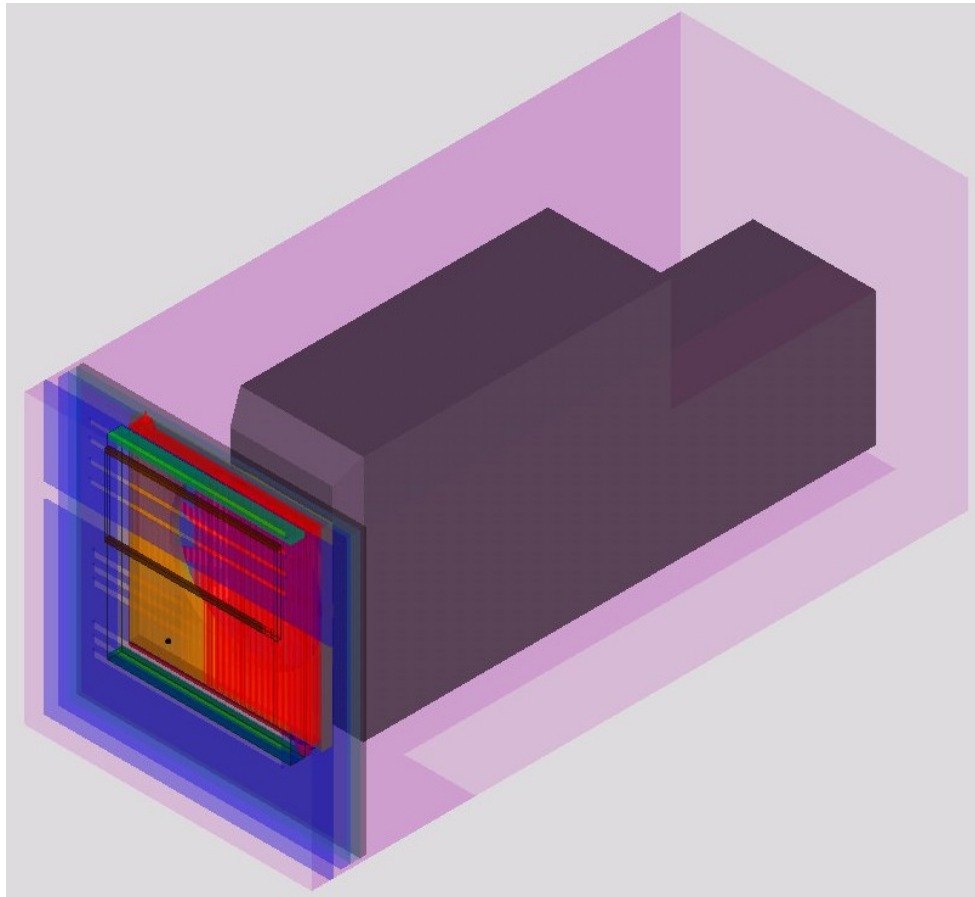


# CHALMERS



## Cooling performance simulations in GT-Suite

Master's Thesis in the Master's programme Automotive Engineering

ALEXEY VDOVIN

Department of Applied Mechanics

*Division of Vehicle Engineering & Autonomous Systems*

CHALMERS UNIVERSITY OF TECHNOLOGY

Göteborg, Sweden 2010

Master's Thesis 2010:28



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Cover:  
3D underhood thermal management model for a Volvo FH truck constructed in  
Cool3D, see Section 3.2 for more information.

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## **Abstract**

This project was performed at Volvo Trucks in Gothenburg, Sweden. It was done in cooperation between Volvo 3P and Volvo Powertrain.

There are different methods for doing cooling performance simulations. These simulations can be done in 3D by using Computational Fluid Dynamics software or by using 1D simulation tools. The main task for this project was to evaluate one of the 1D simulation tools.

The Cooling analysis group at Volvo 3P uses AMESim and KULI as 1D simulation tools in its work. It was decided to try GT-Suite for such simulations. One of the reasons for this decision was that Volvo Powertrain is using this program for engine simulations. When using one tool for both simulations there is a possibility to couple them together and obtain a more precise simulation model with high level of integration.

As a first step for the project a model of the cooling system of a Volvo FH truck was created and the simulation model results were evaluated against the experimental results. Further on a module of GT-Suite for detailed modelling of the underhood flow in 3D environment called Cool3D was used to construct a model of the cooling package and its surroundings. This model was added to the initial model and the results of the simulation were compared to the first simulation and experiment.

The first model constructed was using a mapped engine for obtaining heat release values of different components, meaning that heat release was only dependant on the engine load and speed. To improve this model a mean value engine model was obtained from Volvo Powertrain and the two models were coupled one to another.

As a result of the project it was shown that a simple 1D simulation requires tuning as it is impossible to include all the details for the air side of the cooling system, but after the tuning been done it can definitely be used.

It was shown that tuning could be omitted when using Cool3D tool and taking into account the effect of hot air recirculation via ambient air preheating.

For the coupling of cooling system and engine simulations it was shown that it is possible and can easily be done, a brief description of how to do it was given.

**Key words:** GT-Suite, cooling performance simulation, Cool3D, simulation coupling, trucks, simulation tuning

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## Preface and acknowledgement

This master thesis work was performed from January to June 2010 at Volvo Trucks in Gothenburg, Sweden. It is the final work for a degree at Automotive Engineering Master's Program, Chalmers University of Technology.

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Lastly, I would like to convey my thanks to all of those who supported me in any respect during the completion of this thesis project and was not mentioned above.

Göteborg, June 2010

Alexey Vdovin



# 1 Introduction

In this chapter an introduction to the thesis project will be given.

## 1.1 Background

Cooling system of a vehicle is rather complicated and its complexity is increasing with the advancement of technology. It is becoming even more complicated when speaking about cooling system of a commercial vehicle. To help engineers in building and improving such systems there is a need of using cooling performance simulation software. Simulation has some advantages over performing actual physical test: it can be cheaper, less time consuming and it allows evaluating as many parameters as needed, it can even help engineers to study values that are impossible to get for some reason from a real life experiment. As a drawback of simulation it should be said that any simulation is always a simplification, no matter what level of detail is used. Hence simulation models should always be validated against physical test results.

There are different methods for doing cooling performance simulations. These simulations can be done by using Computational Fluid Dynamics (CFD) software or by using 1D simulation tools. For the second area there are several software products that are being used in industry. The most commonly used are KULI<sup>1</sup>, FlowMaster<sup>2</sup>, AMESim<sup>3</sup> and GT-Suite<sup>4</sup>. Each of these software products has its drawbacks and advantages, but eventually they are all capable of performing the same type of calculations.

## 1.2 Project description

This thesis project is going to be performed in cooperation between Volvo 3P Cooling analysis group and Volvo Powertrain at Volvo Trucks. The Cooling analysis group is doing simulations and testing of cooling system and performance, intake and exhaust systems, and hot spots in heavy trucks within Volvo 3P. As for now, this group uses KULI and AMESim for 1D simulations. To be able to build more precise models of the cooling system a good cooperation with different groups is needed, especially with groups from Volvo Powertrain. Volvo Powertrain uses GT-Suite to perform engine simulations. In order to achieve a better interaction with them a decision to try GT-Suite for cooling performance simulations was made. If having cooling system model and engine model both working in GT-Suite there is a possibility to connect them to each other and make a complex simulation model capable of handling transient situations like engine warm-up or driving with changing engine load and speed.

In this thesis project a 1D simulation model for the Volvo FH truck cooling system is going to be built in GT-Suite graphical interface called GT-ISE. Different components of this system are going to be introduced. The simulation model built will be used for performing thermal simulations and investigating capabilities of the tool.

The Volvo FH truck that is going to be modeled is an in-production vehicle, see Figure 1.1. The variant that is going to be modeled has an EU4 EGR engine.



*Figure 1.1 Volvo FH truck (Volvo Trucks Image Gallery<sup>5</sup>)*

This particular vehicle and engine setup was chosen for the reason that there was a test report available from the cooling performance test conducted with it (ER-606535<sup>6</sup>), therefore it is possible to evaluate the simulation model results against experimental data.

For the first model a mapped engine is going to be used, meaning that heat release at different heat exchangers in the system is obtained from the lookup tables and dependant only on the engine load and speed. After this a cooling performance model will be connected to the mean value engine model obtained from Volvo Powertrain to show the advantages of model coupling.

As another part of the project a subprogram for modeling the underhood flow in 3D environment called Cool3D will be evaluated. The results for the model working with Cool3D are going to be compared with the results from simple 1D simulation.

## 2 Theoretical part

In this chapter theoretical aspects of the project are going to be covered. Firstly heat transfer mechanisms will be described and a quick overview of a truck cooling system will be given. Then GT-Suite and its module called Cool3D are going to be introduced. In addition a discussion on simulation coupling will be performed.

### 2.1 Heat transfer theory

If dealing with computer simulations of the cooling systems it is important to have knowledge about the heat transfer theory. Heat transfer is the transition of thermal energy between bodies or fluids of different temperatures<sup>7</sup>. There are several different mechanisms for the heat transfer: conduction, convection and radiation. All of them occur at the cooling system and they are going to be briefly covered in this section.

#### 2.1.1 Conduction

Conduction is the heat transfer happening when there is a direct contact between particles of matter with different temperatures. Those particles exchange energy without any motion. Conduction acts to equalize temperature gradient, so the heat is transferred from the hotter region to the colder one. The amount of heat being transferred is proportional to the temperature difference, so if the temperature gradient is higher the conduction heat flux will have a bigger value.

In terms of equations the conduction heat flux can be calculated in the following way:

$$q''_{cond} = -k \frac{T_2 - T_1}{L} \quad (2.1)$$

where  $k$  is thermal conductivity in W/m-K,  $(T_2 - T_1)$  is the local temperature gradient (K) and  $L$  is the material thickness (m). A good example of conduction in the cooling system is the heat being transferred through the material of the engine resulting in fast warm up of its outer surface.

#### 2.1.2 Convection

Convection is another heat transfer mechanism that requires a medium. It occurs by means of the molecules movement within fluids. It takes place in two different ways: diffusion and advection. The first is the random Brownian motion of individual particles and the second is the heat and matter transported by the bulk motion of fluid.

For the cooling system the convective heat transfer occurs, for example, in the cooling pipes when there is a temperature different between the wall surface temperature and the temperature of the coolant. The fluid in this case forms a thermal boundary layer where the convection takes place. Near the pipe surface the fluid velocity is low, and diffusion dominates. When moving away from the surface bulk motion starts to play the major role.

The convection can be classified to forced and natural. Forced convection occurs when a fluid flow is affected by external means. In case of coolant pipes it is affected by the pump, therefore the convection heat transfer here can be considered to be forced. On the other hand natural convection occurs when there is no outer influences on the heat transfer.

In terms of formulas one can find the following equation for the convection heat flux:

$$q''_{conv} = h(T_s - T_\infty) \quad (2.2)$$

where  $h$  is the convection heat transfer coefficient (W/m<sup>2</sup>-K),  $T_s$  is the surface temperature (K) and  $T_\infty$  is the fluid temperature (K) outside the thermal boundary layer.

### 2.1.3 Radiation

Radiation is the third heat transfer mechanism. It is concerned with the exchange of thermal energy between two or more bodies and unlike conduction and convection it requires no medium. Heat transfer through radiation takes place in form of electromagnetic waves mainly in the infrared region. The intermediaries are photons which travel at the speed of light.

The total energy radiated per unit surface area of a black body in unit time,  $E_r$ , can be found using Stefan-Boltzmann law:

$$E_r = \sigma T_s^4 \quad (2.3)$$

where  $\sigma$  is a Stefan Boltzmann constant (W/m<sup>2</sup>-K<sup>4</sup>) and  $T_s$  is the surface absolute temperature (K). This equation works only for the ideal case of the black body or the ideal radiator, as for the more general case the body radiates only a portion of the energy calculated by using Equation 2.3. This portion is characterized by the body thermal emissivity,  $\varepsilon$ , which is a non-dimensional coefficient in the range  $0 < \varepsilon < 1$ . The energy emitted by a non ideal radiator surface is given by:

$$E_r = \varepsilon \sigma T_s^4 \quad (2.4)$$

The net radiation heat flux can be calculated using the following equation:

$$q''_{rad} = \varepsilon \sigma (T_s^4 - T_{sur}^4) \quad (2.5)$$

where  $T_{sur}$  is the temperature of surroundings (K). An example of the radiation heat transfer for the vehicle is the engine emitting lots of energy due to high temperature difference between walls and surrounding air.

## 2.2 Overview of a truck cooling system

An internal combustion engine produces lots of energy and a huge part of it goes away with exhaust gases and in terms of heat being released. The main purpose of the cooling system is to handle the heat rejected by the engine and to keep the engine at its most efficient temperature. A simplified version of a cooling system can be seen in Figure 2.1.

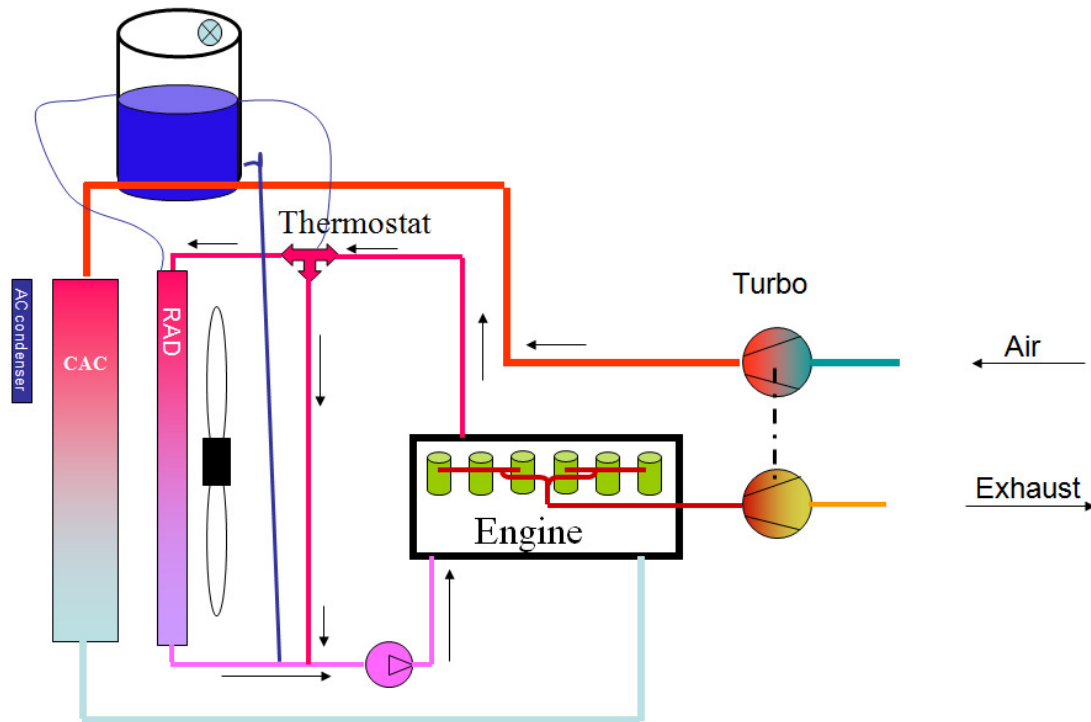


Figure 2.1 Simplified cooling system

Here on the left side one can see a cooling package consisting of air conditioner condenser, charge air cooler, radiator and fan. There are two circuits shown: charged air circuit and coolant one. In case of EGR engine used an EGR cooler could be added for cooling down temperatures of EGR gases.

Different parts of the cooling system are going to be discussed in this section.

### 2.2.1 Coolant mixture

To cool down the engine and other hot components the coolant is circulated around the coolant system by the pump. The engine is cooled by coolant passing by in channels insides the engine block and head. Coolant mixture also absorbs the heat at the EGR-cooler and other components that require cooling and then it releases the heat at the radiator part.

The coolant usually consists of the water mixed with ethylene glycol with some additions. This is done to reduce freezing point temperature and improve corrosion resistance. It also raises the boiling point temperature that is important for the hot day conditions when the higher temperature difference between air and coolant is desirable as it improves the heat transfer performance of the radiator.

### 2.2.2 Pipes and hoses

Pipes and hoses are used to connect different parts of the coolant system together and to transfer the coolant mixture between these parts; therefore they should be designed in the way to be able to withstand high temperatures and pressures that can occur in the coolant system. See Figure 2.2 for the example of the pipe from the coolant system.

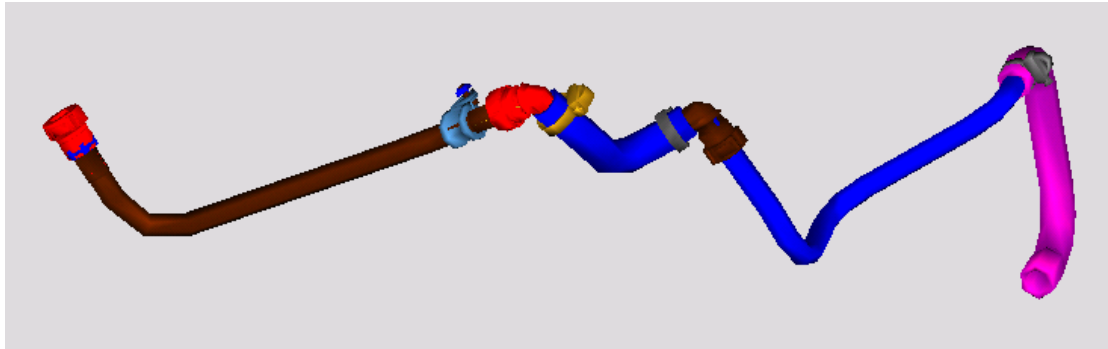


Figure 2.2 An example of pipe in the coolant system

Hoses should be flexible enough even at low atmospheric temperatures to withstand vibrations that usually occurs at the engine compartment. In addition, pipes and hoses in the system should have sufficient radius not to create unwanted pressure losses.

### 2.2.3 Pump

The pump is used to force the coolant to circulate through all parts of the coolant system as all of them, even pipes, have pressure losses that need to be overcome. The most commonly used pumps have mechanical connection to the engine shaft with a fixed pump speed / engine speed ratio, an example of a pump is given in Figure 2.3.



Figure 2.3 Volvo FH centrifugal coolant pump(Gasgoo<sup>8</sup>)



The belt driven pump with a direct connection to the engine shaft is easy to build but it has some drawbacks. As the pump is dependent on the engine RPM the coolant is being pumped through the system even when it is not needed. This may result in engine overcooling, some energy losses and therefore increased fuel consumption.

There are more advanced pumps available on the market and those are electrical ones. They are independent of engine speed and hence much more flexible in control. As a drawback of this solution it can be said that those pump systems are more expensive.

#### **2.2.4 Thermostat**

The thermostat is a thermally controlled valve that regulates the amount of coolant that goes through the radiator. The valve is activated by temperature sensitive wax and usually starts to open at temperatures around 82 °C. An example of thermostat is shown in Figure 2.4.



*Figure 2.4 Thermostat example (eAutoWorks<sup>9</sup>)*

The main reason to have a thermostat is to maintain coolant temperature in a certain range that is needed for improving the engine and radiator performance. It allows to have a quick warm up of the system when thermostat directs the coolant to bypass the radiator and hence the coolant temperature is increasing quickly. At high temperatures thermostat opens and directs coolant through the radiator decreasing its temperature and consequently keeping engine at optimal operating temperatures.

#### **2.2.5 Oil cooler**

In engines, oil not only functions as a lubricant but also as the coolant for a number of parts. As a big part of the engine heat is rejected to the oil there is a need to cool it down. The oil cooler is a heat exchanger that helps to keep the engine oil and hence the engine itself at working temperatures.

## 2.2.6 Accumulator tank

Coolant accumulator tank is located at the highest point of the cooling system, see Figure 2.5 for an example.



*Figure 2.5 Accumulator tank*

It has a number of functions. Firstly, it is used for filling in the coolant circuit. Secondly, there is always a small flow through it to guide air pockets that can occur in the coolant system out from it because the presence of air in the system can decrease its performance. Thirdly, the accumulator tank will contain extra volume of coolant that will appear with the coolant temperature rise and help to maintain a certain pressure in the system. If the pressure gets too high there is a pressure valve in the lid of the tank.

## 2.2.7 EGR cooler

Most new diesel engines and some petrol engines recirculate a fraction of the exhaust gases to the intake manifold, see Figure 2.6. This is mainly done in order to reduce NOX (Nitrous Oxide) emissions level. The exhaust gases could be cooled down before it is mixed with the fresh air, this is done to reduce the combustion temperature which will result in reduced emissions.



*Figure 2.6 EGR cooler(Parts Place Inc<sup>10</sup>)*

### 2.2.8 Radiator

Radiator is one of the main components of the cooling system. It acts as a heat exchanger in-between the hot coolant side and the cold ambient air side. It has two tanks and a number of small tubes that connect those tanks to each other. To increase the heat transfer surface, folded bands of metal, called fins, are put between tubes. The air flows perpendicularly to the direction of the coolant flow, see Figure 2.7 for an example of radiator.



Figure 2.7 A typical automobile coolant radiator(Wikipedia article<sup>11</sup>)

### 2.2.9 Fan

The radiator performance is highly affected by the amount of air going through it. A fan is used for sucking the air in and therefore for increasing this amount. A shroud is added to guide the air and to force it to go through the cooling package, see Figure 2.8.



Figure 2.8 Fan with shroud mounted behind the radiator(Novak Conversions<sup>12</sup>)

As a cooling pump the fan is usually mechanically connected to the engine shaft and its speed is directly dependant on the engine RPM, on the other hand it usually has a viscous clutch that allows to decrease the rotational speed when extra air flow is not needed.

## 2.3 Air recirculation effect

Usually in the cooling package there is a certain amount of air going from the high pressure region after the fan to the area in front of the radiator, charge air cooler and even to the area in front of the whole package as there is an area of lower pressure, see Figure 2.9.

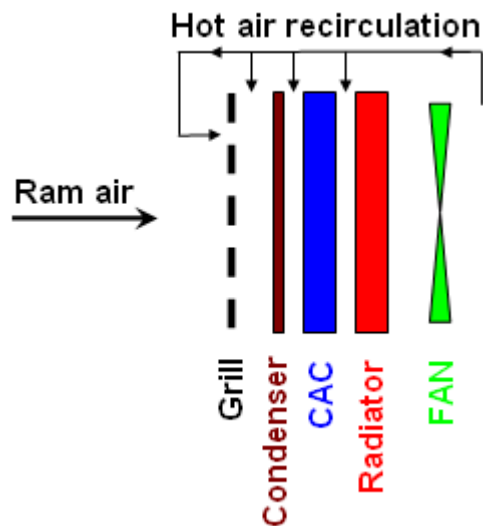


Figure 2.9 Hot air recirculation

The area in-between condenser and radiator is usually well sealed so that the main flow of the hot recirculating air is coming to the front of the whole cooling package. The result of this recirculation is higher temperature values on the air side; therefore it affects temperatures in the whole system. The effect of air recirculation is hard to model in 1D simulation. The usual way around for this problem consists in creating a heat addition object at the air inlet or manual increasing of the ambient air temperature (Hildinger 2007<sup>13</sup>). In other words, preheating of the ambient air that goes through the cooling package is used. Usually the air is heated up by some degrees. This value can be obtained from the test by measuring ambient air temperature and the temperature of the air in front of the cooling package.

In case of the simulation model that is being tuned by the additional pressure loss component on the air side the effect of air recirculation can be taken into account when creating this component. This will result in slightly different values for the temperatures of the air and air flow quantities and therefore in the fan not operating at the correct working point. A more correct way will be to create both heat addition and pressure loss components for tuning the simulation model. The drawback for this option is that generally this will require more test data and it can become complicated to balance these two tuning components.

## 2.4 Modelling and calculations in GT-Suite

In this section GT-Suite software and a module for building 3D underhood thermal management models called Cool3D are going to be introduced and discussed.

### 2.4.1 GT-Suite and its licensing system

GT-Suite is a software tool produced and distributed by Gamma Technologies (GT) that allows modeling and simulation of different systems in automotive and transportation engineering. According to GT website<sup>4</sup> it can work with a number of applications, see Figure 2.10.

- [Engine performance modeling](#) (including combustion and turbocharging)
- [Analysis of measured engine cylinder pressure](#) (combustion profiles)
- [Exhaust aftertreatment](#)
- [Acoustics of intakes and exhaust](#)
- [Sil, HiL and Real-Time simulation](#) of engine, vehicle, and cooling
- [Vehicle dynamics](#) (drive cycles, drivelines)
- [Hybrid and electric](#) vehicles, fuel cells
- [Cooling systems and vehicle thermal management](#)
- [Underhood cooling module analysis](#) (3-D solution with COOL3D)
- [AC and Rankine](#) Two-Phase Flow (AC, Rankine)
- [Lubrication circuits and bearings](#)
- [Fuel injection systems](#)
- [Hydraulics and pneumatics](#) (valve actuators, brakes, steering, power hydraulics)
- [Valvetrain/Camshaft](#) kinematics and dynamics
- [Cranktrain](#) kinematics and dynamics (balancing, engine bearings and mounts)
- [Crankshaft](#) durability and fatigue
- [Chain, gear and belt](#) system dynamics (timing drives)

Figure 2.10 GT-Suite applications (Gamma Technologies website<sup>4</sup>)

GT-Suite can be used for modeling each system independently or for coupling several systems together to make them interact with each other, so more complex systems can be analyzed. Gamma Technologies uses licensing system to give access to different components in GT-Suite. Initially the licenses were named according to the template databases they were providing access to. Starting from GT-Suite version 7.0 the licenses GT-COOL, GT-FUEL, GT-CRANK, GT-VTRAIN, and GT-DRIVE were all absorbed into a single license type called GT-SUITEmp. GT-POWER still has its own license type. In addition, there is a license called GT-SUITE that combines licenses GT-SUITEmp and GT-POWER, therefore covering all available components and providing access to all template libraries.

### 2.4.2 Basics of modelling in GT-ISE graphical interface

Modelling in graphical user interface of GT-Suite, that is called GT-ISE, is object based. Building of a part consists of several steps. At the beginning one needs to find a proper template in the template library and fill in different attributes to make a

component object. After the component object is created it is added to the current model. Next step is creating parts, it can be done just by dragging and dropping the component object to the model map. Parts created from a single object are absolutely identical and use attributes defined for the object, however they should have different names. Using one template it is possible to create many objects of one kind with different attributes. And one object can be used to create as many parts as needed. Attributes of all parts are changed simultaneously when changing object attributes. There is an option to change attributes for the single part without modifying the object, it is called “Part Override” and can be found when trying to edit part properties. This option should be used carefully and preferably only when testing the simulation model. If having different parts with similar attributes it is recommended to copy and modify the object and then create a part of the new object. Figure 2.11 shows representation of parts in the GT-ISE.

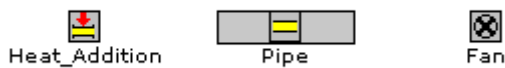


Figure 2.11 Model parts in GT-ISE

A lot of attributes and options in GT-ISE can be parameterized. To do so one should put a variable name in square brackets to the entry field instead of typing in actual value, see Figure 2.12 for example. All the parameters for the current model are defined at the Case Setup that is available from menu or can be accessed by pressing F4.

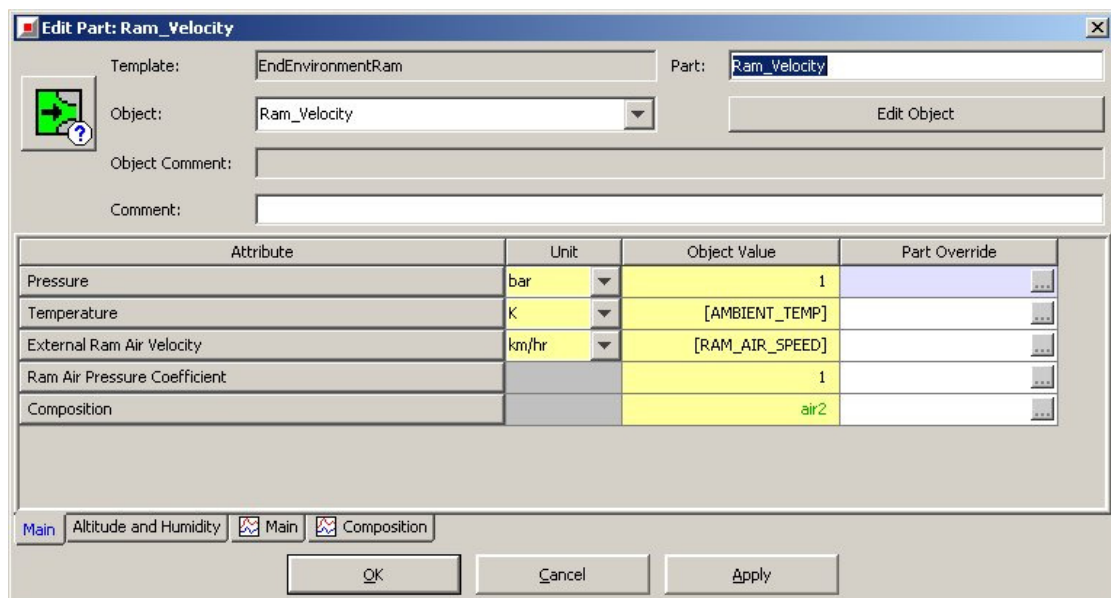


Figure 2.12 An example of parametrized object

To connect different parts of the model together links should be created. Two parts are usually connected by a link and a connector part that is inherited from a connection

object. A connection object must correspond to the way two parts are connected to each other. Examples of different connection objects can be found in Figure 2.13.

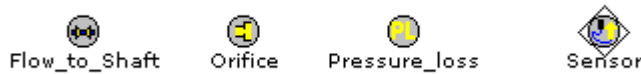


Figure 2.13 Connection examples from GT-ISE

Every object has a number of ports that can be used for the connection. Port numbers are displayed at the project map; the position can be seen in Figure 2.14. The description for the ports can be found by double-clicking the arrow linking objects.

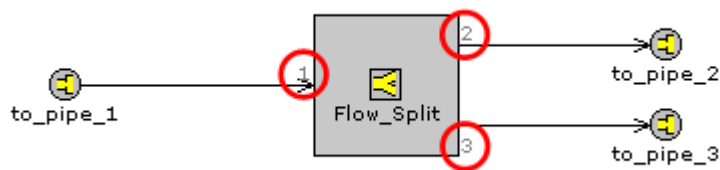


Figure 2.14 Port numbering in GT-ISE

For most of objects it is a crucial issue, meaning that one should always check port numbers used for connection to make sure that the model represents the reality in a correct way. For example, one can have different orifice diameters for each of three pipes connected to the FlowSplit object shown on the Figure 2.14.

In addition to the component objects and connection objects that can be used for part creation there are some kinds of objects that cannot be placed on the project map but they are directly linked to the first two types. Those objects are called reference objects and usually contain different types of data that are used in the simulation models for example lookup tables, boundary conditions, functions, liquid properties etc, see Figure 2.15 for examples.

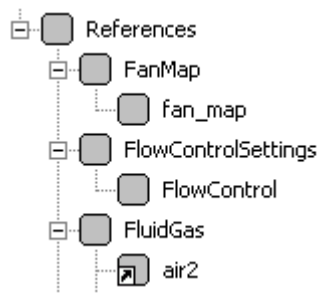


Figure 2.15 Reference objects in GT-ISE

More information about using the GT-ISE interface and some simple tutorials with step-by-step instructions can be found in GT-ISE tutorials (Gamma Technologies (2009a)<sup>14</sup>).

### 2.4.3 COOL3D

There is a special subprogram included in GT-Suite called Cool3D. This is a preprocessing tool that allows building 3D underhood thermal management models of vehicles, constructing it component by component and therefore allowing to include much more details than a usual 1D simulation model made in GT-ISE may have. See Figure 2.16 for an example of such a model.

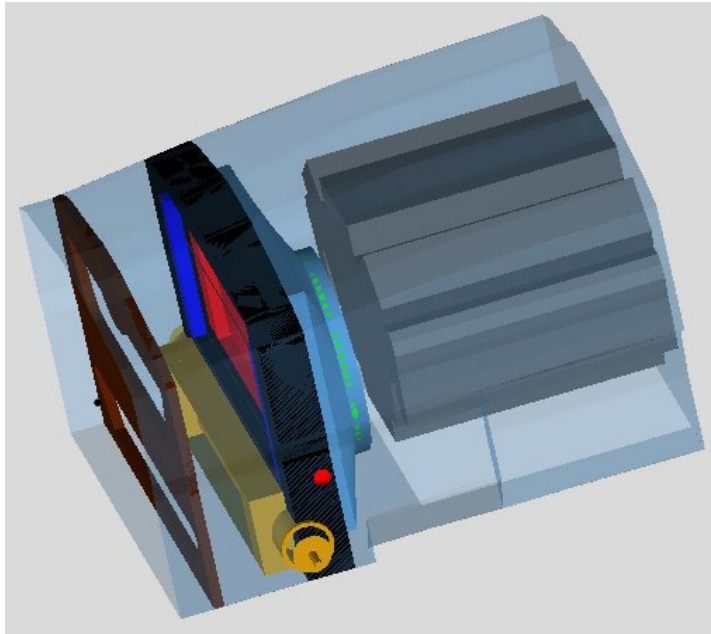


Figure 2.16 Example of the Cool3D model

After the 3D model being built Cool3D automatically discretizes it, as shown in Figure 2.17, and creates a GT model file (\*.gtm).

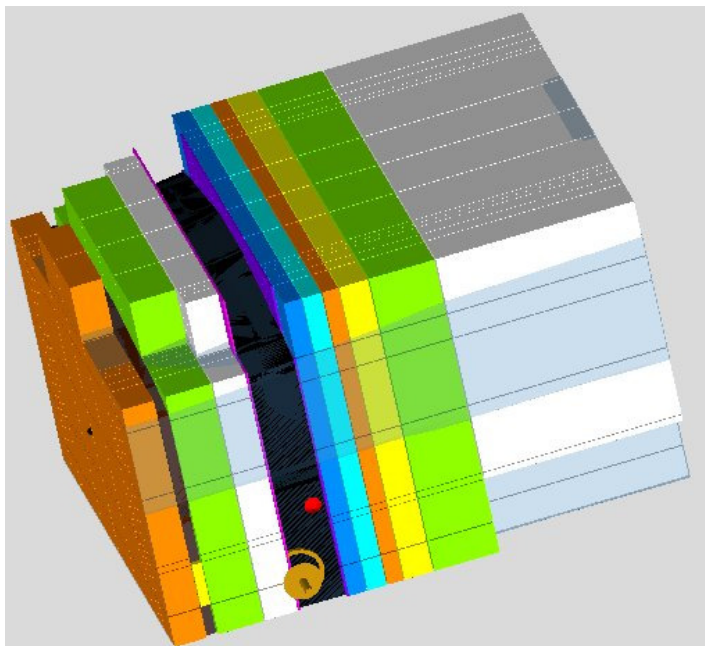


Figure 2.17 Example of the discretised model in Cool3D



Created model file can be added to the GT-Suite simulation as a subassembly and thus be used in calculations, see Figure 2.18 for a view of a subassembly and Figure 2.19 for the connection example.

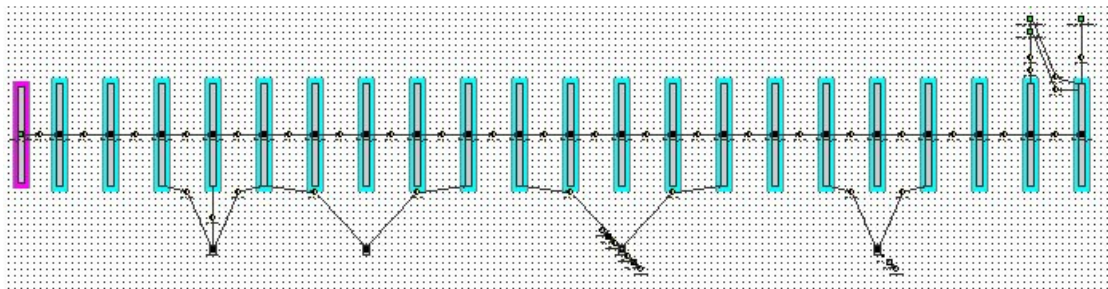


Figure 2.18 Subassembly after discretization

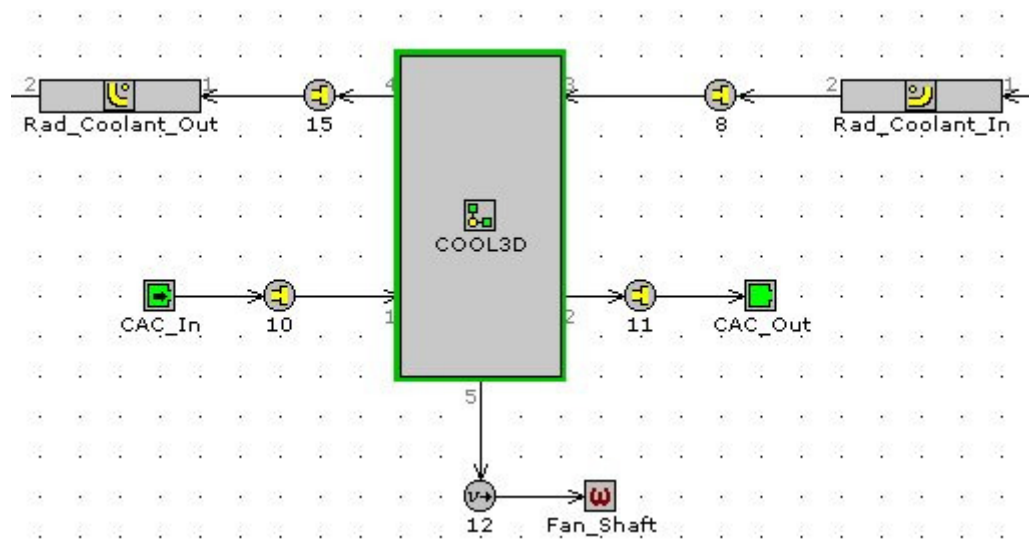


Figure 2.19 Cool3D submodel connected to the main model

It is important to check the connection port numbering when adding Cool3D subassembly to the main model. Information about the connection ports can be found in the .msg file located at the working directory. This file is created when discretizing the model.

## 2.5 Engine simulation coupling

GT-POWER and GT-SUITE licences allow working with engine templates in GT-Suite. Those templates can be used for detailed simulation of the processes in the internal combustion engine. Volvo Powertrain uses this feature of GT-Suite for their simulations. As there is one simulation tool used for cooling system and engine simulations it is possible to couple those simulations together. In this part different engine models used at Volvo Powertrain will be briefly discussed and some general ideas on coupling of models will be given.

### 2.5.1 Engine models

There are a number of engine models with different level of complexity used at Volvo Powertrain. To begin with, there is a very detailed simulation model also known as full combustion model that can be used to calculate characteristics of the working engine. By varying different input parameters the engine can be tested and tuned to achieve maximum performance. The drawback of this model is that it requires great computational power; hence there is a need to have a simpler simulation model that will give results that are close to reality but will be much less resource-consuming. The model that was used in this master thesis project is called mean value model.

The mean value engine model is simplified version of the full combustion model. The big difference between these two models is in the cylinder block object. The mean value model uses the data obtained from the full combustion model without actually performing any kind of calculations, therefore it works much faster. Mean value model allows changing different parameters like engine speed, the amount of fuel being injected, start of injection position, variable geometry turbocharger (VGT) & exhaust gas recirculation (EGR) parameters etc. As being based on the full combustion model this one gives results that can be considered to be accurate enough, that makes the mean value model the best solution for performing fast and reliable simulations of the engine performance.

### 2.5.2 Simulation coupling

The term coupling means connecting two or more models together so that those models exchange data in some way. The simplest way to connect two models is a one-way coupling; it is schematically represented in Figure 2.20.

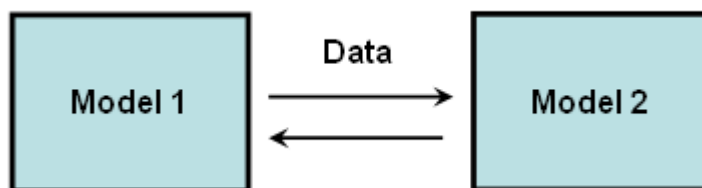


Figure 2.20 One-way coupling

In this case model 1 is generating some output variables that are taken as the input data for the model 2. Any changes inside model 1 that are affecting the output will

result in changing the results of the simulation model 2. On the other hand, changes made to the model 2 are going to affect only the results of the simulation for model 2 and will produce no changes to the model 1. If model 1 has a constant output this scheme even allows running models separately, in other words one comes to the two uncoupled models. Usually it is not the case and when speaking about simulation coupling people assume two-way coupling.

With two-way coupling models should only be run simultaneously as they interchange data between each other. In other words any changes in any of the models should influence the output data for both of them, see Figure 2.21.



*Figure 2.21 Two-way coupling*

This data exchange makes two models to be inseparable and force them to perform as one big simulation model. The system of two models is becoming looped meaning that any major changes in model 1 will influence model 2 and the output of it, therefore changing input for model 1, which will influence the output of model 1 again, etc. So when reacting to changes in variables this combined simulation model will need some iteration to reach the equilibrium point where the output-input variables have stable values.



## 3 Models, results and discussions

In this chapter the models that were built for performing simulations are going to be described. The results of simulations are going to be evaluated.

### 3.1 1D model with mapped engine

As it was already mentioned in this project, a model of cooling system for a Volvo FH truck with EU4 EGR engine is going to be constructed. This particular specification was chosen for the reason that there was an engineering report available for the cooling performance test performed with this truck.

A simple 1D simulation model with mapped engine will be presented in this section. It will be shown that this model requires tuning and this process is going to be performed. The results will be compared with experimental data.

#### 3.1.1 Model presentation

Even for a simple 1D cooling system model a lot data for different components needs to be obtained. It can once again be recommended for engineers to go through the GT-ISE tutorials (Gamma Technologies (2009a)<sup>14</sup>) and try building simple models according it to become familiar with GT-ISE interface. In addition one should look at cooling systems and thermal management tutorials (Gamma Technologies (2009b)<sup>15</sup>) to get a better understanding on how the cooling model is supposed to operate and what are the recommended settings and parameters for template objects and the simulation itself.

A model that was constructed can be observed in Figure 3.1.

As it can be seen there are three sides or three circuits in the model:

- Coolant side – closed loop circuit with pump, accumulator, engine block etc;
- Air side – circuit with Fan object and Condenser heat addition object, having an inlet at Ram\_Velocity and ending with boundary conditions at Air\_Boundary.
- Charge air side – small circuit at the bottom of the model in-between CAC\_inlet and CAC\_out\_bound.



Black lines represent actual connections like a pipe and a pump connected to each other with the coolant flow going from the first component to the second one or the heat being transferred from one side of the heat exchanger to another. On the other hand, blue lines represent signal and sensor connections, they allow to extract different types of data from the model like temperature, mass flow or volumetric flow. In Figure 3.2 one can see a pressure monitor used for measuring the coolant flow pressure before and after the pump object.

A detailed description of how the model was constructed component by component can be found in Appendix A.

### 3.1.2 Evaluation of the simulation versus real cooling performance test

As it has already been mentioned simulation model results are compared to the real cooling performance test results to evaluate the tool and the model. During the test, four experiments were conducted. The same four cases were modeled during the simulation.

#### 3.1.2.1 Cases setup for the real test

Experiments conducted had different engine speeds starting from 1800, then 1600, 1400 and 1200 revolutions per minute. All other parameters were fixed:

- Ram air speed: 39 km/h;
- Ram air temperature: 38 °C
- Pump/engine ratio: 1.91;
- Fan/engine ratio: 1.33;

#### 3.1.2.1 Results comparison

There is not so much data available from the test report results part. There are the values for the heat rejection rates through the radiator. These values were actually used for calculation of the heat rejection at different components when building a model; see Appendix A for the information on how the model was constructed. In Table 3.1 one can see values from the simulation and the test. The values are almost identical, that shows that heat transfer rates at different components were calculated correctly.

*Table 3.1 Heat transfer through the radiator, kW*

Case	1	2	3	4
RPM	1800	1600	1400	1200
Test	245.2	211.7	180.9	151.2
Simulation	245.4	211.9	180.9	151.7

Another thing that can be interesting to look at is the amount of air going through the radiator. Those values can be found in Table 3.2

*Table 3.2 Air mass flow through the radiator, kg/s*

Case	1	2	3	4
RPM	1800	1600	1400	1200
Simulation	8.39	7.65	6.73	5.79

As the engine speed decreases the fan speed is decreasing with it, which leads to the decrease in the air mass flow. There are no data available from the test results for the air mass flow but the simulation values will be further used for the comparison with the tuned simulation. (see section 3.1.3)

An important parameter in the cooling system is the coolant mass flow. It shows how much of the cooling mixture is pumped through the heat exchangers and therefore affects the cooling performance. This data was available from the test report and it can be compared to the simulation results. The comparison data can be found in Table 3.3.

*Table 3.3 Coolant mass flow measured at the radiator inlet, kg/s*

Case	1	2	3	4
RPM	1800	1600	1400	1200
Test	9.7	8.6	7.5	6.4
Simulation	9.7	8.6	7.4	6.3

From this data it is seen that the pump is operating in the way it is supposed to operate and pressure losses in the coolant circuit in general are modeled correctly.

Another interesting thing about the coolant mass flow is the amount of coolant going through the EGR cooler in comparison to the amount going through the engine block. This can be found in Table 3.4.

*Table 3.4 Coolant mass flow distribution according to simulation, kg/s*

Case	1	2	3	4
RPM	1800	1600	1400	1200
Flow through the engine block	6.6	5.8	5.1	4.4
Flow through the EGR cooler	3.1	2.8	2.3	1.9

This data shows that after passing the oil cooler around 30% of the coolant is going through the EGR cooler; other 70% goes through the engine block. This distribution directly corresponds to the reality.



One of the most important parameters for the cooling system and the last parameter to be compared is the top tank temperature or TTT for short. This is a temperature of coolant at the radiator inlet and approximately the highest temperature of coolant in the circuit. If it is too low the radiator performance will drop as the temperature difference between hot side and cold side of the radiator will be small. On the other hand TTT cannot be too high because in that case the coolant will boil. Top tank temperatures are compared in Figure 3.3

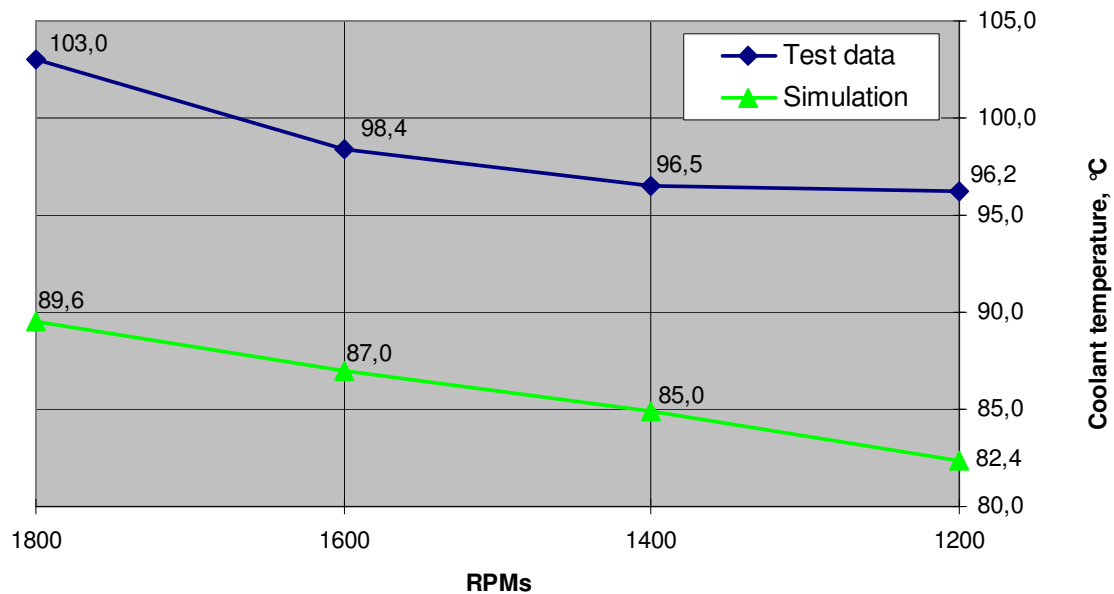


Figure 3.3 Comparison graph for top tank temperatures

As one can see temperatures from the simulation results are far below real temperatures. This happens because the amount of air going through the radiator is higher than it should be. The reason for this is that there are additional pressure losses on the air side that are difficult to measure and that were not included in the simulation, hence the model requires tuning.

### 3.1.3 Model tuning

In this section tuning process and the results of the tuned simulation are going to be shown.

#### 3.1.3.1 Changes made

Initially the condenser part had no pressure loss component as it is hard to predict this pressure loss. Condenser component pressure loss data cannot be used because the air is going through the condenser only partially and detailed modeling of this part will result in a more complex simulation model, so it was decided to model the condenser only as a heat addition object. Having this in mind and the idea of some additional pressure losses that were not taken into account, like grill pressure loss, leads to the fact that the model requires tuning. Another effect that was taken into consideration by tuning the model was hot air recirculation, see section 2.3 for more information.

Tuning was done at four points, one for each of the test cases. It was done by adding a pressure loss component after the condenser with the characteristics that result in temperatures in the cooling circuit that matches test results. This additional pressure loss component is called “Blockage”, it can be seen in Figure 3.4.

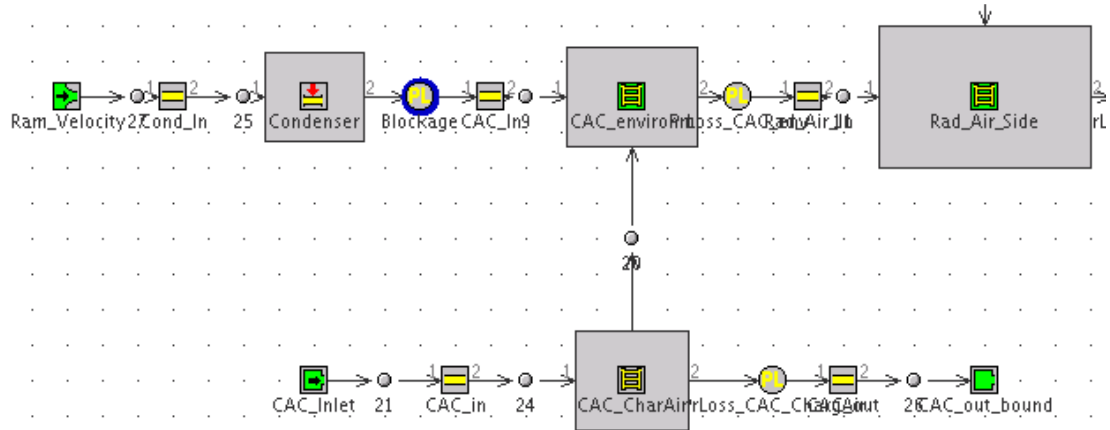


Figure 3.4 Tuning with additional pressure loss component

The pressure loss law that was used for this additional tuning pressure loss component can be seen on the Figure 3.5 where it is compared to other components in the system.

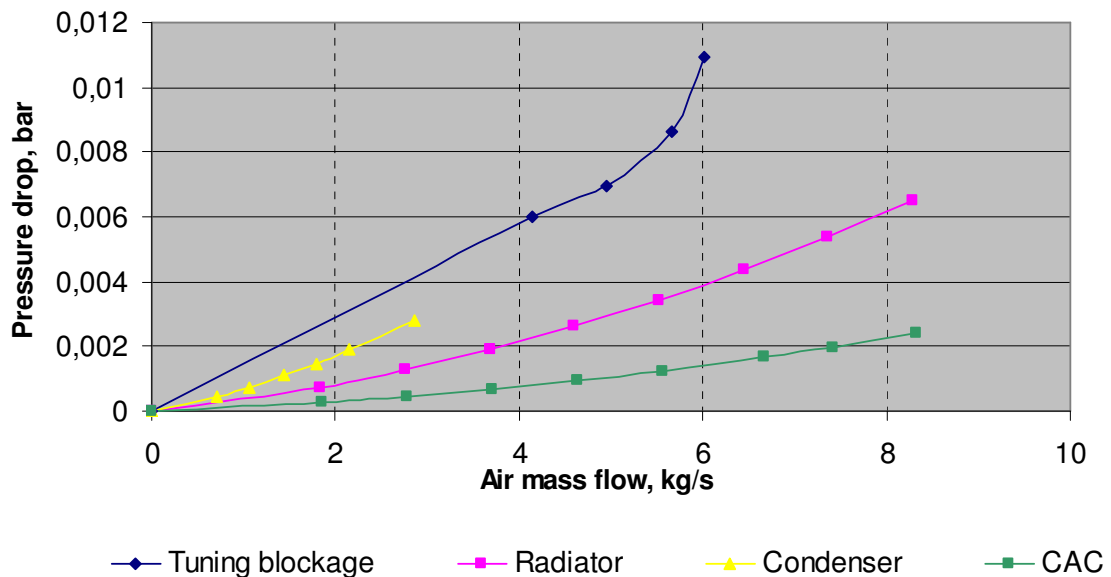


Figure 3.5 Tuning blockage pressure loss law

A fifth point at (0,0) was added since there should be no pressure loss when there is no air going through the component. As one can see tuning pressure loss is rather high in comparison with losses from other components and the curve is not perfectly quadratic. It should be said that the model was tuned for a certain range of air mass flows and if dealing with air flows that are far from this range the model will require additional tuning.

### 3.1.3.2 Results comparison

When comparing tuned model to the untuned one from Section 3.1.1 it can be seen that temperatures for the new model directly correspond to the test data, as shown in Figure 3.6.

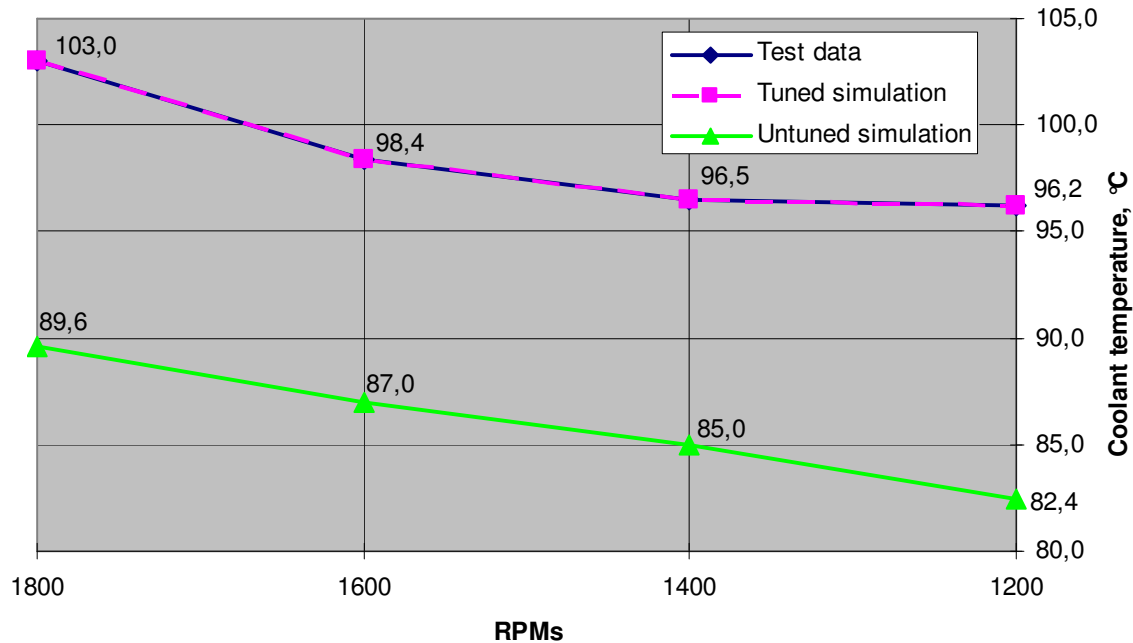


Figure 3.6 Top tank temperatures for the tuned simulation model

Mass flows for the coolant are almost the same but as it can be expected there is a difference in mass flows on the air side. Those differences are shown in Table 3.5.

Table 3.5 Air mass flow through the radiator, kg/s

Case	1	2	3	4
RPM	1800	1600	1400	1200
Untuned simulation	8.39	7.65	6.73	5.79
Tuned simulation	6.02	5.67	4.94	3.98

As one can see the air flow for all cases was decreased by around 30%. This is expected when adding a large pressure loss to the circuit. As a result of the tuning the air flow through the radiator is decreased and the air temperature at the radiator inlet is increased. Both of these facts result in a significant temperature rise at the coolant side.

### 3.1.4 Summary for the 1D modelling

Any simulation model needs to be validated against experimental data. In our case as there were too many uncertainties about the pressure losses on the air side of the system the model required tuning. It was done by adding a new pressure loss component that took into account various things that were missing including the effect

of hot air recirculation. After being tuned the model was producing good results that were matching experimental data.

Instead of tuning the air side of the model with additional pressure loss components Gamma Technologies suggests that one should replace the air side with a Cool3D model as it should produce better results. That is going to be evaluated in the following section.

## 3.2 Cool3D evaluation

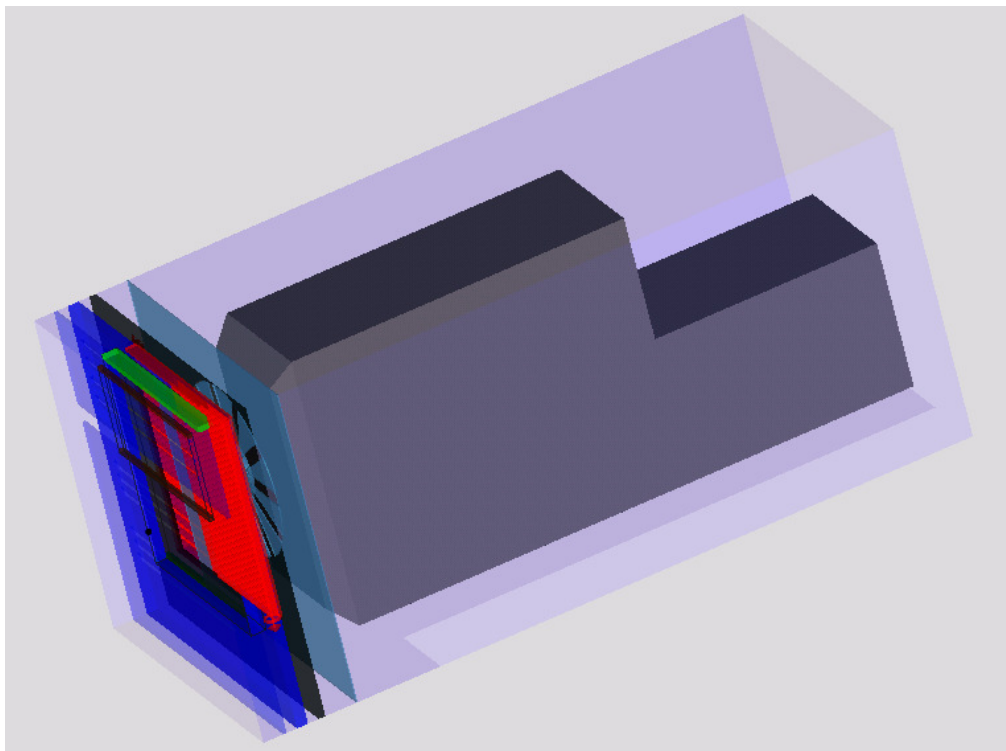
In this section a preprocessing tool called Cool3D that allows building 3D underhood thermal management models is going to be evaluated, see Section 2.4.3 for more information. For this evaluation several models were created. The results of the simulations were compared to the same cooling performance test as in Section 3.1.2. First of all a simple 3D representation model of the cooling package and engine area was created. Secondly different geometry modifications were tested to try including the effect of air recirculation, see Section 2.3 for the description of the effect. In this part models tried and the results achieved will be presented. At the end of this section the results of the evaluation process will be summarized.

### 3.2.1 Model 1: Simplified underhood

In this section the first Cool3D model that was constructed is going to be presented. A process of connecting this model to the simulation model constructed in Section 3.1 will be described and the results of the simulation will be shown.

#### 3.2.1.1 Model description and creation

The first simplified model that was created can be seen in Figure 3.7.



*Figure 3.7 Simplified Cool3D model*

This is a very simplified model as the air flow was forced to go through the charge air cooler radiator and fan not allowing any of bypassing or recirculation. When creating this model CAD data was used to determine parts geometry and position, but still the engine block, front grille and the whole air flow area were simplified significantly. A

more detailed description of this model and part creation can be found in the Appendix B.

As it was described in the Section 2.4.3 after discretization and creation of the subassembly .gtm model file this subassembly can be connected to the main model. The new model that was obtained can be found in Figure 3.8. The Cool3D subassembly is highlighted.

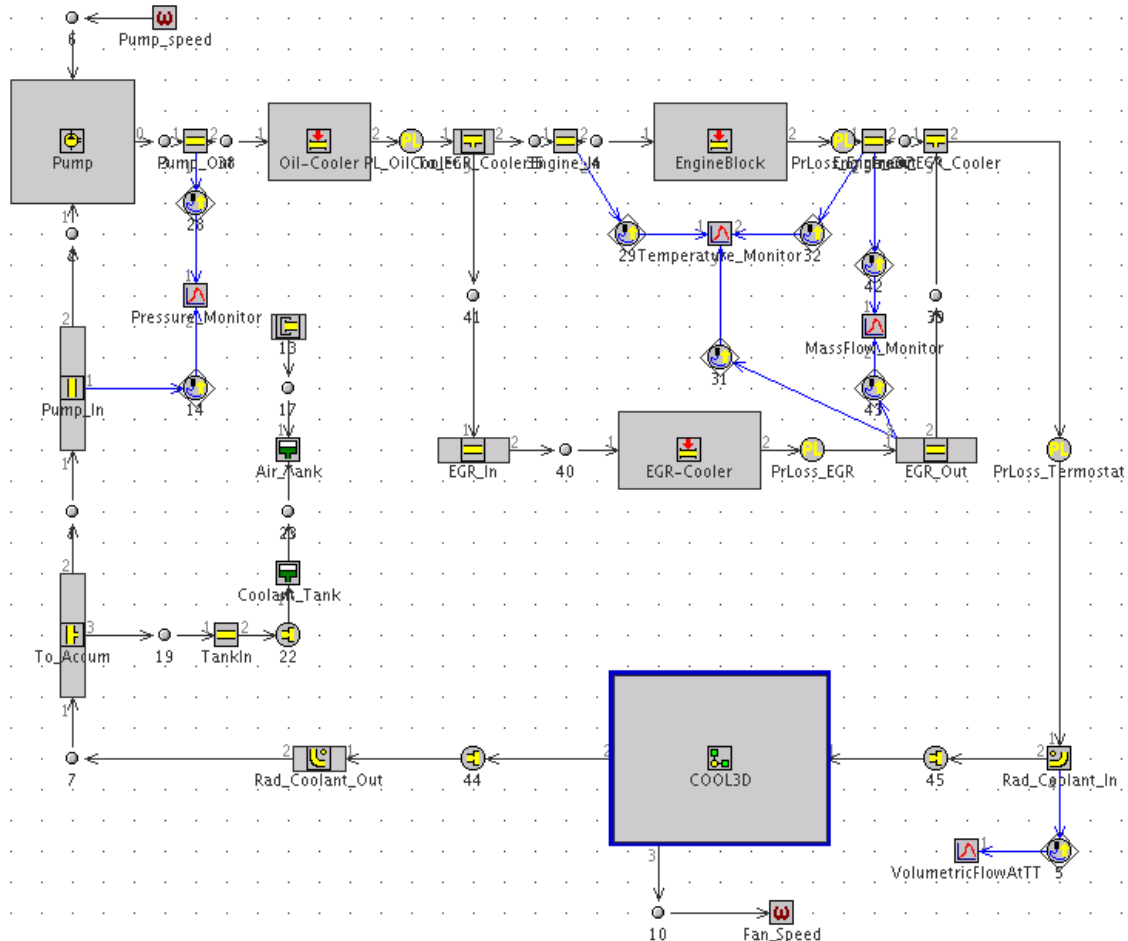


Figure 3.8 Main model with the addition of the Cool3D subassembly

As it can be seen the cold side of the model was completely removed and replaced by the Cool3D subassembly that was connected to the cooling circuit.

### 3.2.1.2 Model results

The model results are again compared to the same data obtained during real cooling performance test of the FH truck.

As in the case of the 1D model without using Cool3D the results for the coolant mass flow are close enough for all four cases. The maximum discrepancy of 3% between test and model was found in case 4 (1200 RPM). The most important comparison can be made when looking at the top tank temperatures. Here the results look promising especially if compared to the results of the untuned simulation model from Section

3.1.2. The comparison graph for the coolant temperatures at the radiator inlet is in Figure 3.9.

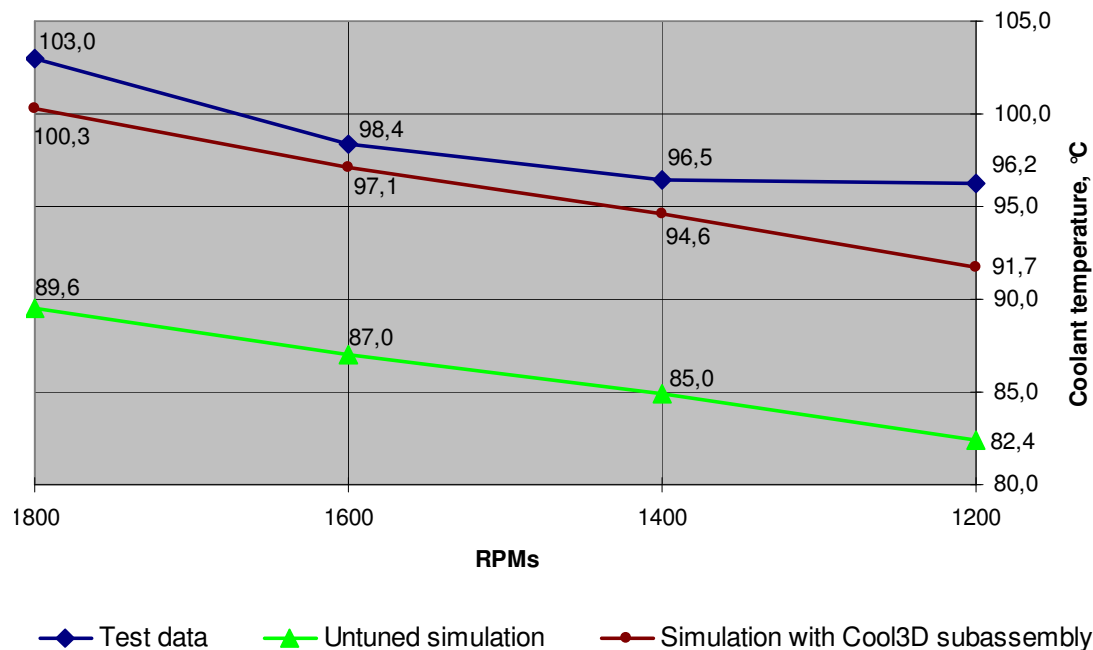


Figure 3.9 Comparison graph for the model with Cool3D subassembly

As one can see coolant temperatures are rather close to the test values but still 2-4 degrees below them. This happens because of numerous simplifications that were made for this model especially the lack of any air bypassing heat exchangers and air recirculation effect described in the Section 2.3. To achieve more satisfying simulation results the decision to try more Cool3D model modifications was made.

### 3.2.2 Model 2: Simplified underhood with ambient air preheating

One of the possible solutions used in the industry for the simulation of hot air recirculation effect is the ambient air preheating. The temperature difference between the ambient air and the air at the radiator intake can be actually measured during the test. For the second Cool3D model ambient air temperature was increased by 3°C. The results for the coolant temperature comparison can be found in Figure 3.10.

In this case the results of the simulation are much closer to the test data and the maximum difference in top tank temperatures was decreased to just 2 degrees. This result can be considered to be good enough but it was decided to try building a model without preheating that can actually include the effect of hot air recirculation as the Gamma Technology support group responded that it is possible with Cool3D.

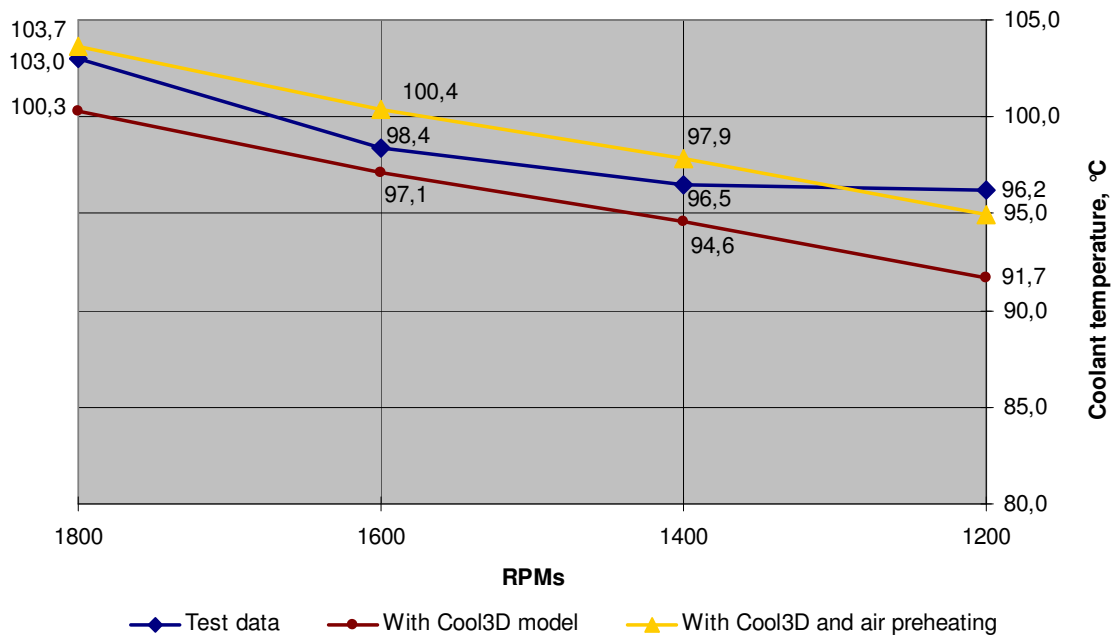


Figure 3.10 Comparison graph for the model with and without ambient air preheating

### 3.2.3 Model 3: Simplified underhood with gaps for recirculation

In this section a modification of the first Cool3D model will be described and evaluated.

#### 3.2.3.1 Model description

To try modeling the effect of hot air recirculation it was decided to try having a 10 mm gap between the flowspace boundaries and all the blockage parts except the front grille. One can observe gaps that were created in Figure 3.11.

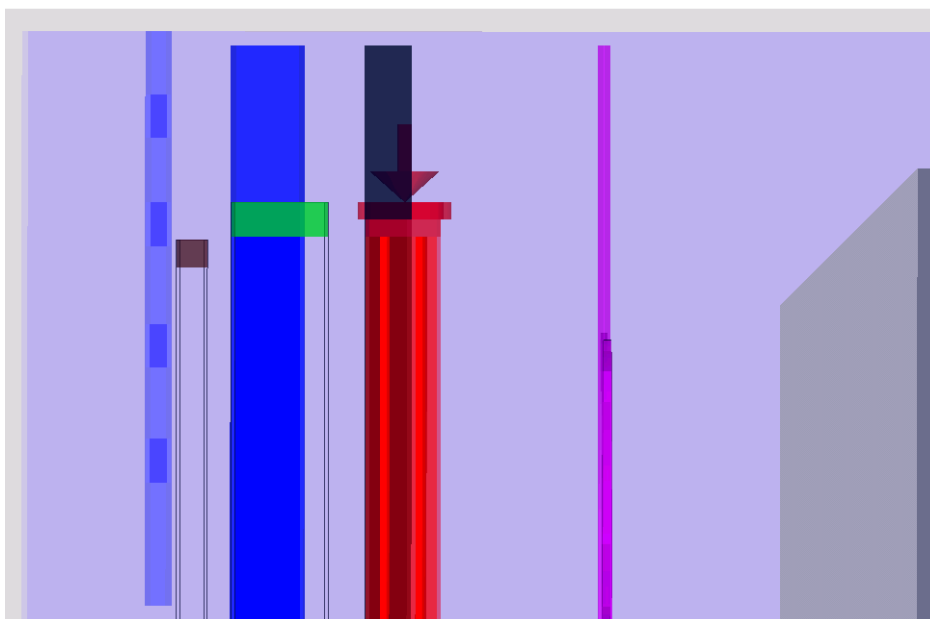


Figure 3.11 Gaps for air circulation in model 3



### 3.2.3.2 Model results

The results of the simulation with this model were not satisfying at all. First of all at the area of the charge air cooler and the radiator the air flow was using gaps to bypass these heat exchangers, for example, only about 80% of the air were going through the radiator, 20% were bypassing. Secondly, the gap at the fan part was used for recirculation of air from one side of the fan to other, therefore decreasing the total amount of air going through the system. This case is shown schematically in Figure 3.12. The weight of the arrow line approximately represents the air flow quantity.

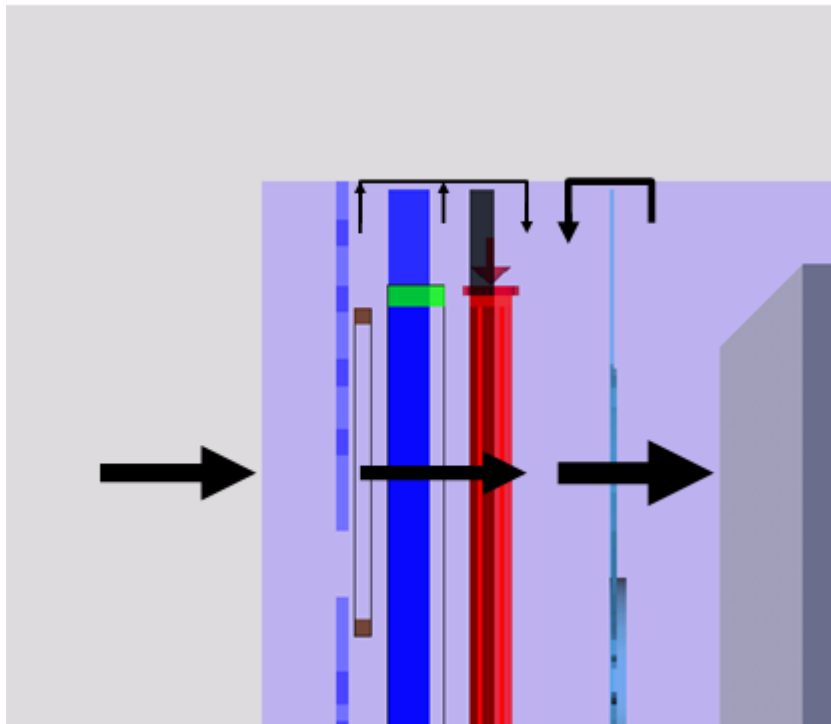


Figure 3.12 Air flows in the system for the model with 10 mm gaps

As the radiator performance is highly affected by the amount of air going through it temperatures in the cooling system were far from the test results. All temperatures were at least 10 degrees higher than the expected values.

### 3.2.4 Model 4: Simplified underhood model with fan shroud

Model 3 was improved by adding a fan shroud. A new model that was obtained is evaluated in this section.

#### 3.2.4.1 Model description

As it was proven by model 3, the fan area obviously needs to be revised. To improve this part of the model the fan shroud was added, therefore not allowing the air to recirculate around the fan only. An improved model can be seen in Figure 3.13.

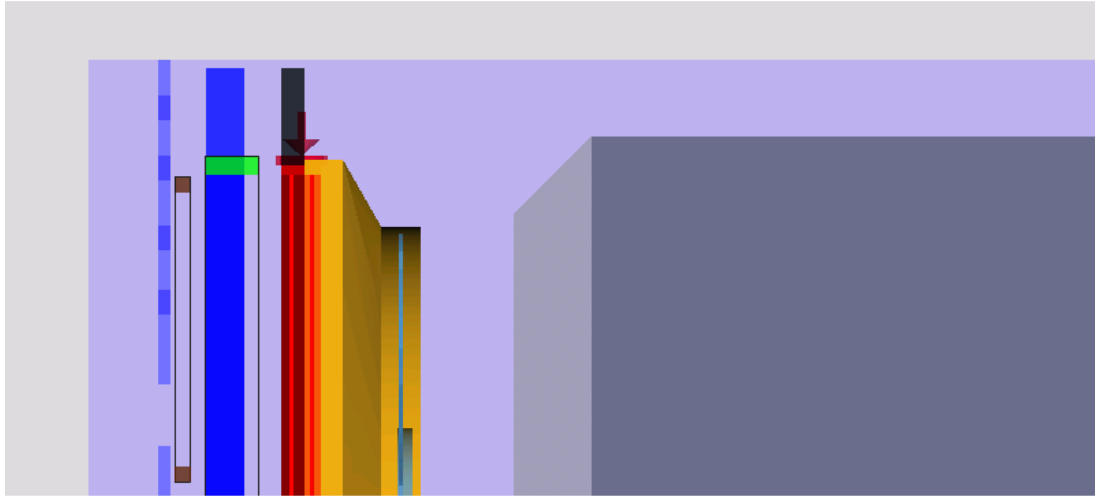


Figure 3.13 Fan shroud introduced to the model

### 3.2.4.2 Model results

As it was the main idea for the fan shroud improvement, air recirculation around the fan only was reduced significantly. A small amount left was due to the fact that there was a small gap between the fan and shroud but the quantity of this air flow was insignificant. In addition to that there was no bypassing of the radiator part; instead some hot air recirculation appeared in this region: about 3-5% of the air passing the radiator and fan was coming back through the gaps and going through the heat exchanger again. For the charge air cooler the effect of the air bypassing it remained but was slightly decreased. The results for this model in comparison with others are presented in Figure 3.14.

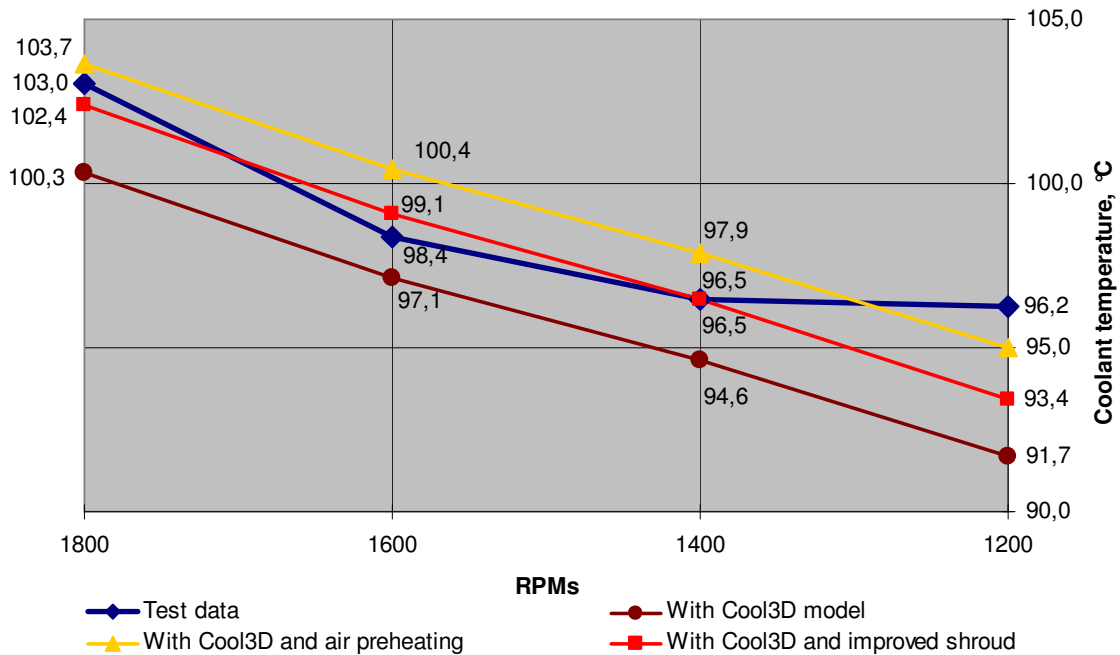


Figure 3.14 Comparison graph for the different Cool3D models

As one can see coolant temperatures in this case were close to the test results but it should be said that this seems to be just a coincidence. This model does not give right

amounts of the hot air recirculation especially in the CAC region, therefore it is hard to trust the results. In reality the gap between charge air cooler and radiator is more or less sealed and the hot air is forced to recirculate around the entire cooling package. Last model was constructed to simulate that.

### 3.2.5 Model 5: Model with fan shroud and sealing

The last model tested, which is the further improvement for the model 3 and 4, and simulation results are going to be described in this section.

#### 3.2.5.1 Model description

As it has been mentioned the amount of air recirculating around the radiator only is rather insignificant in real life, therefore it was tried to seal the gap between CAC and radiator as it can be seen in Figure 3.15.

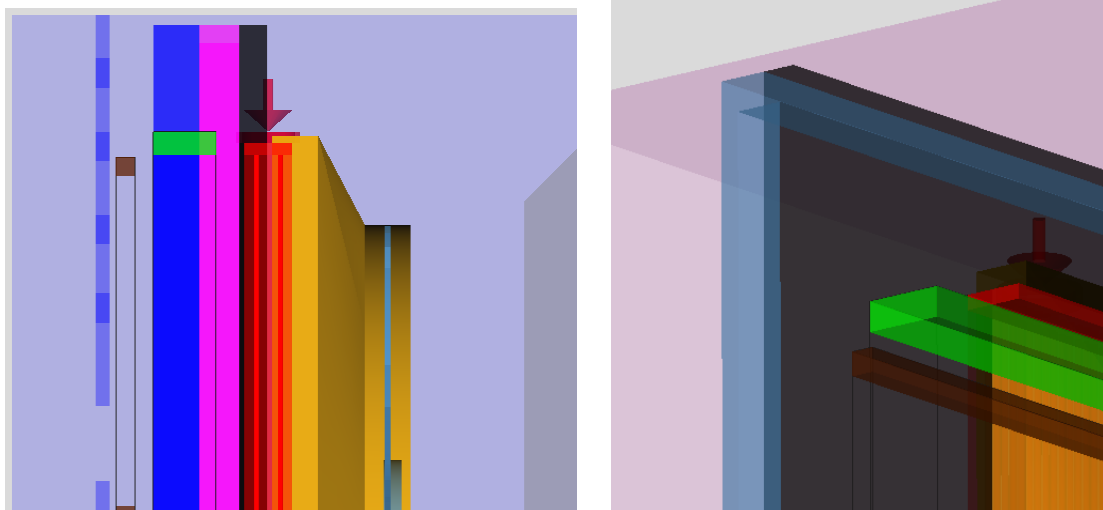


Figure 3.15 Gap sealing to improve recirculation

#### 3.2.5.2 Model results

For the temperatures in this case the results are shown and compared to other cases in Figure 3.16.

As it can be seen the temperatures in this case are a little higher than for the case with preheating, and higher than in previous case because now the air is going from the high pressure region after the fan to the intake of charge air cooler and partially even condenser and not only radiator, hence one should have higher temperatures in front of the condenser, CAC and radiator and all of this should result in higher temperatures of coolant in the system. That is exactly what can be observed. Here it can once again be said that having a 10 mm gap for air recirculation was just an assumption and it is hard to expect exact test values to appear.

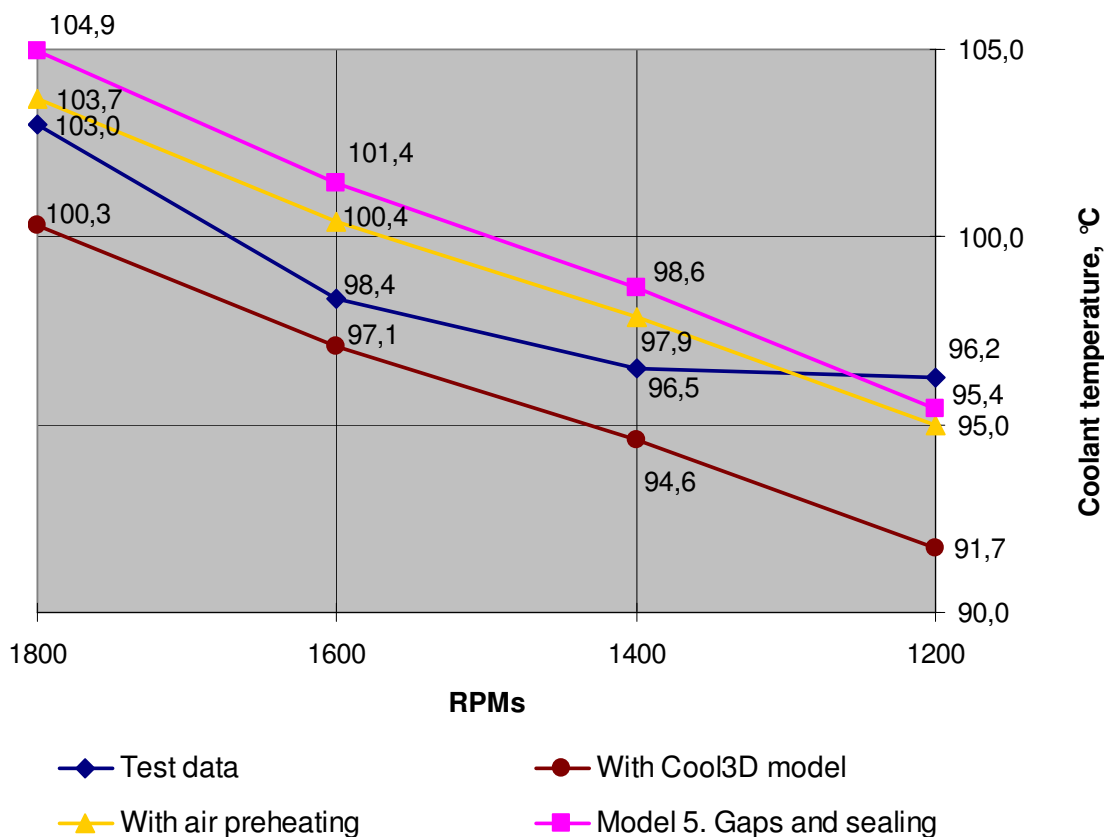


Figure 3.16 Comparison graphs for model 5

### 3.2.6 Results of the Cool3D evaluation

It should be said that it took some time for the author to understand the tool and to make the model operate in the way needed, but in the end the Cool3D software appeared to give the results that were rather close to the test data and to do it without any additional tuning of the model.

When speaking about the effect of hot air recirculation it should be said that the effect can be captured by Cool3D, but in this case it will require the user to create a rather detailed model of the cooling package. Having a model with insufficient amount of details can result in incorrect air flow quantities through different heat exchangers and fan, hence leading to incorrect results for the simulation in total.

It seems that the best way to take the effect of hot air recirculation into account is to have a preheating of the ambient air as it was done for the model 2, see Section 3.2.2. This will allow the user to have a very simplified model of the cooling package and still get reasonable and reliable results.

As the drawback of the Cool3D subprogram it should be mentioned that the simulation time for one case run can increase significantly depending on the discretization of the flow space. Another drawback is that Cool3D does not allow importing any CAD data forcing the user to create all the geometry more or less manually.

### 3.3 Evaluation of simulation model coupling

As it was said in Section 2.5 Volvo Powertrain is using GT-Suite for engine performance simulations, therefore there is a possibility to couple those simulation models with the cooling performance simulation model built in Section 3.1. It could have been possible even if another simulation tool was used but common simulation software makes it much easier.

In this section coupling process will be described and a response test for the obtained model will be performed.

#### 3.3.1 Coupling of two models

A mean value engine model for US10 EGR engine was received from Volvo Powertrain. The cooling system that is used with this type of engine is very close to the cooling system used with EU4 EGR engine that has already been modeled. It only requires few modifications to be done.

To couple two systems four heat exchangers at the cooling system model needs to be connected to the engine model by four connection links.

First of all charge air circuit from the cooling system model was merged with the same circuit available in the engine model. The HxMaster object was connected to the HxSlave object at the air side of the original cooling system model, therefore making a two-way coupling connection link. The same was done for the exhaust gas recirculation cooler, creating a second two-way coupling connection link.

For the oil cooler and the engine block the mean value model does not allow having a two-way coupling, it only gives the amount of heat release that should be taken away by the cooling system. That limits the user to have a one-way coupling connection links.

The value for the heat input rate from the engine block can be directly extracted from the engine cylinder mean value object (EngCylMeanV). The output variable is called "Heat Transfer Rate". The value is in watts so it needs to be scaled by 1000 to obtain data in kW needed as an input valuable at EngineBlock object of the cooling system model.

For the oil cooler things are a little bit more complicated. In order to calculate the heat exchange rate the friction torque should be calculated. For this purpose a MathEquation object was used. The CrankShaft object of the mean value model allows extracting the values "Inst. Indicated Torque" and "Inst. (Indicated-Friction) Torque". Subtracting second from the first will give the value for friction torque in Nm. To obtain the value of friction power that is exactly the value needed one should use the following formula:

$$P_{fric} (W) = \tau_{fric} (Nm) \cdot \omega (rad / sec) = \tau_{fric} (Nm) \cdot 2\pi \frac{rpm}{60} \quad (3.1)$$

Again this value should be divided by 1000 because the Heat Input Rate parameter at the oil cooler heat addition object uses values in kW. A complexity of the system of two coupled models can be observed in Appendix C. Different colors represent borders of different models. Blue corresponds to the cooling system and red to the engine. Details are omitted due to secrecy reasons.

In general two models are connected in the way presented in Figure 3.17.

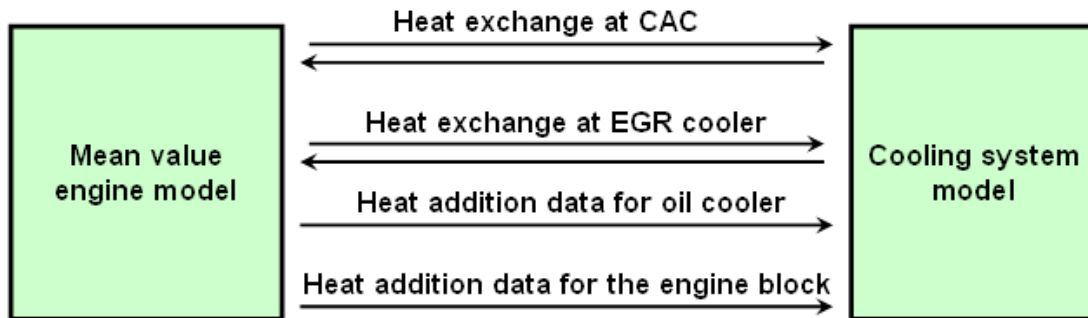


Figure 3.17 Coupling of engine and cooling models

To finish merging of two models together separate solvers for different circuits should be defined in Run Setup. The explicit solver is going to be used for the engine model circuit and implicit one for cooling circuit and air circuit at the cooling system model. Some parameters also need to be changed at the case setup for the engine simulation model like the ambient air temperature and pressure or initial temperatures in the system. Pump speed ratio for the coolant also needs to be changed to 1.76 as it is the one that is used with US10 EGR engine model.

The main controls for the mean value model are located at the SimulinkHarness object called simulink-1. Originally this engine model was intended to run simultaneously with the Simulink software<sup>16</sup> that allows the user to control and change some important parameters while the simulation is running. If Simulink is not found the model uses default values that are defined in the object mentioned above. As the cooling system model from Section 3.1 has a thermostat modeled to be fully open initial inputs at simulink-1 object should be set in the way that engine will work at high RPMs and high load, therefore generating high heat release rates to the cooling system. That will cause high temperatures of coolant in the system and hence the assumption of fully open thermostat will be valid. The model could easily be rebuilt with a controlled thermostat; however this has not been studied in this project.

### 3.3.2 Coupling results and response test for the system

After running the coupled simulation model of engine and cooling system certain results were obtained. It should be said that the amount of heat release at different heat exchangers was reasonable, therefore temperatures, mass flows and pressures at all parts of the merged simulation model had values in the expected range. It was proven that coupling of two simulation models is possible and easy to make. In order to test the coupled system it was decided to study the system response on changing of the fan speed ratio from 1.33 to 1.5.

In theory, a higher fan ratio will lead to an increase of air mass flow going through the radiator; that will affect the heat exchange through this component. Consequently lower temperatures on the coolant side will be obtained. With lower temperatures in the coolant system one should get lower temperatures of EGR gas after the EGR

cooler. In the same way increased air flow through the charge air cooler will result in the decreased temperature of charged air. Having both EGR gases and charged air temperatures dropped, their mixture at the intake manifold will also have a lower temperature.

After running the simulation with two different fan speeds and no other changes made the following results were obtained:

- Air mass flow through the system increased by 10%;
- Temperatures in all parts of the coolant circuit decreased by more than 4°C;
- Temperature of the charged air after the heat exchanger decreased by 1°C;
- Temperature of the EGR gases after the ERG cooler decreased by more than 3°C;
- Temperature of the EGR-Air mixture at the intake manifold decreased by 1.5°C
- Temperature of exhaust gasses decreased by 1°C;
- Heat release to the coolant system decreased insignificantly for the oil cooler and the engine block;
- Heat release for the EGR cooler increased by 1kW.

When speaking about the heat release at the oil cooler and the engine block one should remember that those parts are having only a one-way coupling. For the engine block with only intake mixture temperature decreased, it is normal to expect slightly lower heat release. In fact the decrease is so small that those values can be considered to remain constant.

For the EGR cooler the situation is different. From the exhaust gas side the temperature is changing rather insignificantly; there is a change of 1°C when the temperature of exhaust gases after the combustion is around 580°C. From the coolant side of this heat exchanger relative change in temperatures is much higher. Coolant temperature is decreased by more than 4°C. Having a higher temperature difference on different sides of the heat exchanger without other parameters being changed, one should expect to see an increase in heat transfer; that is exactly what can be seen from the results of the simulation.

### **3.3.3 Summary for the simulation coupling**

Coupling of engine and cooling system models allow engineers to get a better understanding of how the whole system it operating and how it can be improved. The results of such merged model simulation in general can be more reliable than the results of the cooling simulation with mapped engine data. Some effects can only be modeled with the coupled simulation, for example, the change in amount of the heat rejected to the coolant system when changing the temperature of the coolant.

One should remember that with increasing complexity of the simulation model the possibility to make a mistake and the time needed to find and correct this mistake increases, therefore constructing a very complex simulation model without testing its parts separately can be considered to be not the best idea. Hence, different models can be tested separately by different engineers and then they can be coupled together using a small number of connection links. In this case the only thing that will need to be tested is the data values transferred through these links.

On the other hand, one should remember that running coupled simulations it can be useful to have some additional computational power, otherwise the simulation time can increase significantly.



## 4 Software problems and limitations

GT-Suite is constantly developing software; it works on different operation systems and has many different versions. As any of big software products this one has some software bugs, problems and limitations.

### 4.1 Software problems

The worst thing found during the project execution was the lack of downward or backward compatibility for a few templates between different versions of software: some object templates for engine simulations created in GT-Suite v.6.2 refused to work properly in version 7.0. If forward compatibility issues are assumed to be something rather normal in software world, programmers usually tend to make their developing products backwards compatible. In the software defense it should be said that for everything else model update wizard was working correctly.

Another problem found during the project is an issue with the runtime monitors on Redhat Enterprise Linux causing the simulation to shut down. This was reported to the GT support group and the work on resolving this issue was begun.

### 4.2 Software limitations

During the project work a number of limitations of the GT software were found. As being in constant contact with support group of Gamma Technologies, some complains were sent and a number of problems faced are going to be fixed in upcoming versions of the software.

In this section different problems with software that occurred during the project are going to be covered, in addition the possible way around for some of them will be given.

#### 4.2.1 No egl-4060 mixture and the FluidMixture template limitation

Volvo is using special mixture called Havoline XLC mixed with water as a coolant for trucks cooling system. It is a mixture of ethylene glycol, water and some special components. As a rough estimation it can be said to contain 40 per cent of ethylene glycol and 60 per cent of water. Such mixture is not available in the GT database. The GT support group suggested to use the FluidMixture template with mixing of water and egl-pure. Firstly that did not work generating critical error but after updating software and model files to the latest version it worked generating only warning. There were two problems with such an assumption. Firstly, GT FluidMixture template allow only mass fractions and does not allow to set volume fractions, in reality 40/60 are volume fractions. So to compose the right mixture in GT-Suite mass fractions need to be calculated. Secondly, the template used was dealing with mixture components almost independently and water has a boiling temperature at 100 °C while cooling mixture is supposed to be working on temperatures up to 108 °C, in addition there was another critical warning generated for the bad enthalpy fitting for pure ethylene glycol on high temperatures. The decision of using the mixture of egl-

2080 and egl-5050 was made as they are closer in composition to the coolant fluid that needs to be created. Mass fraction calculations for these mixtures to compose egl-4060 can be found in the Appendix D.

#### 4.2.2 Pressure loss connection object limitations

There are two limitations with pressure loss connections. Firstly interpolation between points and what is more important extrapolation seems to be linear. That cannot be correct because usually pressure loss grows proportional to the second order of the flow. The way around this problem that was used in this project is to make manual extrapolation and interpolation in additional software and then use it when creating a PL component. In this case inter/extrapolation was done in MATLAB<sup>17</sup>. An example of the experimental data and the data obtained after performing the operation described is shown in Figure 4.1.

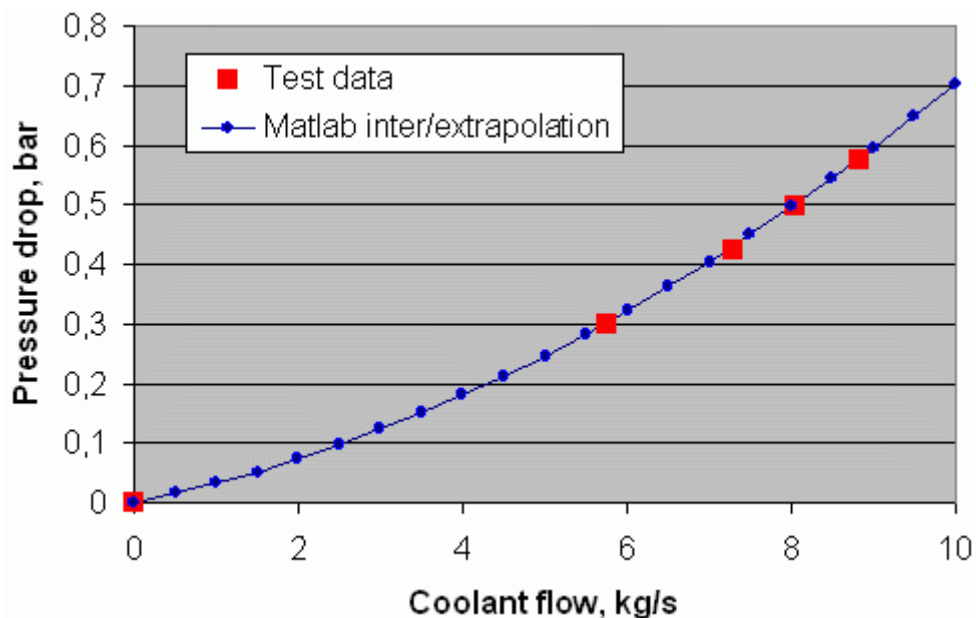


Figure 4.1 Pressure loss data for the fully open thermostat

The second problem with the pressure loss connection is that generally it is not dependant on the fluid and temperature of the fluid that was used for the test when obtaining data. There is a way to include the temperature dependency into the pressure loss component by using Table2D object when defining input data type for PL component but in this case in addition to the flow rate used needs to define only upstream fluid temperature and not both up/downstream temperatures as it is done in KULI. That can be a crucial issue for a heat exchanger with a high temperature change like the EGR cooler.

### **4.2.3 Fan object limitations**

The fan performance in GT-Suite is dependent on the fan speed, even for the overblown conditions. The fan speed cannot be calculated by the software and should always be directly defined by the user. If defining fan speed as zero this component will work as a complete blockage not allowing any air to path through. Hence, if trying to model fan-off conditions one should set the fan speed to some modest value that will correspond to the speed of fan free rotation.

### **4.2.4 Cool3D limitations**

One should be as precise as possible, depending on available data, when building a Cool3D model. It should be said that overlapping components may result in wrong processing of the data entered and hence undesirable results for the whole simulation. For example, the fan shroud intersecting with radiator object can result in first not to be seen by software at all and consequently the fan not operating appropriately.

Next thing that should be mentioned is that depending on the discretization mesh size that is going to be used in Cool3D program, time for the main simulation can increase significantly. Cool3D automatically discretizes the air space around the important objects so there is no need to have fine mesh everywhere, but still having a smaller mesh size will increase the accuracy. Based on simulations carried out during the master thesis project one should expect at least 10 times longer simulation times in case with Cool3D model included in comparison with simulations without it.

This computation time can increase even more in case if one is running a closed loop simulation. Another thing that can add a significant run time is initial boundary conditions that should be set close to the final state conditions expected in case if there is no need for warm up modeling. The third important thing here is a simulation type, meaning that if one is running transient simulation and not using steady wall temperature solver this will also increase the simulation time. Based on everything mentioned above, it can be said that if running simulation models with Cool3D subassemblies included, one should preferably have a higher computation power than when performing a simulation with a simple 1D model.



## 5 Conclusion

As a result of the project a simulation model of a cooling system of the FH truck was created. It was shown that a simple 1D simulation model requires tuning as it is impossible to include all the details for the air side of the cooling system, but after the tuning it can definitely be used as the simulation results that were obtained directly corresponded to the experimental data.

It was shown that tuning could be omitted when using Cool3D module for creating a 3D model of the underhood flow of the vehicle. In this case the effect of hot air recirculation should be taken into account. The most efficient way to do it, as it was shown in Section 3.2.6, is to use ambient air preheating.

For the coupling of cooling system and engine simulations it was shown that it is possible and can easily be done, a brief description on how to do it was given. It was shown that coupled system respond to changes in the way it is expected.

Speaking about GT-Suite as a tool for cooling performance simulations it can be said that as any of others big software products it has some problems and limitations that were partially covered in Chapter 4, but a general impression that was left by the software is very good. It can definitely be used for modelling cooling systems, it has a nice user-friendly interface and good help and tutorial manuals. It should also be said that the author was impressed by Gamma Technology support group competence, they were responding with very fast and detailed answers.

It has been very inspiring to work with the front line technologies in the area of cooling performance simulations. The author hopes that this thesis project can contribute to further development of simulation methods used for cooling analysis at Volvo 3P.



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## 7 Appendices

### A. 1D model construction

#### Boundary conditions

- Coolant side is a closed loop circuit so there are no boundary conditions for it;
- For the air side boundary conditions were defined in the following way:
  - For the air inlet EndEnvironmentRam object was used defining ram air static pressure, temperature, velocity and composition;
  - EndEnvironment object was used for the outlet, defining static pressure and temperature at the end of the circuit;
- Charge air circuit had EndFlowInlet object as an inlet with mass flow, temperature and composition of charged air defined. For the outlet EndEnvironment object was used as for the air side.

#### Initial conditions

- Initial temperatures in the coolant circuit are set to ambient temperatures, initial coolant pressure is set to 1 bar;
- For the air and charge air side initial conditions are the same: pressure is equal to 1 bar, temperature is equal to ambient temperature.

#### Composition

- Creating of a coolant mixture was a challenge. Volvo is using a special Volvo Havoline mixture as coolant and there is no such mixture available in the GT template library. A mixture that can be considered to be a good assumption is a 40% ethylene glycol and 60% water mixture. This one is not available from the template library either so it was created using FluidLiquid template. For more details on how it was done see Appendix D;
- For the air side FluidGas object “air2” was used as this is the recommended air object for noncombustible air;
- Charge air was modeled as an “air2” object too.

#### Pipes

- Pipes for the coolant circuit were modeled according to the data for diameters and lengths that was available;
- In reality there are no pipes on the air side but as the software requires to have it those pipes were created. The diameter of 750 mm, same as the diameter of the cooling fan, was used. The length was set to 10 mm as it is insignificant for calculations;

- For the charge air side pipes dimensions were measured and the values obtained were used in the model.

## **Radiator**

To model the radiator one should use two objects HxMaster and HxSlave for different circuits. Those objects are connected to each other to perform the heat transfer. All the test data is entered at the HxNuMap object that is linked to HxMaster and HxSlave as a Heat Transfer object.

Usually a radiator is tested with air on one side and hot water on the other side and in the simulation a coolant mixture is used on the hot side. GT-Suite is capable of dealing with such situation; radiator characteristics will be scaled according to the mixture used. There are some parameters in the HxNuMap template that are not very clear even after reading the supporting documentation. Those are going to be described here:

- *Reference Length*
  - For the hot side of the radiator a hydraulic diameter of a single tube should be used;
  - For the air side this parameter value should be set to the fin height or the distance between two tubes.
- *Heat Transfer Area*
  - For the hot side this is a total internal heat transfer area (tube circumference \* tube length \* number of tubes);
  - For the cold side it is a total area where the air is interacting with aluminum surface of the radiator.
- *Flow Area*
  - For the coolant side this is a total internal tube flow area (tube flow area \* number of tubes);
  - For the air side this parameter value can be obtained just by multiplication of height and width of the radiator.

## **Charge air cooler**

CAC is modeled in the exactly the same way as the radiator.

## **Condenser**

A condenser is modeled as a simple HeatAddition object. A certain amount of heat is being added to the air flow here.

## Oil cooler, engine block and EGR cooler

For this simplified model all of these heat exchangers are modeled as a simple heat addition objects. Values for the heat rejection at different components were obtained using following technique:

Firstly, the data for US10 engine heat rejection was obtained from Volvo Powertrain. Secondly, as the amount of heat rejected through the radiator was known from the cooling performance test results for the EU4 engine installation. US10 heat rejection data was scaled to obtain known values for the radiator heat rejection.

## Pressure drops

As a general recommendation from Gamma Technologies one should use separate pressure loss connection objects for components of the cooling circuit that are supposed to have a pressure drop through them. A cut from the model to show those objects is given in Figure 7.1.

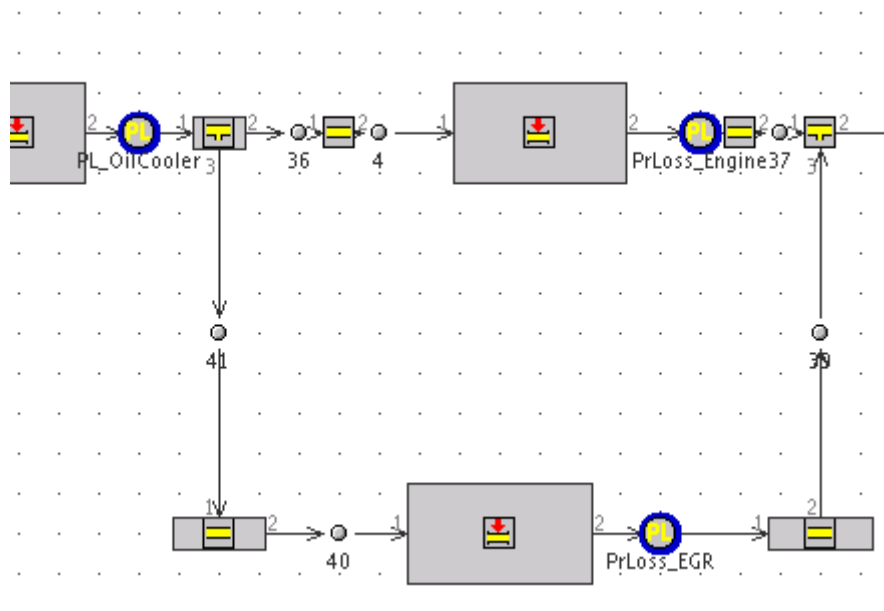


Figure 7.1 Pressure loss connection objects

Pressure losses through different parts of the model can be seen and compared in Figure 7.2. One can see that pressure drop at EGR cooler is significantly higher than the one at the engine block. As those components are located on parallel branches of the cooling circuit, the pressure losses difference affect coolant flow at different branches, resulting in about 30% of coolant going through EGR cooler and the rest going through the engine block.

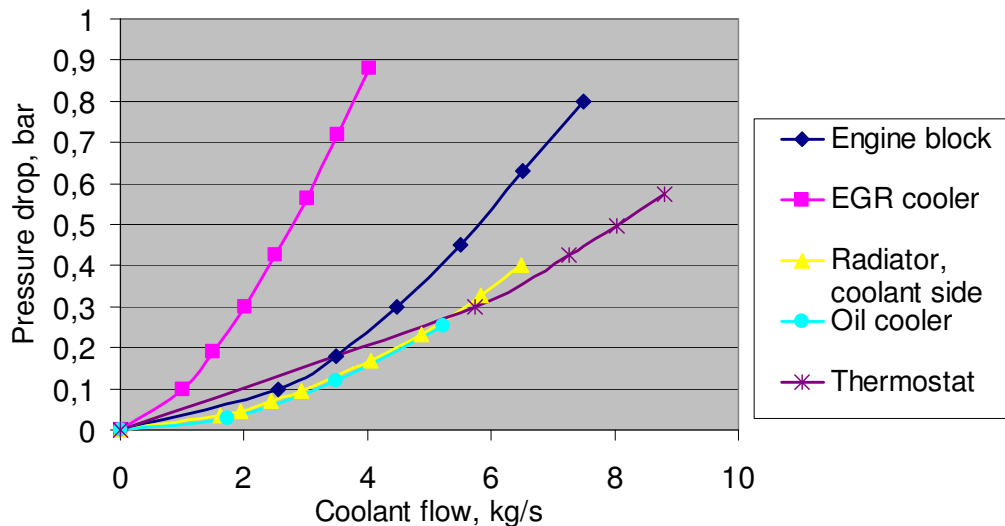


Figure 7.2 Pressure losses through different components in coolant circuit

Pressure losses at the air side can be compared when looking at Figure 7.3. One can see that pressure drop at the condenser component is high but not all the air flow is going through it, therefore one cannot put this data to the model without revising. This pressure loss at the condenser will be used for tuning the system in section 3.1.3, for the first model it was considered to be equal to zero.

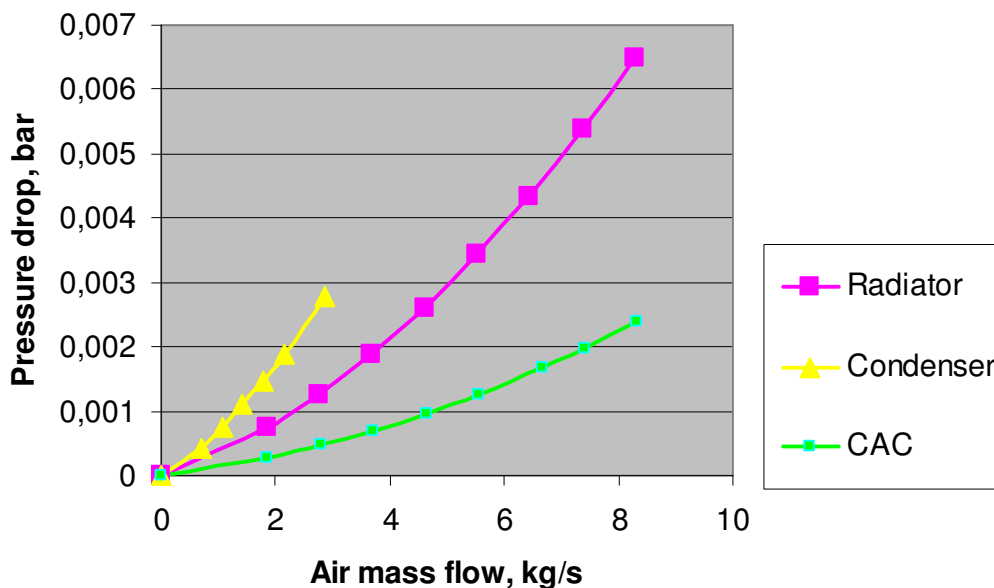


Figure 7.3 Pressure losses through different components at air side

### Thermostat

During the cooling performance test thermostat was kept fully open, so for the simulation thermostat was modeled as just a pressure loss and there was no coolant flow bypassing the radiator.

## Accumulator

The accumulator was modeled using two Accumulator object templates representing two fluids separated by weightless membrane in a constant volume space. Initially accumulator tank was divided 50/50 to air and coolant mixture. Further as the temperature was rising during the simulation of the warm-up the amount of coolant in the accumulator tank was increasing as it is shown in Figure 7.4.

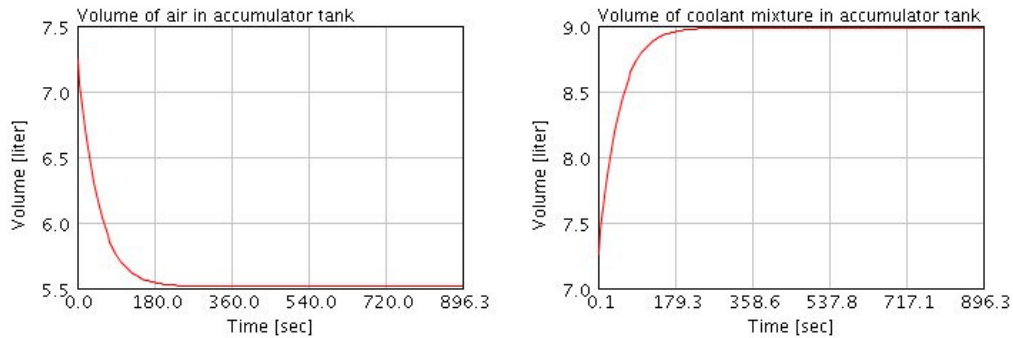


Figure 7.4 Accumulator tank model

## Pump

The Pump template was used for modeling this component. The pump map needed was obtained from Volvo Powertrain; the pump/engine ratio was set according to the cooling performance test setup to 1.91. A 98% of mechanical effectiveness was assumed for the pump shaft.

## Fan

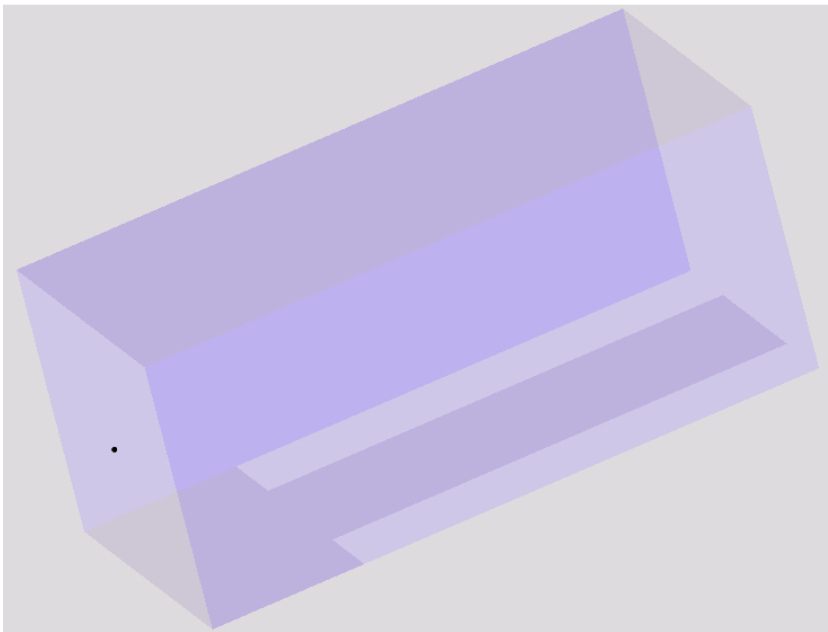
Similar to the pump, fan speed is directly dependant on the engine speed. The fan speed/engine speed ratio was set to 1.33 as it was during the test. But due to losses in the belt system actual fan drive speed is reduced. In addition, there are some losses in the fan clutch that are represented by the fan slip value in the test data. Because of it, RPM speed of the cooling fan is further reduced. During the test actual cooling fan speed was measured, so those values were directly used in simulation.

When working with a fan map there is an efficiency parameter that cannot have negative values. As the fan cannot be used for generating energy in our case this parameter was set to the lowest allowed value of 0.0001 for the overblown case.

## B. Cool3D model construction

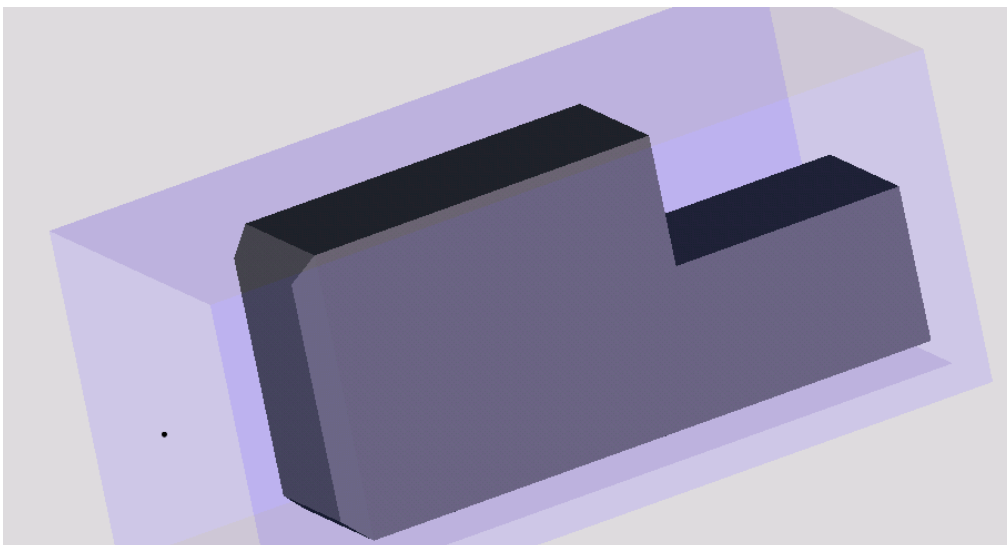
To create a simplified underhood model a lot of assumptions were made.

Flow space or the area where air is actually allowed to pass was simplified to the rectangular with the dimensions 3200 x 1400 x 1400 mm. All the front face of this rectangular was considered to be an inlet. For the air flow outlet the bottom openings of 2000 x 700 were used in addition to the back face of the rectangular as it can be seen in Figure 7.5.



*Figure 7.5 Flowspace for the model*

For the engine part representation CAD data was used then it was simplified to the geometry that can be seen in Figure 7.6.



*Figure 7.6 Engine block representation*

To create front grille openings the image from the public image gallery of Volvo Trucks<sup>5</sup> was used. This photo picture and the simplified representation of the grill made in Cool3D can be found below in Figure 7.7.



Figure 7.7 Grille openings modelling (Volvo Trucks Image Gallery<sup>5</sup>)

COOLBlockage object template of Cool3D does not allow to have more than 32 holes in the blockage therefore vertical bars were ignored.

For the condenser and charge air cooler COOLHeatAddition templates were used. It allows modeling the pressure drop and heat input rate for the components. In addition the air was limited not to allow any bypassing around the CAC as it can be seen in Figure 7.8.

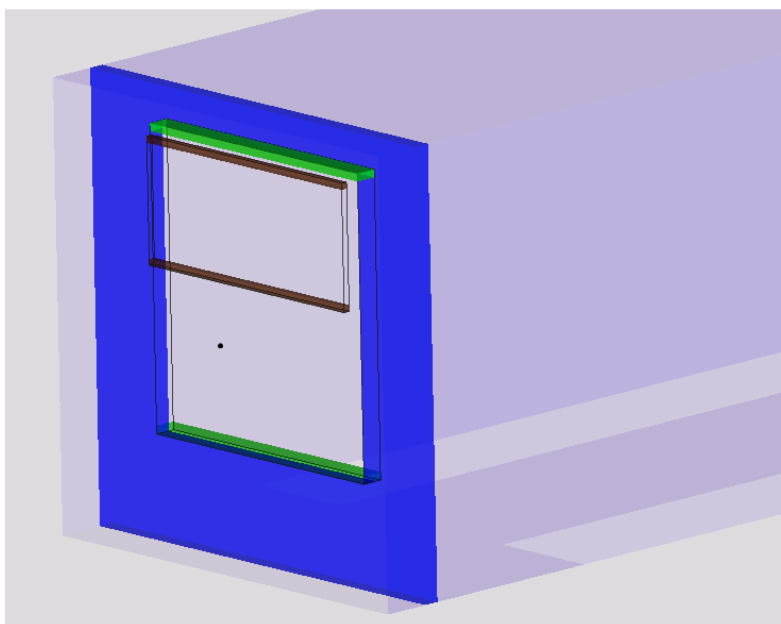
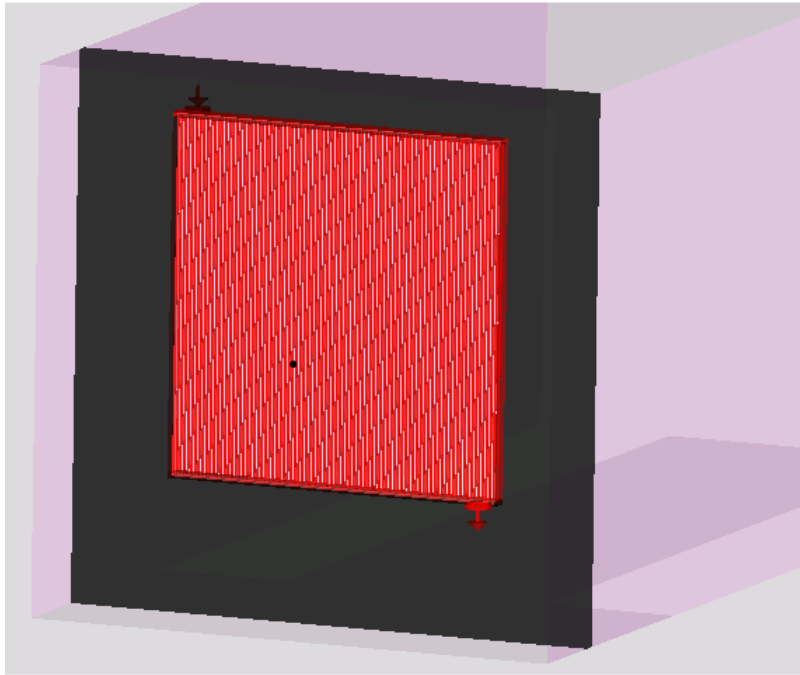


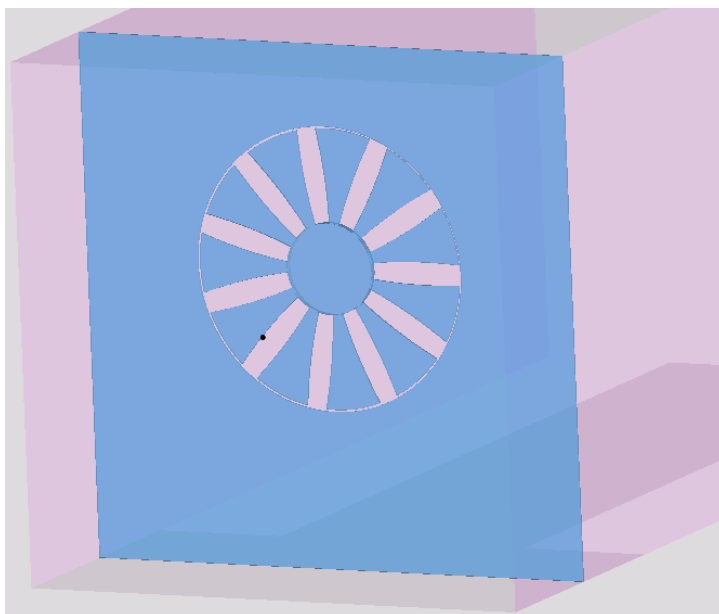
Figure 7.8 Condenser and CAC modelling

Radiator was the only part modeled in all the details. COOLHeatExchanger template was used to do it. It was done for the reason that the template mentioned requires the same amount of data that was used for modeling of the radiator part in GT-ISE. Once again the air flow was limited not to allow any bypassing. See Figure 7.9 for the model of this part.



*Figure 7.9 Radiator representation*

Last but not the least, the fan was also simplified. COOLFan object template was used. Fan shroud was simplified in the way shown in Figure 7.10.



*Figure 7.10 Model of the fan*



## C. Coupled models

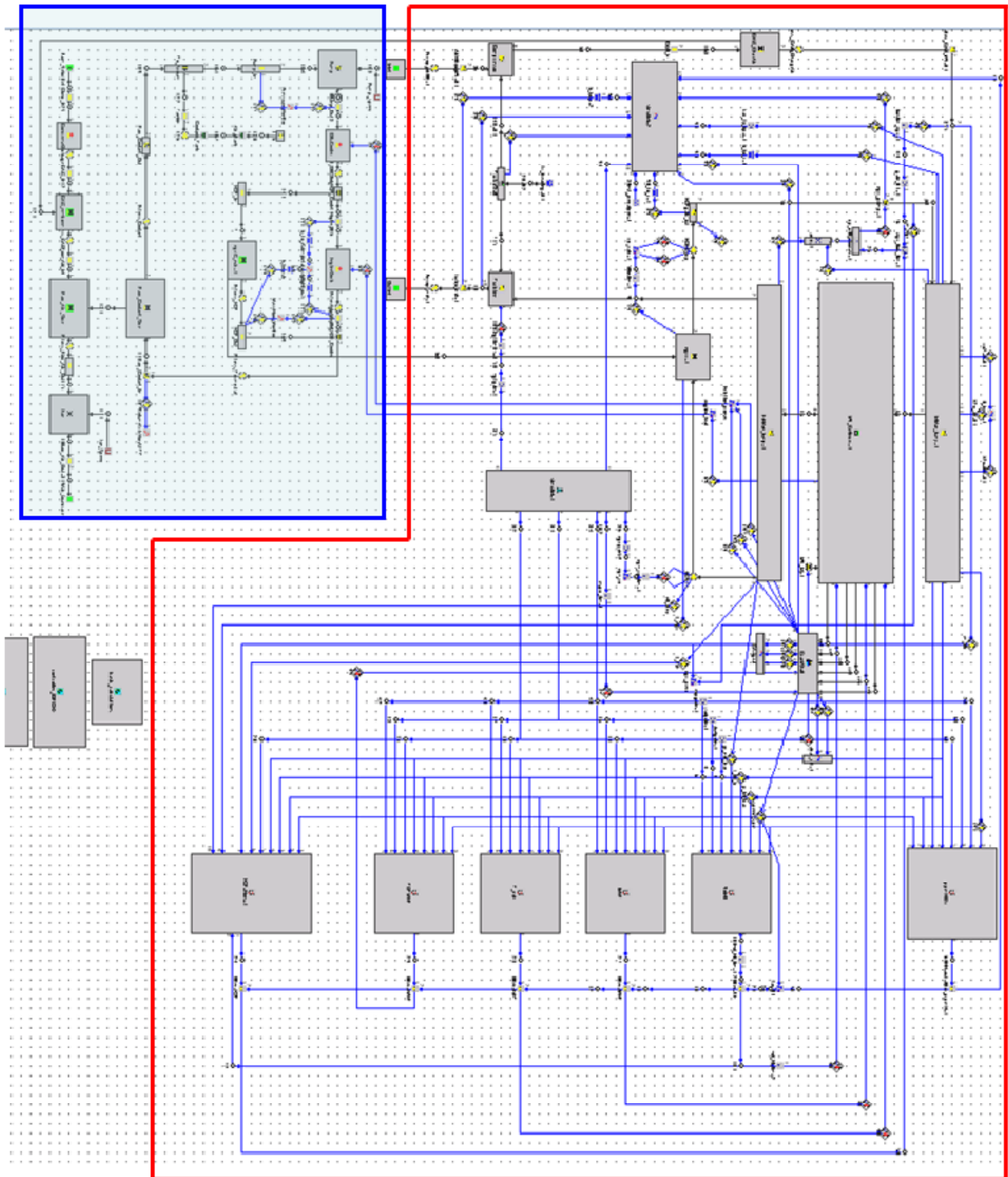


Figure 7.11 Coupled simulation models

## D. Coolant mixture creation

To create an analogue to Volvo Havoline cooling mixture two available mixtures from the GT template library was mixed. Those fluids were ethylene glycol mixtures with water with different concentrations of components: 20/80 and 50/50 ethylene glycol / water.

One of the weak points of the current version of GT-Suite is a FluidMixture template that does not allow using volumetric fractions; it works only with mass fractions. And as 20/80, 40/60 and 50/50 are volumetric fractions the calculation needs to be performed to obtain the proper mass fractions for the new FluidMixture object simulating 40/60 mixture. According to the template library here are the densities for the different fluids:

Table 7.1 Densities of different mixtures

Mixture	Density from library object, kg/m3
egl-5050	1071,11
egl-2080	1027,93
egl-pure	1113,05
water	1002,50

Using these densities mass distribution for the final egl-4060 mixture components can be quickly calculated using simple equations for the ethylene glycol and water mass balance for the mixture of two liquids and the fluid being created.

Mass fraction of ethylene glycol in the egl-5050 fluid  $\omega_{egl\_in\_5050}$  can be calculated in the following way:

$$\begin{aligned}\omega_{egl\_in\_5050} &= 0.5\rho_{egl-pure} / (0.5\rho_{egl-pure} + 0.5\rho_{water}) = \\ &= 0.5 \cdot 1113 / (0.5 \cdot 1113 + 0.5 \cdot 1002.5) = 0.526\end{aligned}\quad (7.1)$$

where  $\rho_{egl-pure}$  and  $\rho_{water}$  are densities of egl-pure and water from the Table 7.1.

Mass fraction of water in egl-5050  $\omega_{water\_in\_5050}$  is obviously equal to:

$$\omega_{water\_in\_5050} = 1 - \omega_{egl\_in\_5050} = 1 - 0.526 = 0.474 \quad (7.2)$$

Mass fraction of ethylene glycol and water in egl-2080 can be calculated in the similar way:

$$\begin{aligned}\omega_{egl\_in\_2080} &= 0.2\rho_{egl-pure} / (0.2\rho_{egl-pure} + 0.8\rho_{water}) = \\ &= 0.2 \cdot 1113 / (0.2 \cdot 1113 + 0.8 \cdot 1002.5) = 0.217\end{aligned}\quad (7.3)$$

$$\omega_{water\_in\_2080} = 1 - \omega_{egl\_in\_2080} = 1 - 0.217 = 0.783 \quad (7.4)$$

After these mass fractions being calculated wanted mass fractions of 5050 and 2080 mixtures in the 4060 fluid can be found using following volumetric fraction balance equation:

$$\frac{\omega_{5050\_in\_4060} \cdot \omega_{egl\_in\_5050} + \omega_{2080\_in\_4060} \cdot \omega_{egl\_in\_2080}}{\omega_{5050\_in\_4060} \cdot \omega_{water\_in\_5050} + \omega_{2080\_in\_4060} \cdot \omega_{water\_in\_2080}} = \frac{0.4\rho_{egl-pure}}{0.6\rho_{water}} \quad (7.5)$$

Keeping in mind that

$$\omega_{2080\_in\_4060} = 1 - \omega_{5050\_in\_4060} \quad (7.6)$$

and substituting other known values, the value for  $\omega_{5050\_in\_4060}$  can be found:

$$\frac{\omega_{5050\_in\_4060} \cdot 0.526 + (1 - \omega_{5050\_in\_4060}) \cdot 0.217}{\omega_{5050\_in\_4060} \cdot 0.474 + (1 - \omega_{5050\_in\_4060}) \cdot 0.783} = \frac{0.4 \cdot 1113,05}{0.6 \cdot 1002,5} \quad (7.7)$$

After simplification one can get the mass fractions wanted:

$$\omega_{5050\_in\_4060} = 0.674 \quad \text{and} \quad \omega_{2080\_in\_4060} = 0.326$$

Therefore to obtain egl-4060 mixture one should take 67.4% of egl-5050 and 32.6% of egl-2080. These are mass fractions and these values should be put into FluidMixture template.

To compare obtained mixture of 40% ethylene glycol and 60% water with Volvo Havoline cooling mixture the following graphs can be used. Density, thermal conductivity and dynamic viscosity curves can be found in Figure 7.12, Figure 7.13 and Figure 7.14 respectively.

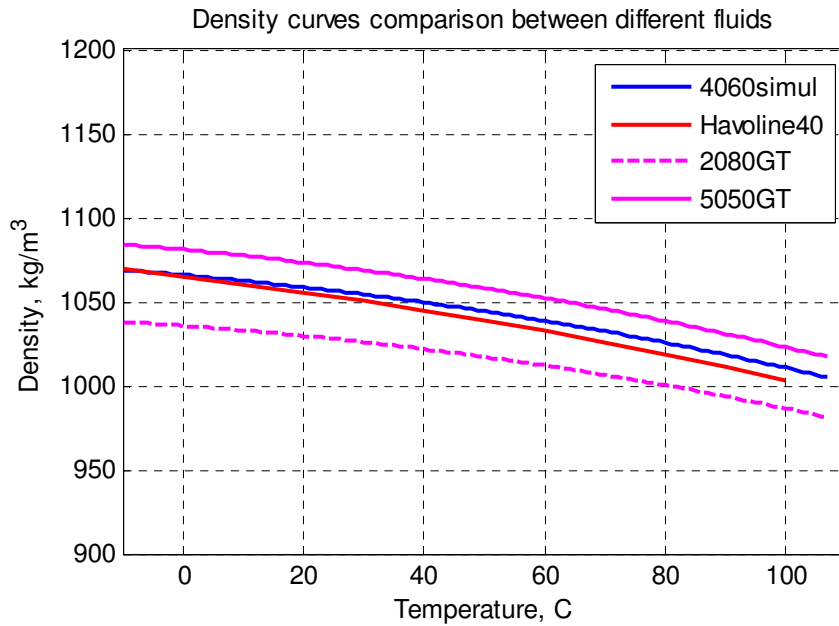


Figure 7.12 Density curves comparison between different mixtures

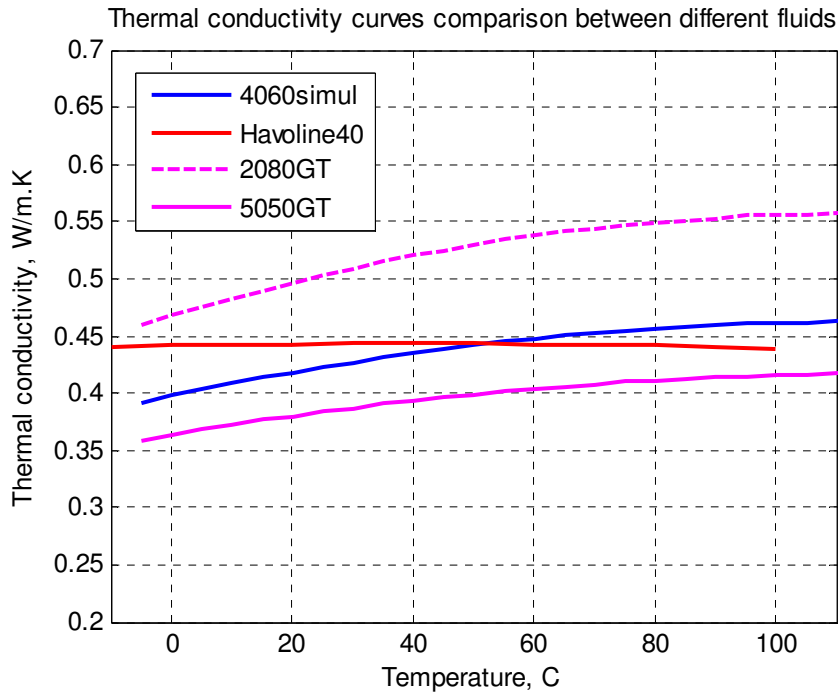


Figure 7.13 Thermal conductivity curves comparison

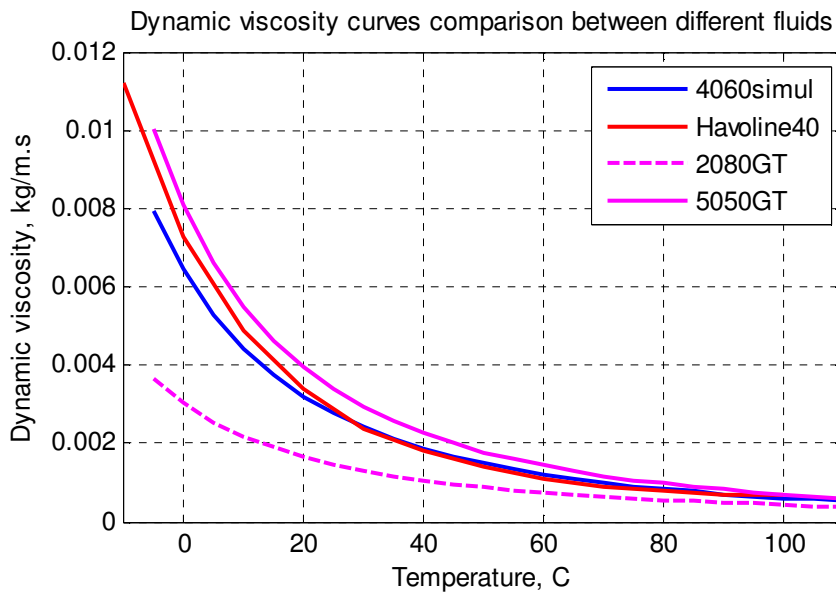


Figure 7.14 Dynamic viscosity curves comparison

As one can see the mixture created is rather close in its properties to the Volvo Havoline cooling fluid. For the thermal conductivity the graph can seem not to be a perfect fit but it is definitely closer than any of the composition fluids and hence fluid composition can be considered to be good enough.