs, component data is collected from both the model and the vehicle. The fault diagnosis algorithm compares the predicted behavior of the cooling system (Model) to the observed behavior (Vehicle) and indicates the presence of any fault.

Proposed Fault Diagnosis Procedure

1. Give the same 'Throttle Position', 'Air Temperature' and 'Supply Voltage' as inputs to both the model and vehicle.
2. Run the vehicle with specified inputs and collect the data of engine cooling components (sensor, thermostat and pump) from vehicle. Signals collected from vehicle while it is running are- **Ti, AngVel, ThrmVal,** (represented by orange colored text) where **Ti** is engine coolant temperature of vehicle, **AngVel** is pump angular velocity of vehicle, **ThVal** is thermostat valve opening of vehicle.

   In the next section, the proposed method will be illustrated by using data obtained using faulty values for the simulink model instead of data from the vehicle. This is done since no access to real vehicle data was possible during this project.
3. Run the simulation of model with specified inputs and collect the data of engine cooling components from the model. Signals collected from model after simulation are- **Ti, AngVel, ThrmVal,** (represented by blue colored text) where **Ti** is engine coolant temperature of model, **AngVel** is pump angular velocity of model, **ThVal** is thermostat valve opening of model.
4. Use diagnostic algorithm to detect possible faults. The steps for diagnostic algorithm are given below:

Step 1: Compare Ti with Ti,

If a match ➔ No sensor fault; go to Step 3

If many deviating values are found, <u>Sensor may be faulty,</u>

Step 2: Checking Sensor faults

Test 1: Is maximum of **Ti** > 300? if true→"Reading out of Range" fault; go to step 8

Test 2: Is String_Length of **Ti** > 40? If True→ "Erratic Temperature Reading" fault; go to step 8

If both test 1 and test 2 are false,➔ No Sensor fault

Step 3: Compare AngVel with AngVel

If a match ➔ No pump fault; go to Step 5

If many deviating values are found, Pump may be faulty,

Step 4: Checking Pump faults

Test 1: Are all values of **AngVel** == 0? if True→"Pump Damaged" fault; go to step 8

Test 2: Is maximum of **AngVel** < 300? If True→ "Low Efficiency Pump" fault; go to step 8

If both test 1 and test 2 are false,➔ No Pump fault

Step 5: Compare ThVal with ThVal

If a match ➔ No Thermostat fault; go to Step 7

If many deviating values are found, Thermostat may be faulty,

Step 6: Checking Thermostat faults

Test 1: Are all values of **ThVal** == 1? if True→"Thermostat Stuck Open" fault; go to step 8

Test 2: Are all values of **ThVal** == 0? If True→ "Thermostat Stuck Closed" fault; go to step 8

Step 7: Print "No Fault Found in Engine Cooling System"; go to step 9

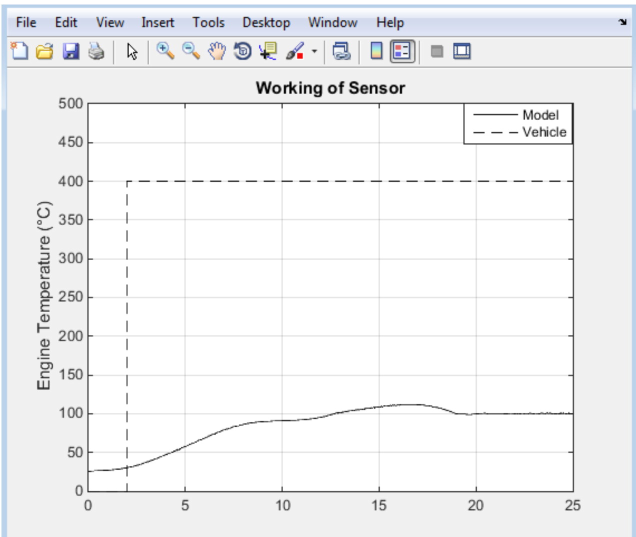
Step 8: Print "Fault Present- {Name of fault}" go to step 9

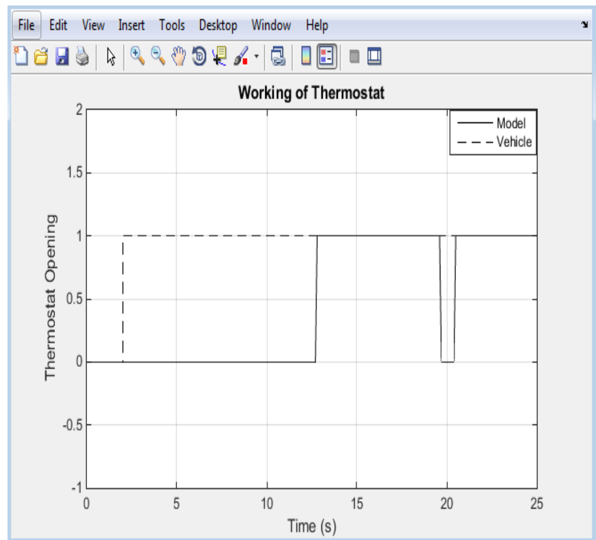
Step 9: End

4.5 Illustration of Proposed Fault Diagnosis of Engine Cooling System - Comparison of Data

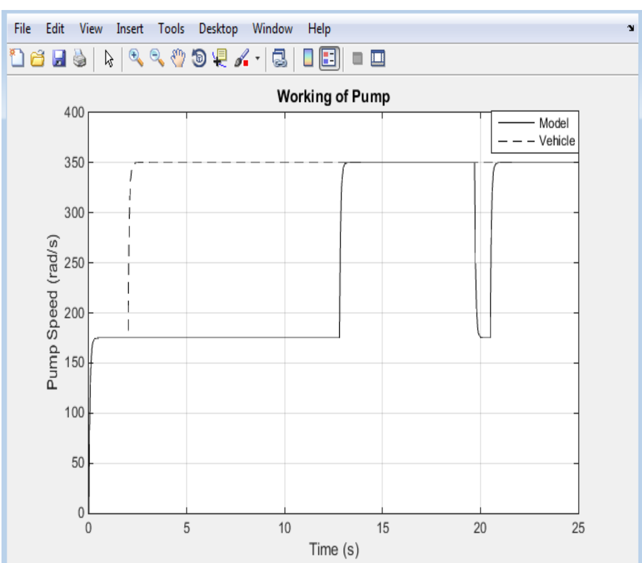
In this section, the working of proposed fault diagnosis system will be illustrated using some examples of typical faults.

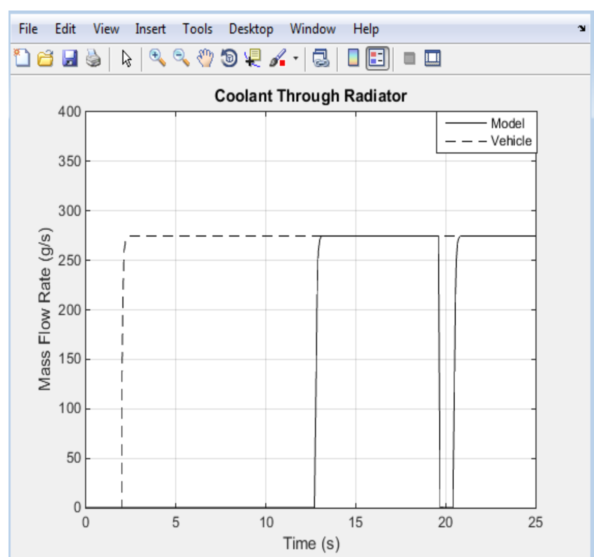
1. Component- Temperature Sensor, Fault- "Reading out of Range".





a. Temperature Sensor , Ti **b. Thermostat Valve Opening, Th**





c. Pump Angular Velocity, AngVel **d. Mass Flow Rate of Coolant in Radiator**

Figure 21: Faulty Sensor (Reading out of Range), Behavior of Engine Cooling Components

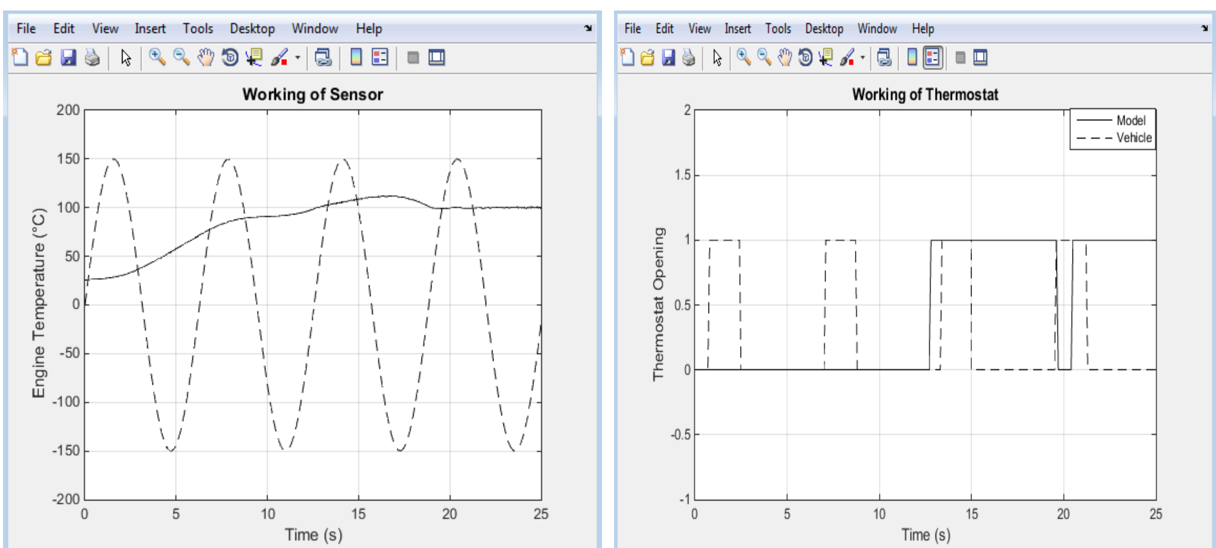
Description of Figure 21

Figure 21 depicts the working of the engine cooling system when the sensor is faulty and has a "reading out of range" fault (dashed line in Figure 21a). The dashed lines in the graphs are component data from a virtual faulty vehicle and the solid lines are component data from the model representing a healthy system. A high sensor reading will falsely keep the pump working at full speed all time (Figure 21c) and cause the thermostat to be open all time (Figure 21b). An always open thermostat will thus allow all the coolant to pass through radiator (Figure 21d)

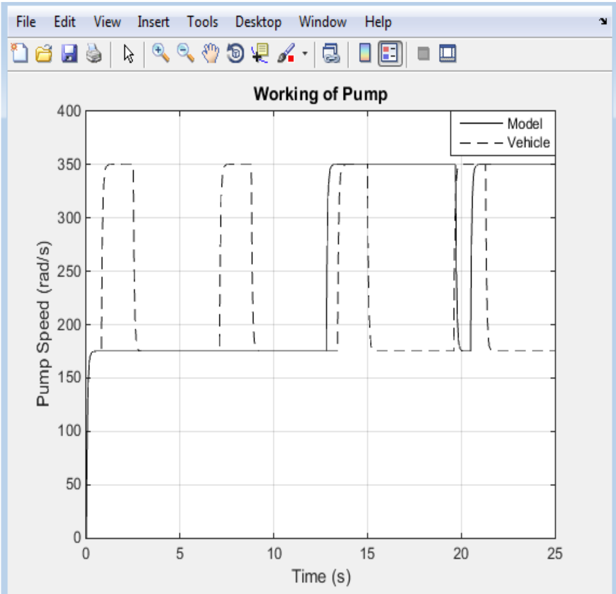
Fault Diagnosis by Diagnostic Algorithm

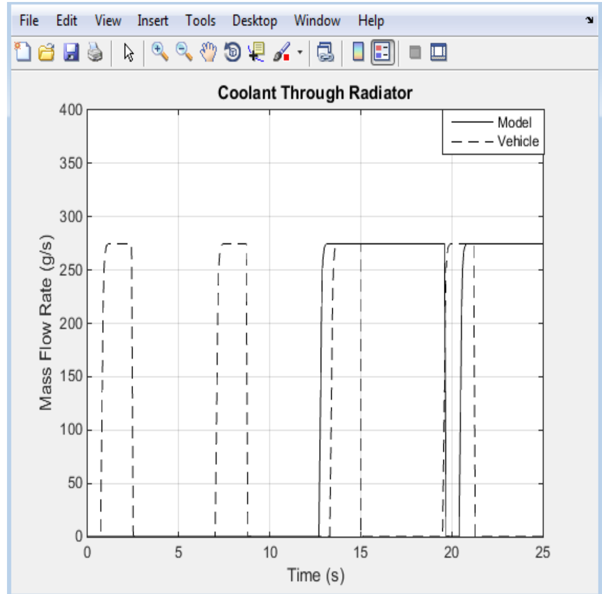
The diagnostic algorithm detects the faulty sensor in the system. In step-1 where Ti of the vehicle is compared to Ti of the model, a large number of deviating values are found leading to the conclusion that the sensor may be faulty. According to Test 1: Is maximum value of Ti > 300? This is true confirming that the sensor is faulty with a fault reading out of range.

2. **Component- Temperature Sensor, Fault-"Erratic Temperature Reading".**



a. **Temperature Sensor , Ti** b. **Thermostat Valve Opening, Th**





c. Pump Angular Velocity, AngVel **d. Mass Flow Rate of Coolant in Radiator**

Figure 22: Faulty Sensor (Erratic Temperature Reading) and Behavior of Engine Cooling Components

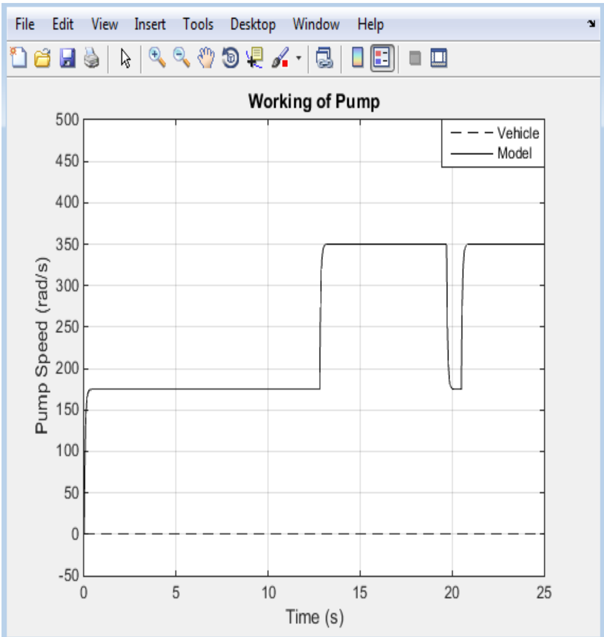
Description of Figure 22

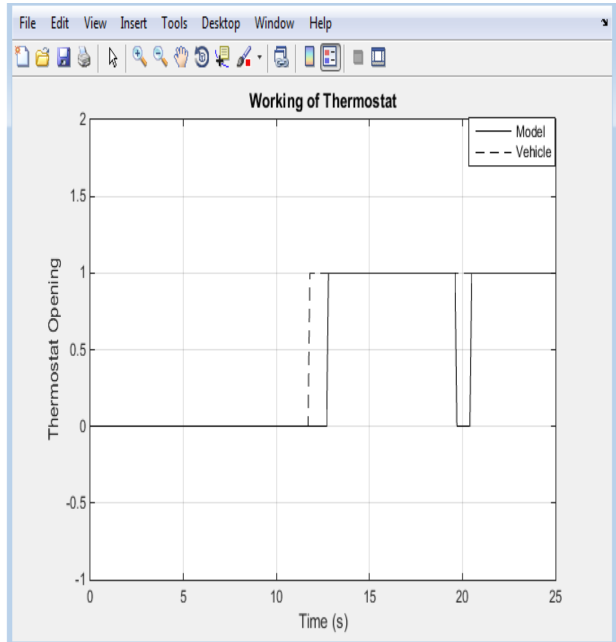
Figure 22 depicts the working of the engine cooling system when the sensor is faulty and has an "erratic temperature reading" fault (dashed line in Figure 22a). The dashed lines in the graphs are component data from a virtual faulty vehicle and the solid lines are component data from the model representing a healthy system. An erratic sensor reading will falsely keep the pump to work at varying speed (Figure 22c) and cause the thermostat to open and close multiple times (Figure 22b). Based on varying speed of the pump and thermostat valve opening, mass flow rate of coolant through the radiator also varies (Figure 22d).

Fault Diagnosis by Diagnostic Algorithm

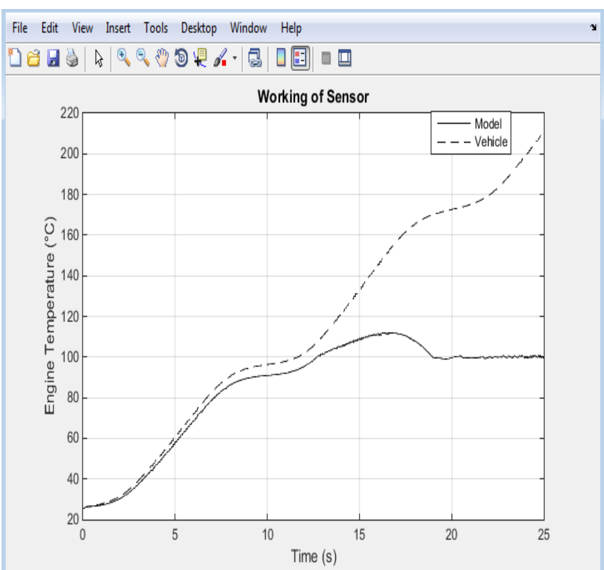
The diagnostic algorithm detects the faulty sensor in the system. In step-1 where Ti of the vehicle is compared to Ti of the model, a large number of deviating values are found leading to the conclusion that the sensor may be faulty. According to Test 2: Is String_Length of Ti > 40? This is true confirming that the sensor is faulty with a fault- erratic temperature reading.

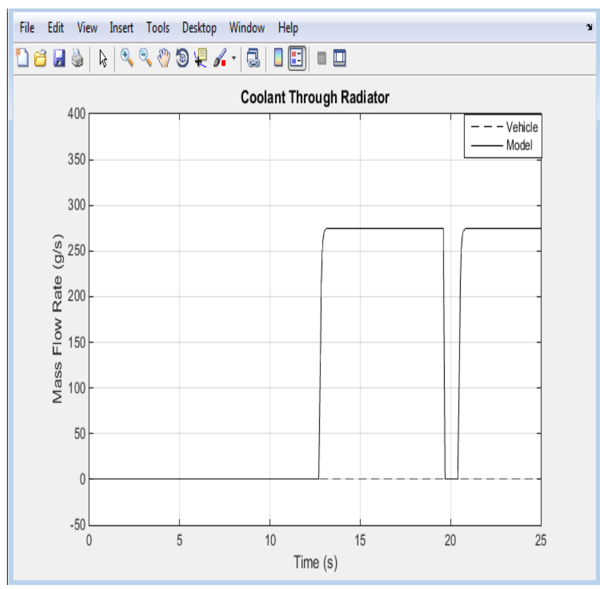
3. Component- Pump,
Fault- "Damaged Pump".





a. Pump Angular Velocity, AngVel **b. Thermostat Valve Opening, Th**





c. Temperature Sensor , Ti **d. Mass Flow Rate of Coolant in Radiator**

Figure 23: Faulty Pump (Damaged Pmup) and Behavior of Engine Cooling Components

Description of Figure 23

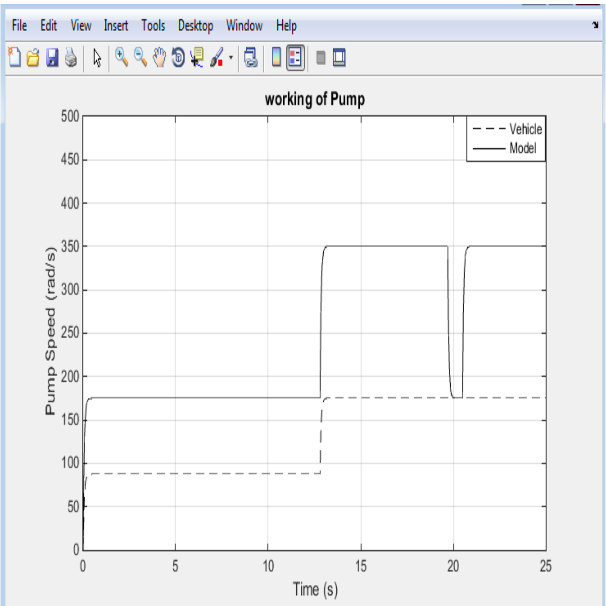
Figure 23 depicts the working of the engine cooling system when the pump is faulty and is damaged (dashed line in Figure 23a). The dashed lines in the graphs are component data from a virtual faulty vehicle and the solid lines are component data from the model representing a healthy system. A damaged pump that does not move at all will result in no circulation of coolant inside the cooling system. This will cause engine temperature to rise (Figure 23c) as heat is not dissipated due to lack of coolant flow. High engine temperature will cause the thermostat to be open at all times (after temperature rises above 100°C, Figure 23b). Since there is no flow of coolant inside the radiator, the mass flow rate of coolant through radiator becomes zero (Figure 23d).

Fault Diagnosis by Diagnostic Algorithm

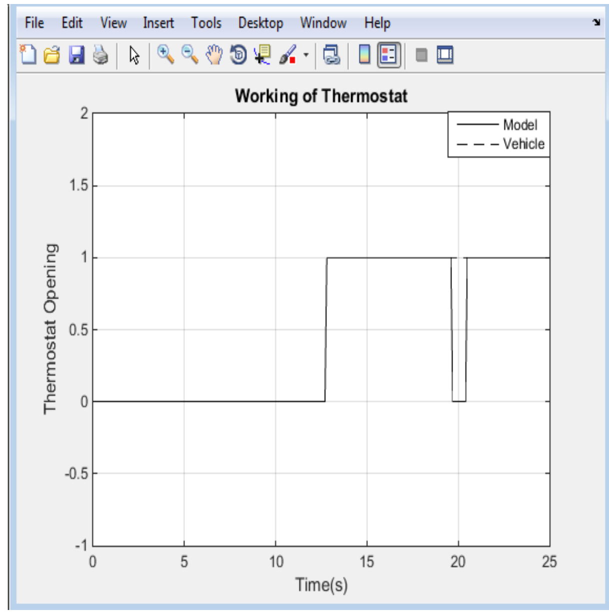
The diagnostic algorithm detects the faulty pump in the system. In step-1 where Ti of the vehicle is compared to Ti of the model, a large number of deviating values are found leading to the conclusion that the sensor may be faulty. However, in step 2, Test 1 and Test 2 fail confirming that the sensor is not faulty.

In step 3 where AngVel of the vehicle is compared to AngVel of the model, a large number of deviating values are found leading to the conclusion that the pump may be faulty. In step 4 with Test 1: Are all values of AngVel == 0? This is true proving that the pump is faulty with a fault-damaged pump.

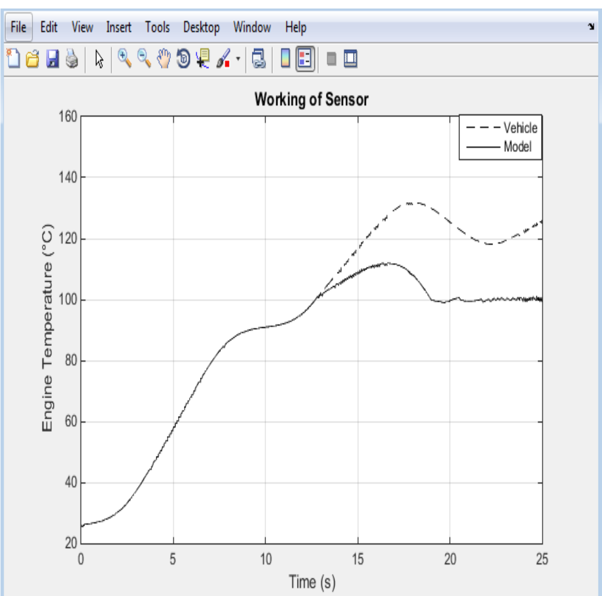
4. Component- Pump,
Fault- "Low Efficiency Pump".



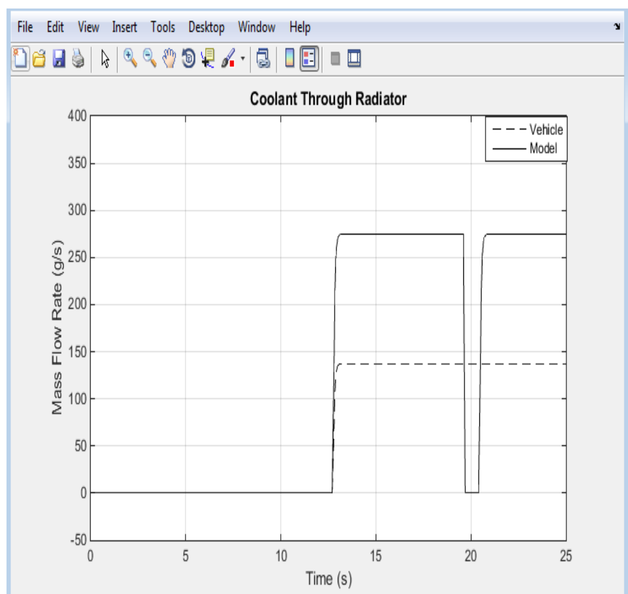
a. Pump Angular Velocity, AngVel



b. Thermostat Valve Opening, Th



c. Temperature Sensor , Ti



d. Mass Flow Rate of Coolant in Radiator

Figure 24: Faulty Pump (Low Efficiency Pump) and Behavior of Engine Cooling Components

Description of Figure 24

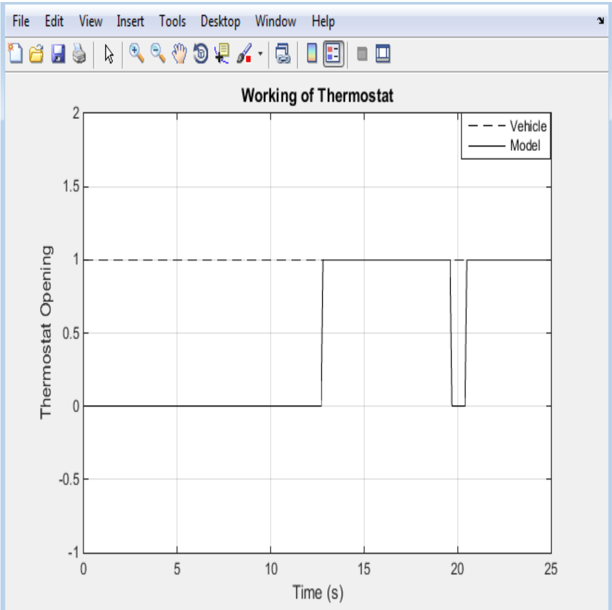
Figure 24 depicts the working of the engine cooling system when the pump is faulty and is working with low efficiency (dashed line in Figure 24a). The dashed lines in the graphs are component data from a virtual faulty vehicle and the solid lines are component data from the model representing a healthy system. A pump working with lower efficiency will result in less circulation of coolant inside the cooling system. This will cause engine temperature to rise (Figure 24c) as heat is not dissipated quickly due to a low coolant flow. High engine temperature will cause the thermostat to be open at all times (after temperature rises above 100°C, Figure 24b). Since the pump is working with lower speed, the mass flow rate of coolant through radiator also gets reduced (Figure 24d).

Fault Diagnosis by Diagnostic Algorithm

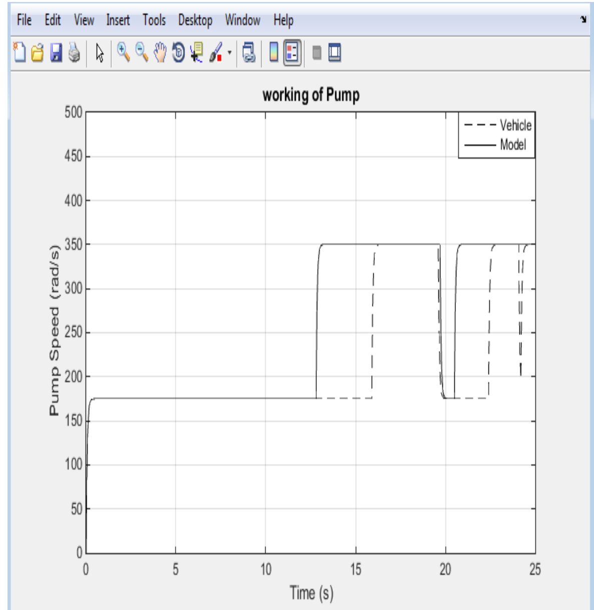
The diagnostic algorithm detects the faulty pump in the system. In step-1 where Ti of the vehicle is compared to Ti of the model, a large number of deviating values are found leading to the conclusion that the sensor may be faulty. However, in step 2, Test 1 and Test 2 fail confirming that the sensor is not faulty.

In step 3 where AngVel of the vehicle is compared to AngVel of the model, a large number of deviating values are found leading to the conclusion that the pump may be faulty. In step 4 with Test 2: Is maximum of AngVel < 300? This is true proving that the pump is faulty with a fault-low efficiency pump.

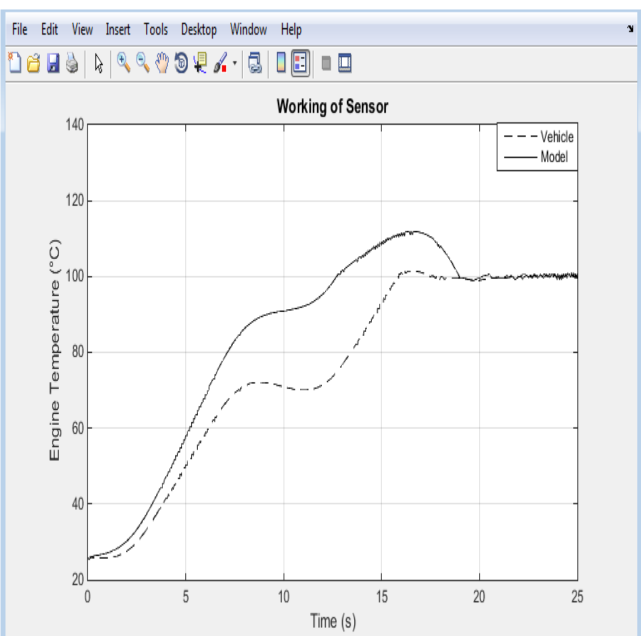
5. Component- Thermostat,
Fault- "Stuck Open Thermostat".



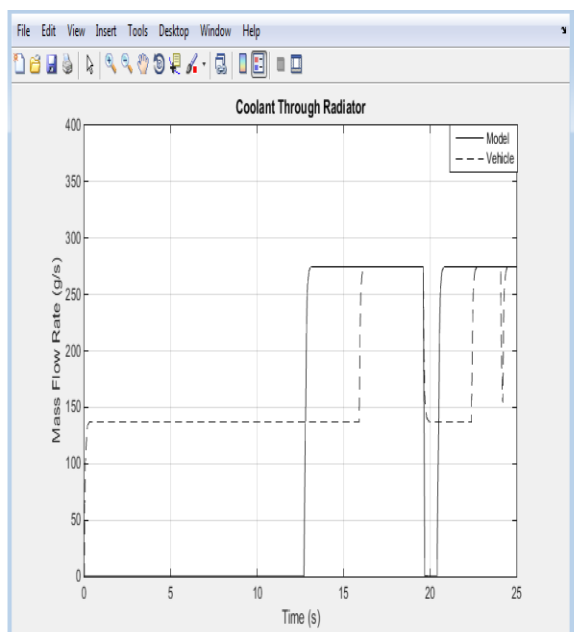
a. Thermostat Valve Opening, ThVal



b. Pump Angular Velocity, AngVel



c. Temperature Sensor , Ti



d. Mass Flow Rate of Coolant in Radiator

Figure 25: Faulty Thermostat (Stuck Open) and Behavior of Engine Cooling Components

Description of Figure 25

Figure 25 depicts the working of the engine cooling system when thermostat is faulty and is stuck open (dashed line in Figure 25a). The dashed lines in the graphs are component data from a virtual faulty vehicle and the solid lines are component data from the model representing a healthy system. A stuck open thermostat will delay the warm-up time of engine (Figure 25c). The pump works at a lower speed to compensate for the excessive loss of heat (Figure 25b). Based on the speed of pump, the mass flow rate of coolant through radiator also varies (Figure 25d).

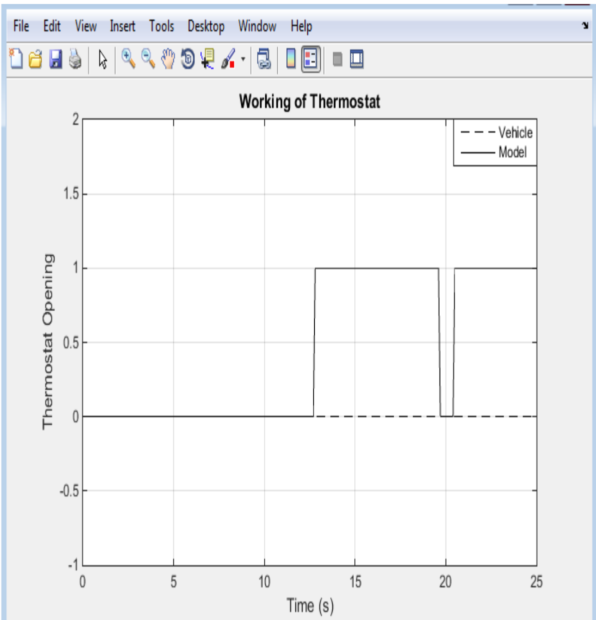
Fault Diagnosis by Diagnostic Algorithm

The diagnostic algorithm detects the faulty thermostat in the system. In step-1 where Ti of the vehicle is compared to Ti of the model, a large number of deviating values are found leading to the conclusion that the sensor may be faulty. However, in step 2, Test 1 and Test 2 fail confirming that the sensor is not faulty.

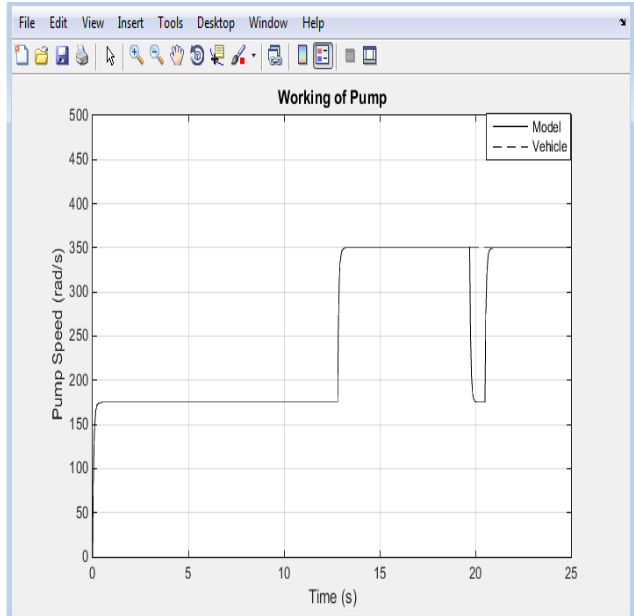
In step 3 where AngVel of the vehicle is compared to AngVel of the model, a large number of deviating values are found leading to the conclusion that the pump may be faulty. However, in step 4, Test 1 and Test 2 fail confirming that the pump is not faulty.

In step 5 where ThVal of the model is compared to ThVal of the vehicle, many deviating values are found leading to the conclusion that the thermostat may be faulty. In step 6, with Test 1: Are all values of ThVal == 1? is True proving that the thermostat is faulty with ”Thermostat Stuck Open”.

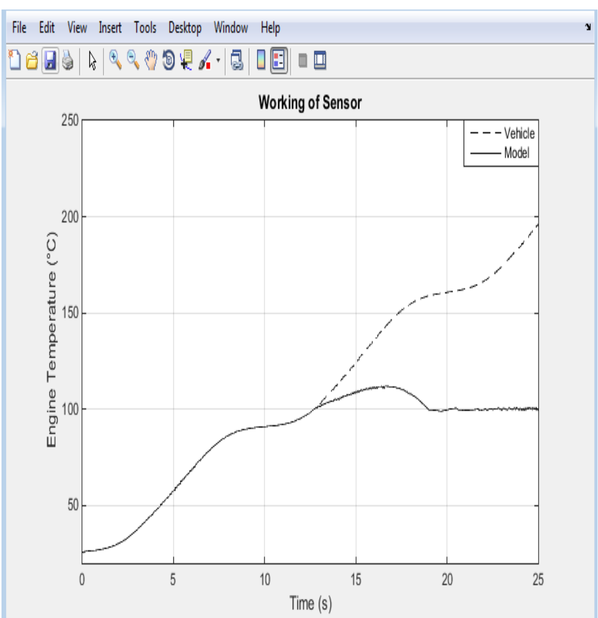
**6. Component- Thermostat,
Fault- "Stuck Closed Thermostat".**



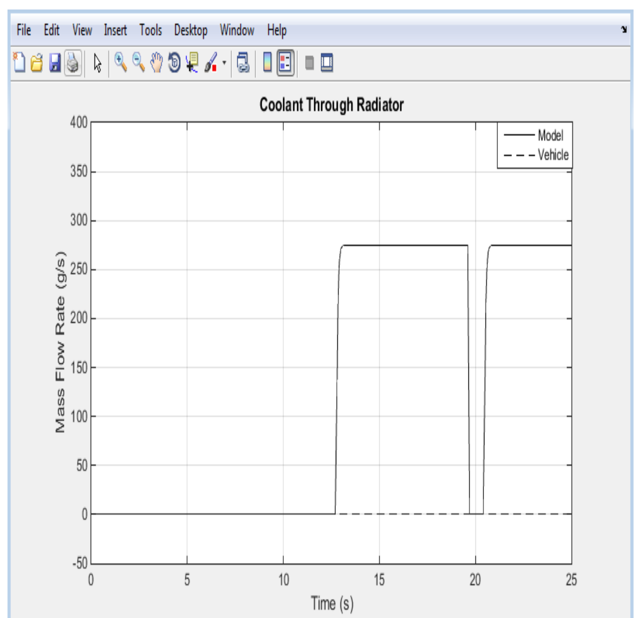
a. Thermostat Valve Opening, ThVal



b. Pump Angular Velocity, AngVel



c. Temperature Sensor , Ti



d. Mass Flow Rate of Coolant in Radiator

Figure 26: Faulty Thermostat (Stuck Closed) and Behavior of Engine Cooling Components

Description of Figure 26

Figure 26 depicts the working of the engine cooling system when thermostat is faulty and is stuck closed (dashed line in Figure 26a). The dashed lines in the graphs are component data from a virtual faulty vehicle and the solid lines are component data from the model representing a healthy system. A stuck closed thermostat will lead to engine overheating (Figure 26c) as the coolant is blocked from reaching the radiator and dissipate its heat. The pump works at full speed (after 100°C) to compensate for the excessive addition of heat (Figure 26b). However, since the thermostat is closed there is no coolant flow through radiator (Figure 26d).

Fault Diagnosis by Diagnostic Algorithm

The diagnostic algorithm detects the faulty thermostat in the system. In step-1 where Ti of the vehicle is compared to Ti of the model, a large number of deviating values are found leading to the conclusion that the sensor may be faulty. However, in step 2, Test 1 and Test 2 fail confirming that the sensor is not faulty.

In step 3 where AngVel of the vehicle is compared to AngVel of the model, a large number of deviating values are found leading to the conclusion that the pump may be faulty. However, in step 4, Test 1 and Test 2 fail confirming that the pump is not faulty.

In step 5 where ThVal of the model is compared to ThVal of the vehicle, many deviating values are found leading to the conclusion that the thermostat may be faulty. In step 6, with Test 2: Are all values of ThVal == 0? is True proving that the thermostat is faulty with ”Thermostat Stuck Closed”.

4.6 Conclusion

In this chapter, the working of fault diagnosis system using the proposed method is explained. The designed model of engine cooling system is used to develop healthy data. Different types of faults are introduced in the system model and faulty data is collected. Fault diagnosis algorithm is used to detect and isolate engine cooling system related failures by comparing the two sets of data. The method is successfully able to detect faulty component i.e. temperature sensor, pump and thermostat inside the engine cooling system.

Chapter 5. Conclusion and Future Work

5.1 Conclusion

A Simulink model of an engine cooling system has been developed by using thermodynamic laws, Newton's law of cooling and other mathematical equations. The designed model uses a coordinated control strategy to regulate the engine coolant temperature. The working of each of the engine cooling components and their ability to maintain the desired engine temperature is illustrated with the help of simulink graphs.

Chapter 3 explains different types of faults that might occur in the engine cooling system and their effect on the capacity of the system to dissipate heat. It was concluded that fault diagnosis is necessary as a faulty component can lead to engine overheating and increased air emissions.

Chapter 4 explains the proposed fault diagnosis system. The simulink model of engine cooling system was used to produce output signals for both cases of a healthy and a faulty engine cooling system. The working of the method is based on comparing output signals obtained from a test vehicle and the simulink model using the same input conditions for both. The proposed fault diagnosis algorithm was used to detect and isolate engine cooling system related failures.

Results show that the method was successfully able to detect faulty component i.e. temperature sensor, pump and thermostat inside the engine cooling system along with a type of fault present. The work might contribute in its own minute way to help car manufacturers to efficiently and quickly locate faulty components inside a vehicle.

5.2 Future Work

The future work of the project is to validate the developed simulink model of an engine cooling system using a real vehicle data. In order to validate the model, real time component's data may be collected during the normal driving condition of a vehicle. All these collected data may be used to calibrate the model and test it. An equivalent set of data collection may be done with and without faulty engine cooling component in order to validate the proposed diagnostic algorithm ability to detect a defective component.

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