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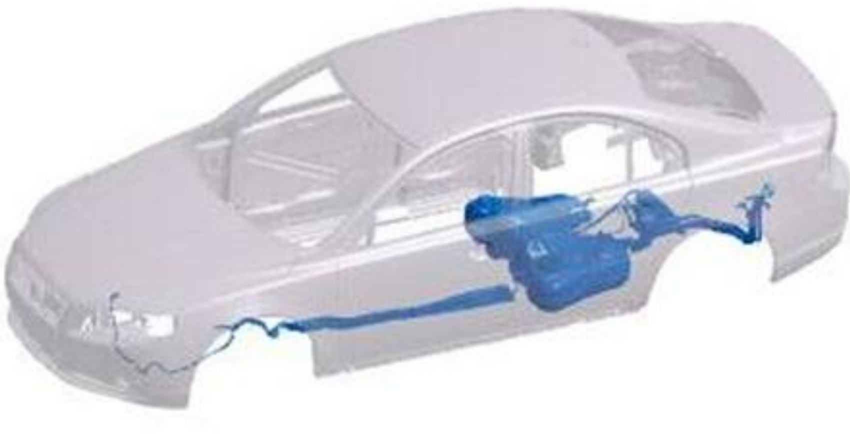

Modelling of pressure losses in the Evaporative Emission System

Master's Thesis within the Sustainable Energy Systems programme

MERETHE HAUGLAND

JOSEFIN PETTERSSON

Department of Energy and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2013
Report no. T2013-395

MASTER’S THESIS

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Cover:
Schematic layout of the vehicle with the position of the EVAP system, including the fuel tank and the filler pipe.

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ABSTRACT

This thesis investigates the possibility to use a simulation tool to study pressure drop in the Evaporative Emission (EVAP) system, exemplified with the system for the car model S60 sold on the US market, called USS60. The EVAP system is a part of the fuel system in the vehicle and prevents evaporated hydrocarbons from the fuel to escape to the environment. As the performance of the system is strongly dependent on the flow and pressure it is of great importance to have knowledge about the pressure losses in the system. A reliable simulation tool would save both time and money in the design of the system since less prototype tests would be needed if it is possible to replace tests with simulations.

In this work, the simulation software, GT Suite, has been used to model pressure losses in the EVAP system, and to investigate how changes in the system influence the pressure drop during the two main processes; purge and refuelling. First, experiments on the real EVAP system were carried out to obtain data for validation of the model and to obtain data needed for modelling of the more complex components. A model was then set up for simulation of the system and finally a sensitivity analysis was performed to investigate the impact on the pressure losses when changes in the EVAP system were made.

The results show that the pressure losses in the Pipe 5 has the largest impact on total pressure drop in the system during the purge process and corresponds to 75% of the total pressure loss. During the refuelling process the canister affects the pressure losses the most. The simulation model is a simplification of the real system, but it gives an indication of how chosen design parameters influence the pressure drop. The model can be used for predictive analyses as long as the simulation results match the characteristics of the complex components.

Keywords:

Volvo Cars Corporation, EVAP (Evaporative emission) system, GT-Suite, CAE (Computer-aided engineering) simulation tool, pressure losses, pipes, purge, refuelling

Tryckfallsmodellering i EVAP systemet
Examensarbete inom masterprogrammet Sustainable Energy System
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SAMMANFATTNING

Detta examensarbete undersöker möjligheten att använda ett simuleringsverktyg för att simulera tryckförlusterna i EVAP systemet, exemplifierat med systemet för bilmodellen S60 som säljs i USA, kallad USS60. EVAP systemet är en del av bränslesystemet i bilen och förhindrar att förångade kolväten från bränslet når omgivningen. Eftersom systemets egenskaper är starkt beroende av flödet och trycket är kunskap om tryckförlusterna i systemet viktiga. Ett tillförlitligt simuleringsverktyg skulle kunna spara både tid och pengar på grund av att mindre prototypprovningar behövs när det är möjligt att ersätta tester med simuleringar.

I detta arbete har simuleringsprogrammet, GT Suite, använts för att modellera två olika processer i EVAP systemet, kallade purge processen och tankningsprocessen, för att undersöka hur förändringar i systemet påverkar tryckförlusterna. Först genomfördes experiment på själva EVAP systemet för att få fram data för användning i modelleringen av de mer komplexa komponenterna och för att få underlag för validering av modellen. Därefter formulerades en modell och slutligen genomfördes en känslighetsanalys för att undersöka påverkan på tryckförlusterna vid förändringar i EVAP-systemet.

Resultaten visar att tryckförlusterna i Ledning 5 har störts inverkan på det totala tryckfallet i system under purgeprocessen och det motsvarar 75% av det totala tryckfallet. Under tankningsprocessen har kanistern störst inverkan på tryckfallet. Simuleringsmodellen är en förenkling av det verkliga systemet, men den ger en indikation på hur valda design parametrar påverkar tryckfallet. Modellen kan användas till analyser för att förutspå framtida händelseförlopp så länge som simuleringsresultatet matchar de komplexa komponenternas egenskaper.

Nyckelord:

Volvo Personvagnar, EVAP (Evaporative emission) system, GT-Suite, CAE (Computer-aided engineering) simuleringsprogram, tryckförluster, ledningar, purge, tankning

Contents

Preface

This report is a result of a Master Thesis project carried out as a part of the Master Programme "Sustainable Energy Systems" at Chalmers University of Technology in Gothenburg. The aim of this thesis work was to investigate the possibility to use a simulation tool to simulate the EVAP system. The purpose with the simulation tool was to simulate pressure losses in the system and to do a sensitivity analysis.

First of all we want to thank our supervisor Elisabeth Örgård at Volvo Cars Corporation for her support and knowledge regarding this master thesis. We also want to thank our supervisor Robert Johansson and our examiner David Pallarès at Chalmers University of Technology with the help and guidance through this master thesis. Many thanks to the employees at the department of the EVAP system at Volvo Cars Corporation for their help and expertise in the EVAP system. A special thanks to Christer Berg with the help of performing the experiments in the test rig, required to verify the simulation in practice. Furthermore we want to give our great gratitude to Stefan Bohatsch and David Willermark at Volvo Cars Corporation for always taking time to assist us with the GT Suite program. We also would like to thank Shawn Harnish and Matt Massaro at Gamma Technology for excellent support with our modeling and simulation.

Torslanda, June 2013

Merethe Haugland

Josefin Pettersson

Notations

Abbreviations

CARB	California Air Resources Board
DC	Duty cycle
DMTL	Diagnostic Module Tank Leakage
ECU	Engine Control Unit
EVAP	Evaporative Emission (System)
HC	Hydrocarbons
LEV II	Low Emission Vehicle II
ORVR	On-board Refuelling Vapour Recovery

Letters

A	Flow area (cross sectional) [m^2]
A_s	Heat transfer surface area [m^2]
C_f	Skin friction coefficient [-]
C_p	Pressure loss coefficient [-]
ρ	Density [kg/m^3]
D	Diameter [m]
e	Total internal energy (internal energy plus kinetic energy) [J/kg]
h	Heat transfer coefficient [W/m^{2}K]
H	Total enthalpy [kJ/kg], $H = e + \frac{p}{\rho}$
$\dot{m}$	Mass flow rate [kg/s], $\dot{m} = \rho A u$
m	Mass [kg]
p	Pressure [kPa]
Re_D	Reynolds number
T_{fluid}	Fluid temperature [°C]
T_{wall}	Wall temperature [°C]

u	Velocity at the boundary [m/s]
V	Volume [m^3]
dx	Length of mass element in the flow direction [mm], (discretization length)

1 Introduction

The fuel system in cars running on petrol is divided into four different sub-categories, i.e. the tank system, the distribution system, the evaporative emissions (EVAP) system, and the distribution pipes, Fig. 1.1.

Figure 1.1 – Illustration of a vehicle showing the EVAP system with tank and filler pipe.

The purpose of the EVAP system is to prevent hydrocarbons (HC) evaporated from the fuel to escape to the environment. This is done both to avoid odours from the petrol but also to prevent release of too much HC into the atmosphere. This should be taken care of when the car is parked, during refuelling and during driving.

The EVAP system consists of different components depending on the car model, the year of manufacturing, type of engine and emission legislations around the world. Volvo manufactures two different EVAP systems. One system for USA, Canada and South Korea, called the US system, and another system for Europe and the rest of the world, called the EU system. The EVAP system can be seen in Fig. 1.2. The main difference between these two systems is that an air filter and a Leakage Detection unit are required for the US system, but not for the EU system due to stricter emission legislations in USA. These stricter legislations are primarily due to health reasons to prevent smog in cities like Los Angeles, where this requirement started. For the EVAP system analysed in this thesis, the leakage detection unit is a Diagnostic Module Tank Leakage (DMTL) pump. The main components in the EVAP system are the purge valve, the canister, the DMTL pump (US only), the air filter (US only), the check valve and the distribution pipes, Fig. 1.2.

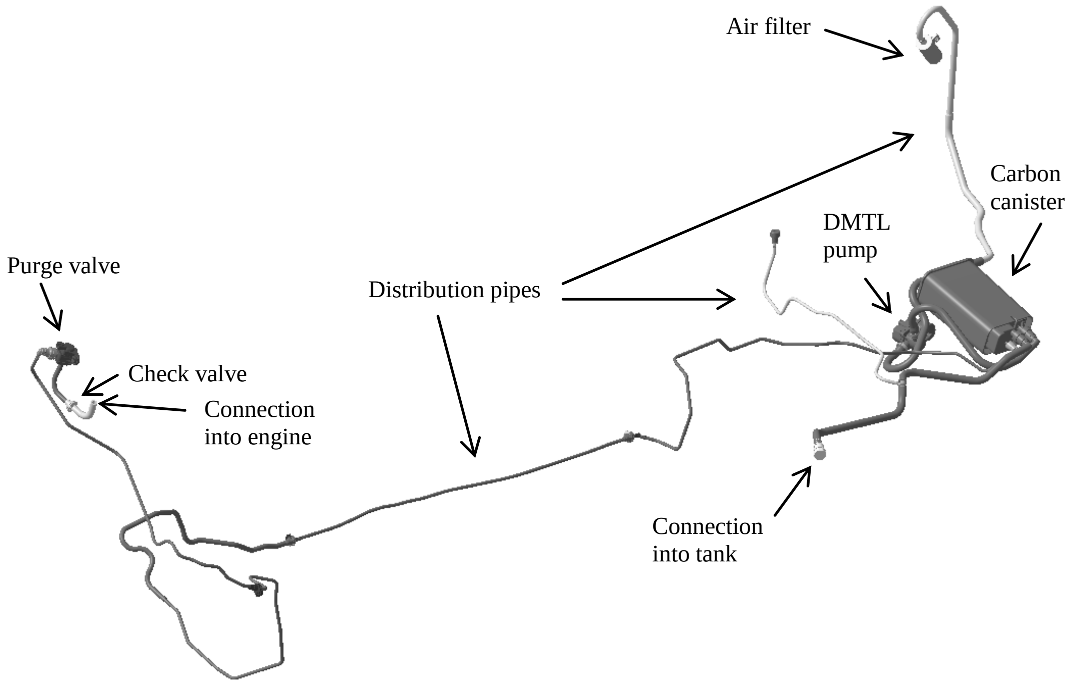

Figure 1.2 – The figure shows the EVAP system in the car with the main components.

The gas inside the fuel tank consists of a mixture of air and HC where the concentration of HC varies due to changes in the ambient temperature and increasing temperature in the tank during driving. A higher temperature results in evaporation of fuel and this process leads to emissions of fuel vapour from the fuel tank. There will also be evaporative emissions, called permeation losses, from all fuel system components. These losses are controlled by reducing the use of plastics with high permeation, and also using metallic fuel system components instead of plastics [1].

During refuelling HC will flow from the tank through the canister, where the HC are adsorbed by activated carbon and clean air leaves the canister on the other side. When the car is running, during low engine load, e.g. at idling or calm driving, vacuum pressure will be created in the engine and air will be drawn from the atmosphere through the canister where the HC are released from the carbon and sucked into the engine where they are combusted. This process is called purge it takes around 20 seconds and the flow is controlled by opening and closing the purge valve.

The engine is designed to withstand a maximum vacuum pressure of 60 kPa. This means that the pressure losses through the EVAP system during purge should not be higher than that, otherwise the vacuum in the engine will not be able to draw the gas through the system to the engine. Parameters that influence pressure losses are for example pipe lengths, pipe diameters, bends, flow velocity etc. Knowing the pressure losses in the EVAP system and how different changes in the design affect the losses are thus of great importance to evaluate the performance of the system.

As for now, there is no easy way to evaluate the pressure losses and Volvo Cars has to test the system physically in different labs. For current systems, these tests are performed on prototypes in the lab. This means that, for each system, prototypes have to be constructed before the pressure loss tests can be performed. If the tests show some deviations and/or there is a need to make some changes on the system (e.g. changes on pipe lengths, pipe diameter, curvature changes etc.) a new prototype needs to be constructed, and new tests have to be performed. This process is both time consuming and cost consuming and there is a need to make it more efficient.

In other words, there is a need to find a simulation tool which is able to model the pressure losses in the EVAP system of different car models. By having a reliable tool that can simulate the tests, tests can be run in advance and it will be easier to make changes in the system and evaluate how these changes will influence the pressure losses. More tests can be accomplished in shorter times without having to manufacture a lot of prototypes, which will save both time and money.

In this thesis work a modelling tool is evaluated for simulation of the EVAP system. To simulate the pressure losses in the EVAP system the simulation software called GT Suite has been used. The GT Suite is provided by the company Gamma Technologies Inc. (GTI) and is a CAE (Computer-aided engineering) simulation tool used for applications in the engine and vehicle industries [2]. This software is already in use as a simulation tool in other departments at Volvo Cars, and it would therefore be of interest to see if this tool could be implemented for the EVAP system as well.

1.1 Aim

The purpose with this thesis work was to investigate the possibility to use a simulation tool for simulation of the EVAP system. A model of the EVAP system should be modelled using the simulation tool GT Suite. The model should be able to simulate the pressure loss in the EVAP system and to identify components with high pressure drops. A validation of the modelled EVAP system should be carried out by comparing the model with the actual EVAP system. The model should also be able to show how changes of different design parameters would influence the pressure losses in the system.

1.2 Limitations

Some important boundaries that have been set for the work are:

- One EVAP system for car model S60 sold on the US market have been analysed and simulated, called USS60.
- Permeation losses from the fuel system components are neglected.
- Heat transfer in the system has been neglected and the temperatures of the materials are therefore considered to be equal the gas temperature.
- The experiments and simulations are carried out with air which is assumed to have similar properties as the HC. In the sensitivity analysis a test with a mixture of air/HC is done.
- Due to time limitations and complex design of the air filter, DMTL pump, canister, purge valve and check valve, these components have been treated in an

approximate way and values from experiments are used to simulate the behaviour by fitting the pressure drop of the boxes to the experimental data.

- The increase in pressure drop over the air filter due to an accumulation of particles is not considered.
- The canister is assumed to be empty, that is no HC are trapped inside.
- The system is analysed at steady state conditions, which means that the purge valve is considered to be fully open at all time.
- The amounts of gas that will be drawn from the fuel tank during purge are considered to be small, and are therefore neglected when modelling the system.

1.3 Method

First a literature study of the EVAP system was carried out to get a general knowledge and understanding of the system. An introduction to the EVAP system was given by the system manager, and then the product managers held lectures about each specific component of the system, i.e. the air filter, carbon canister, DMTL pump, purge valve, check valve and the distribution pipes. This gave a general knowledge of the EVAP system. An introduction to the simulation program GT Suite was performed in order to learn the software program.

One EVAP system was selected for analysis, the system for the US market. The chosen car model was an S60 from year 2012 with a five cylinder injection turbo engine (I5T) called I5T US S60. This system was selected based on the fact that this Master Thesis would be a public document and therefore an already existing car model, already released on the market would be of interests.

The whole EVAP system was set up in a lab and connected to a test rig, and pressure sensors were connected to the system at different measurement points to get the total pressure losses in the system as well as the pressure losses over each component. Two different test scenarios were performed for collection of test data needed for validation and modelling of the complex system components. One scenario intended to simulate the purge process of the system and the other scenario the filling process (filling gasoline in the car).

Computer-aided designs (CAD) drawings of the EVAP system was imported into the GT Suite program. Thus, all the specific data such as pipe lengths, curvatures and volumes was obtained. Then specific details of each component such as flow direction, component material and the connections of each component to the whole system were set in the program. However, for the complex components (the air filter, carbon canister, DMTL pump, purge valve and the check valve), CAD drawings were not available because the design of these components is classified. Therefore an approximate treatment of each of these complex components had to be done, and different design objects from the GT Suite library were used to model them in order to make the mass flow and the pressure drop over each of them fit the experiments.

When the modelling of the system was completed the test results from the laboratory work were compared with the results obtained by the GT Suite to validate the model.

Once this model showed similar pressure losses as the ones measured in the physical system a sensitivity analysis was performed on the system to see how the model would respond on changes in the system.

2 Description of the EVAP system

The EVAP system consists of different components depending on car model, year of manufacturing, type of engine and emission legislations where the car is sold. The main components in the EVAP system for the US region are the purge valve, the canister, the DMTL pump, the air filter, the check valve and the distribution pipes.

Figure 2.1 shows a schematic picture of the EVAP system when the gas flows from the fuel tank, point 1 to the surroundings, point 4. The dashed line represents the boundaries for the EVAP system investigated in this work. From the fuel tank to the surroundings the system is an open system close to ambient pressure, i.e. atmospheric pressure. The purge valve (between point 5 and 6) is normally closed. When the pressure rises in the tank, i.e. during refuelling or when temperature rises in the tank causing the fuel to evaporate, the gas will be pushed through the system due to the pressure differences and flow out to the surroundings, point 4. Since the purge valve is closed the gas flows through the canister, where the gas is cleaned by adsorption of HC, the DMTL pump and the air filter on its way out.

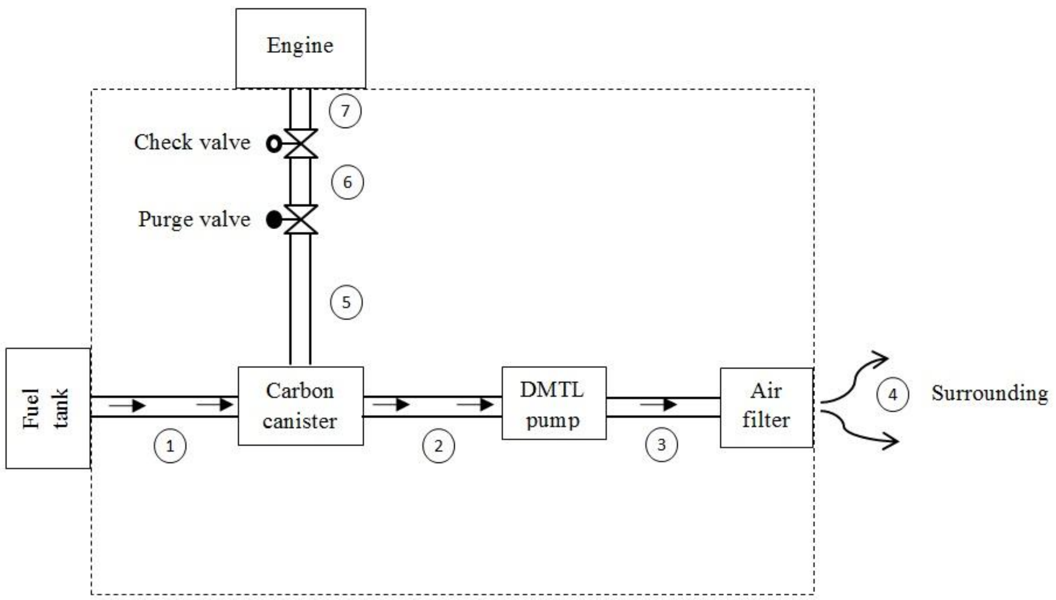

Figure 2.1– Schematic picture of the US system showing the refuelling process when gas is flowing from the fuel tank and out to the surrounding. The dashed line represents the boundary of the EVAP system.

When the car is running, vacuum is created in the engine by the downward movement of the piston stroke whenever the fuel intake valve opens [3]. A unit in the engine, called the engine control unit (ECU), controls the purge valve of the EVAP system. The ECU decides how much air and HC that can be released through the purge valve to the engine and still maintain stoichiometric conditions in the engine. Figure 2.2 shows a schematic picture of the EVAP system during a purge process. When the purge valve opens, air from the surroundings (point 4) are drawn through the air filter. The air passes the DMTL pump (point 3) and the canister (point 2). Inside the canister the HC are desorbed and drawn with the airflow through the purge valve (point 5) and the check valve (point 6) and into the engine (point 7) where they are combusted. The check valve shall prevent gas from flowing from the engine and back out in the system again. The purge process can only be carried out when the engine is running and there is a vacuum pressure in the engine. Whenever the purge process takes place, some gas will be drawn from the fuel tank as well, but the amount of gas that is drawn is very small and is in this work therefore neglected when modelling the system. Each component of the system is further described in the following sections.

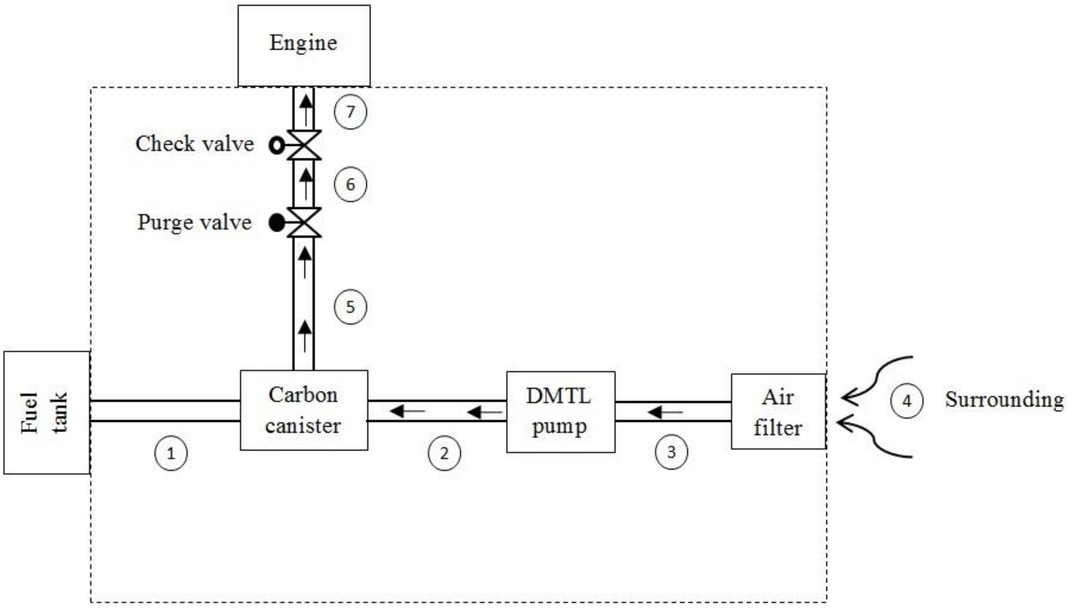

Figure 2.2– Schematic picture of the purge process for the US system when air is drawn from the surrounding and into the engine. The dashed line represents the boundary of the EVAP system.

2.1 Carbon canister

The purpose of the carbon canister (hereby called canister) is to capture HC evaporated in the fuel tank. The canister contains activated carbon that adsorbs the HC due to van der Waals forces between the HC and the carbon molecules. When the pressure in the fuel tank increases and the gas flows from the tank and passes the canister on its way out, the gas enters the canister through the fuel nipple, which has an inner diameter of 13.5 mm, Fig. 2.3. When entering the canister the gas flows all the way to the other side, makes a U-turn and exits the canister through the air nipple with an inner diameter of 13.5 mm. When air and evaporated HC from the tank passes through the canister the HC gets adsorbed inside the canister and clean air (i.e. no HC) is released to the surroundings. With increased amount of adsorbed HC the pressure increase over the canister and a higher vacuum pressure in the engine is required to empty the canister [4, 5].

During purge, the air enters the canister through the air nipple. The air flows through the canister in the opposite direction, desorbs the HC molecules and exits through the purge nipple. The purge nipple has an inner diameter of 6.0 mm. The volume inside the canister is approximately 2438 cm^3.

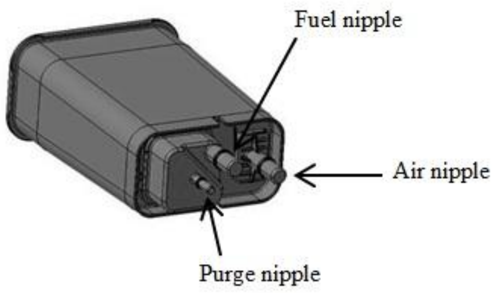

Figure 2.3 – The carbon canister.

The size of the canister house for the US market is determined by the On-board Refuelling Vapour Recovery (ORVR) legislation. ORVR states that the canister should manage to capture all HC vapours formed in the tank while refuelling. The quality of the carbon used in the canister is determined by the LEVII legislation. The emission requirement in LEVII, states that the canister for the US system should manage to adsorb HC during 48 hours when the temperature rises from 18°C in the evening to 41°C in the middle of the day and down to 18°C again in the first 24 hours and the same procedure for next 24 hours [6, 7].

2.2 Air filter

The purpose of the air filter is to protect the DMTL pump (see Section 2.6) from dust during purge. The filter is installed at the entrance point to the EVAP system, where the entrance point of the filter (i.e the atmospheric side) is pointing down, Fig. 2.4. This is to allow particles collected on the filter surface to fall out by gravity or by vibrations during driving, and also when the particles are being pushed out by the gas flow from the fuel tank. The diameter of the air filter nipple is 13 mm and the volume of the air filter is approximately 101.5 cm^3. The pressure drop over the air filter might increase due to dust collection, as more particles get trapped in the filter as the filter is aged.

Figure 2.4 – The air filter.

It is important that the filter is protected from water splash, thus some sort of protection shield should be used (e.g. the wheel house). It is also important that the air filter is installed high enough to prevent water from entering the EVAP system during purge when the car is wading [4]. Apart from the US system the air filter is sometimes used in markets with high level of pollutants to prevent particles to enter the EVAP system [8].

2.3 Purge valve

The purge valve is placed between the canister and the engine and is controlled by the ECU which regulates the amount of air and HC transported into the engine, so that stoichiometric conditions in the engine can be maintained. The opening and closing of the purge valve is called the duty cycle (DC). The DC regulates how much the purge valve should open with a frequency of 10 Hz, which means that if the duty cycle is 50% the purge valve will open/close from 0-50 % ten times in one second. The purge valve is active during 70 % of the time that the engine is running, and is constantly fluctuating. The purge valve has a maximum flow rate capacity of 120 l/min. During purge the gas is entering the purge valve through the purge nipple and exits through the engine nipple, Fig. 2.5. The inner diameter of the purge nipple and engine nipple is 10 mm respectively [4, 6].

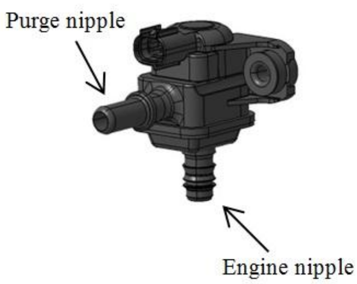

Figure 2.5 – The purge valve.

2.4 Check valve

The check valve is placed between the purge valve and the engine intake, and shall prevent gas from flowing from the engine and back to the system again. The check valve contains a disk that is normally closed by gravity. When the pressure of inlet side (upstream flow) is higher than the pressure of the outlet side (downstream flow), e.g. when there is a vacuum in the engine, the disk is lifted to allow flow to the engine. The disk will close when the pressure of the downstream side gets higher than the upstream side, shutting the valve and stopping reverse flow. To allow the check valve to be closed by gravity, Fig. 2.6, the valve is installed so that the inlet (purge nipple) is located at the same height or lower than the check valve outlet (engine nipple). The inner diameter of the purge nipple is 6 mm and the engine nipple inlet diameter is 8 mm [4, 6]. As for the purge valve, the check valve has a maximum flow capacity. This capacity is however unknown, but during the experiments in this work the volumetric flow rate was probably within the critical region of this capacity.

Figure 2.6 – The check valve.

2.5 Distribution pipes

All distribution pipes in the EVAP system transports only gaseous compounds (i.e. air and HC), and have different dimensions and purpose. The pipes can be divided into three sections, the front, the middle and the rear section. The front pipes are placed on the front axle, the middle pipes are connected between the front (placed in a plastic strip under the car) and rear axles, and rear pipes are placed at the rear axle of the vehicle. The distribution pipes should meet requirements such as having a lifetime of 16 years or 300 000 km, to withstand specific temperatures and pressures etc. The pipes can have 2-6 different layers of material to ensure that the requirements are fulfilled. In addition fire protection, chafe protection and in some cases also heat protection can be used. Which materials to use in each distribution line are determined by the fuel and lifetime required. Some extra length of the pipes are necessary for two reasons, first the shortest way is not always possible to use and second, different parts (e.g. the engine and the car body) can move in opposite directions to each other which demands flexibility of the pipes.

To connect the pipes, connectors are used. These connectors can be of different shape, material and size. The connectors are the weakest link regarding the lifetime of the distribution pipes. In case of a crash, connectors made of steel are used in the front area of the car to prevent leakages.

The pipes and connectors in the EVAP system are made of rubber, polyamide (PA), except one pipe and one connector from the middle section to the front, which are made of steel [9]. An overview of the different pipes in the EVAP system and the dimensions are presented in Table 2.1.

Table 2.1 – An overview of the pipes in the EVAP system, their position, inner diameter and length. Pipe3 consist of two pipes connected together with different diameter each.

Pipe	***Position of the pipe***	***$Ø_{inner}$ [mm]***	***Length [mm]***
Pipe1	Fuel tank – Carbon canister	16	1166
Pipe2	Carbon canister – DMTL pump	16	416
Pipe3	DMTL pump – Air filter	16/13	1574
Pipe5	Carbon canister – Purge valve	6	5405
Pipe6	Purge valve – Check valve	10	76
Pipe7	Check valve – Engine	10	80

2.6 DMTL pump

According to legislation on the US market, called the California Air Resources Board (CARB) legislation, a DMTL pump is required for the EVAP system. The purpose of the DMTL pump is to find leakages in the EVAP system, and holes larger than 0.5 mm in diameter must be detected. Leaks must be found within the gas volume defined by the fuel tank, the fuel cap, the canister, and all the pipes connected from the air filter until the purge valve. A leakage check is performed whenever the engine is shut off and takes around 15 minutes to perform depending on the amount of fuel in the tank and the tank size. For detecting leaks in the EVAP system, the system is pressurized by the DMTL pump to a pressure of approximately 6 kPa. If the pressure then decreases below the reference limit of 4 kPa, this means that there is a leakage in the system. The DMTL pump is thus only active during leakage detection and is otherwise normally open, i.e. so that the gas can flow freely through the pump. The inner diameter for the canister nipple and the air nipple is 15.7 mm respectively, Fig 2.7 [4, 10].

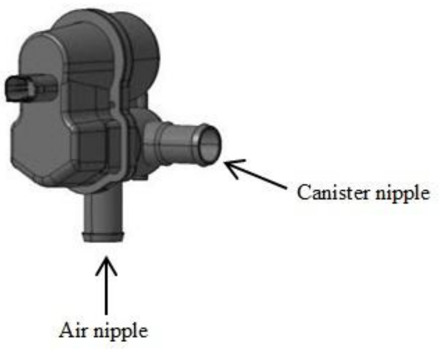

Figure 2.7 – The DMTL pump.

3 Experiment

To be able to simulate the purge process and the refuelling process a validation of how the pressure losses in the real EVAP system is influenced by the volumetric flow rate was needed. The EVAP system, in full scale, was set up in a laboratory and connected to a test rig. The test rig regulates and measures pressure, temperature, density, flow rate, etc. The working fluid used in the experiments was air at 101.325 kPa and 20^{o}C.

To measure the pressure in the system, pressure gauges were used and placed at different locations in the system. To be able to connect them to the EVAP system the pipes in the system had to be cut in half and connected with extra pipe lengths so that the nipples for measuring could be included. These extra pipe lengths had the same dimensions as the pipes they were connected to. However, after connecting these measurements it was noticed a small leakage in the system that could not be located. This leakage and extra pipe lengths would probably cause some measurement deviations. It is important to mention that it was not possible to calibrate some of the pressure gauges, causing some additional small measurement deviations.

3.1 Purge Test

Figure 3.1 shows a picture of the test rig when it was connected to the EVAP system to run the purge test. The silvery tube was connected to the test rig and regulated the atmospheric pressure and temperature of the air into the air filter.

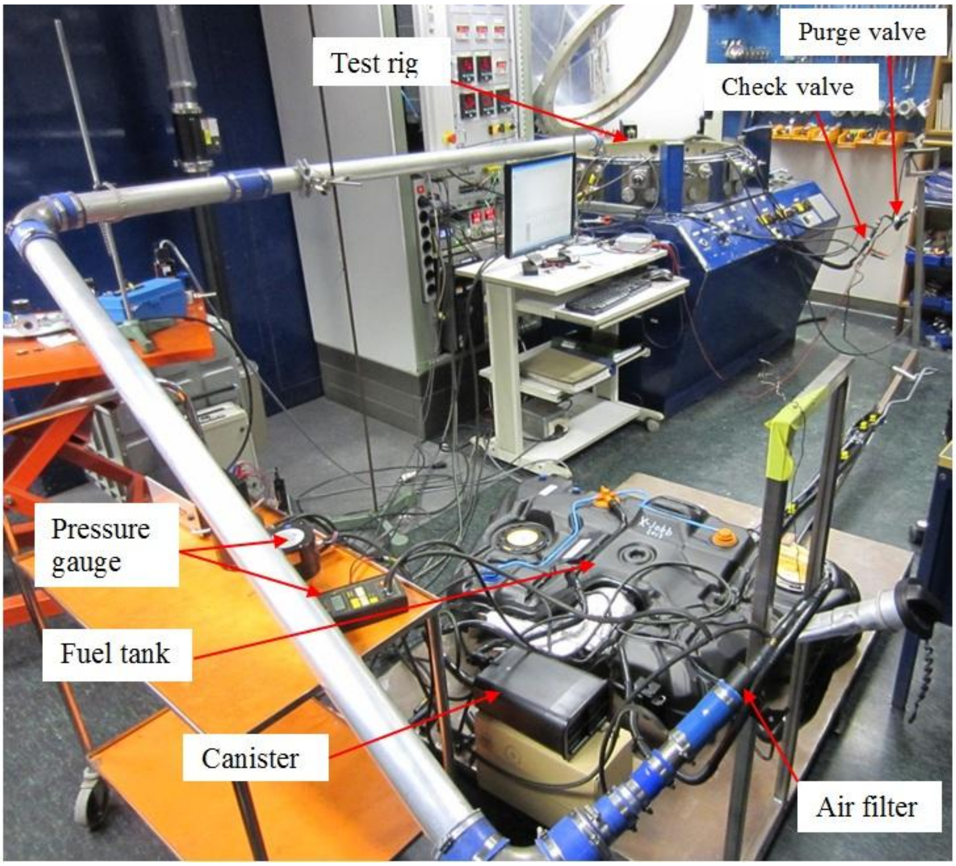

Figure 3.1 – The test rig, when the whole EVAP system was connected to run the purge test.

The pressure gauges used were placed at different locations, as shown in Fig. 3.2. Hence the pressure drop could be obtained for the pipes and complex components. A vacuum pressure was created in the rig and was varied between 5 and 90 kPa, with an interval of 5, to represent the vacuum in the engine. This vacuum pressure was applied at point E in the figure. The vacuum created a flow through the system, from the air filter, through the DMTL pump, canister, purge valve, check valve and to the "engine". The fluctuating movement of the purge valve created an unsteady flow in the EVAP system, which generated unreasonable results, therefore the purge valve was "shut off". The purge valve was set to be fully open to obtain a maximum flow through the EVAP system.

The pressure losses in the pipe between the purge valve and check valve was assumed to be very small due to the short distance, so only one measurement point was set between these two valves to get the pressure losses. The measured data from the purge test are presented in Appendix A.

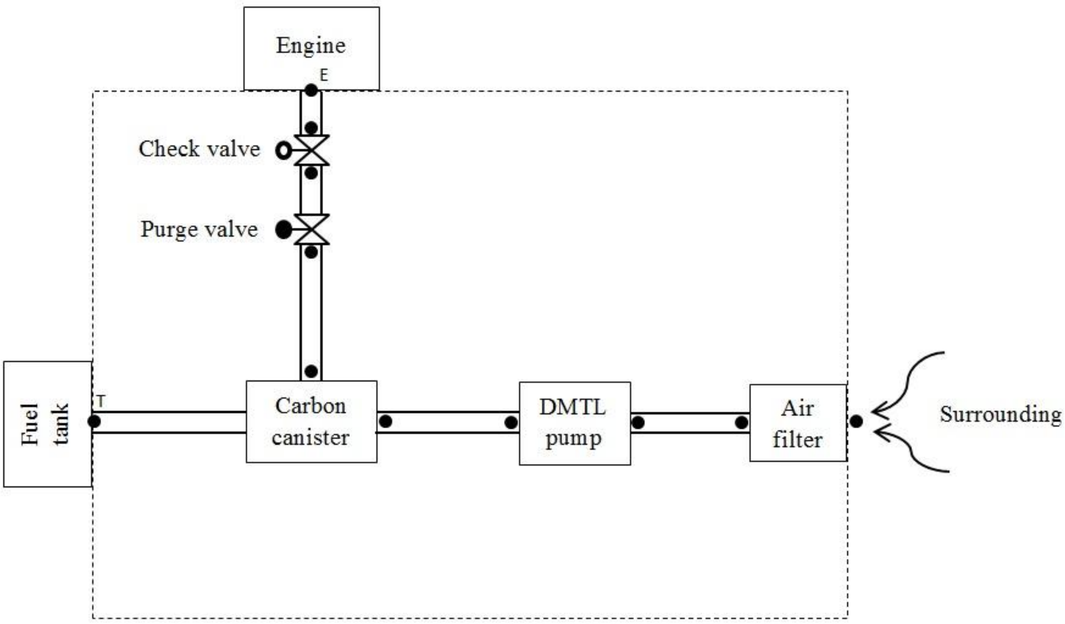

Figure 3.2 – The EVAP system during the purge test showing where the pressure gauges were placed (shown as black dots in the figure).

3.2 Refuelling Test

In the refuelling test, the filler pipe was removed and air was entered directly into the tank at point D, Fig. 3.3. The pressure at the outlet of the tank was measured in point T, thus pipe A and B was considered to be included in the fuel tank.

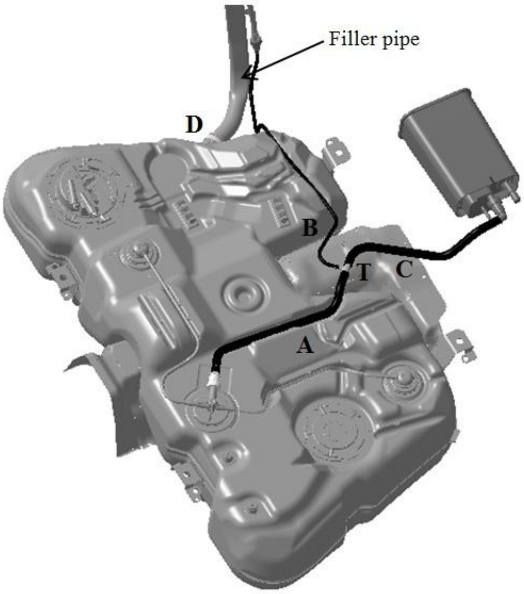

Figure 3.3 – The picture shows the EVAP system connected to the fuel tank. The outlet pressure from the tank was measured in point T.

For the refuelling test the rig regulated the volumetric flow rate, starting with 5 l/min up to 100 l/min with an interval of 5 l/min. These flow ranges were chosen because they were within the range of refuelling. The air flow went through the fuel tank, canister, DMTL pump and out through the air filter. The outlet from the check valve, point E Fig. 3.4, was held closed. Thus there was no flow from the canister in this direction. The positions of the pressure gauges during this test are illustrated in Fig. 3.4. The measured values from this test are presented in Appendix A.

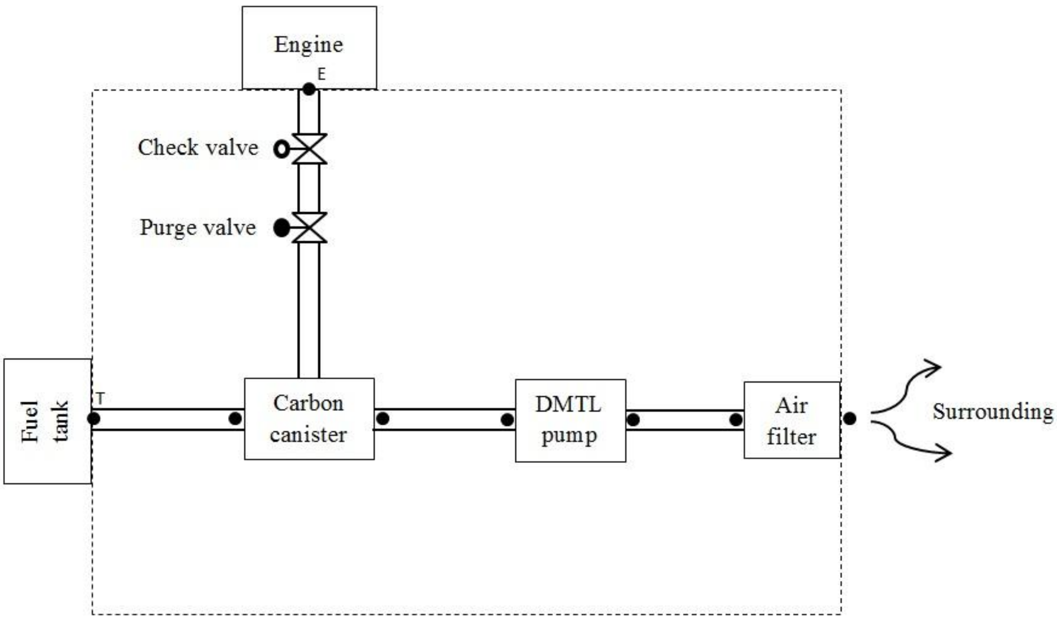

Figure 3.4 – The EVAP system during the refuelling test showing where the pressure gauges were placed, shown as black dots.

4 Modelling

In GT Suite there are several ways to model the performance of a component, and the performance can either be imposed or it can be predicted. For example, if modelling a positive displacement pump, the pump can be modelled as a pressure drop dependent on the flow rate, which can be constant or vary in time or angle. But the pressure drop profile of the pump must be specified by the user. This would be to impose the performance of the pump. To predict the pump behaviour the pump can be modelled based on its geometry and technical drawings thus the volume of the chamber, inlet/outlets valves, leakage, cam profile, etc. are included, but this higher level of complexity requires more data.

The GT Suite contains a library of templates developed by Gamma Technologies for modelling. These templates contain attributes that can be used to define the components being modelled. For example, the template for a pipe has attributes for diameters, lengths, etc. From the templates, objects are created that have their own unique name and with specific values of the attributes. An object can either be a component, connection or a reference item. Components are typically things that contain mass or volume, such as a pipe. Connections are typically things that have no mass or volume, such as an orifice, a contact between two mechanical bodies, etc. A reference item is typically "referenced" by a component or a connection, and describes for example the initial fluid condition. When linking objects on the modelling map, components and connections must always alternate (i.e. component-connection-component-connection etc.) [11].

CAD drawings of the EVAP system were imported into the GT Suite program so that specific data such as lengths, curvatures and volumes was obtained for the pipes and connectors. The complex components, the air filter, DMTL pump, canister, purge valve and the check valve, were modelled by the imposing procedure, using a set of templates from the GT Suite library for each component instead of considering their full internal geometry. The templates used to model these components are described below. The influence of the mass flow on the pressure drop of these components was fitted (imposed) to the experimental data. To achieve a good fit, values of different attributes in the templates were changed until the pressure drop matched the lab result. When the mass flow and the pressure drop over each of the complex components fitted the lab results, they were linked together with the pipes and connectors to form the total EVAP system. The build-up of templates in the total system and the complex components is given in Appendix D.

The following sections will give a description of the flow solver in GT Suite and how to model fluid flow through an internal network. This includes theory and description of the templates used in the modelling, that is: pipes, orifices, flowsplits, pressure loss connections, and environment boundaries [11].

4.1 General Flow Solution

The model in GT Suite solves the conservation equations of continuity, energy and momentum in one dimension (1D), which means that all quantities are averaged across the flow direction. GT Suite uses two types of time integration methods to solve the secondary variables, such as pressure and temperature, called the explicit method and the implicit method. The primary solution variables in the implicit method are mass flow, pressure, and total enthalpy. For the explicit method the primary solution variables are mass flow, density and internal energy. For this project the explicit solver is chosen since the working fluid used in the modelling is air, which is a compressible gas. For use of the implicit solver two conditions need to be met; that wave dynamics is unimportant and that the Mach number is less than 0.3, of which the last was not applicable in this case.

The 1D conservation equations solved by GT Suite are:

Continuity: $$\frac{dm}{dt} = \sum_{boundaries} \dot{m} \tag{4.1}$$

Energy: $$\frac{d(me)}{dt} = -p\frac{dV}{dt} + \sum_{boundaries} (\dot{m}H) - hA_s(T_{fluid} - T_{wall}) \tag{4.2}$$

Momentum: $$\frac{d\dot{m}}{dt} = \frac{dpA + \sum_{boundaries} (\dot{m}u) - 4C_f \frac{\rho u|u|}{2}\frac{dxA}{D} - C_p(\frac{1}{2}\rho u|u|)A}{dx} \tag{4.3}$$

The left hand side of the equations represents the time derivatives of the primary variables (mass flow, density and internal energy). In the simulations the transient process is modelled as a series of time steps small enough for the variables to be constant. In each time step the right hand side of Eqs. (4.1- 4.3) are calculated and integrated over the time step to obtain the variables at the end of the time step. If the steady state solution is of interest, which is the case in this work, the simulation is run until the variables at the end of the time step don’t change anymore, i.e. steady state is obtained.

GT Suite discretizes, i.e. splits the whole system into many sub-volumes called computational cells. The discretization length is the length of a cell in e.g. a pipe. Larger discretization lengths will give a shorter simulation time, but comes at the expense of a lower accuracy. A finer discretization results in a better accuracy but the computational time increases. The cells are connected by boundaries, and the scalar variables such as pressure, temperature, density, internal energy, enthalpy, species concentrations, etc. are assumed to be uniform over each cell. For each boundary the vector variables such as mass flux, velocity, mass fraction fluxes, etc. are calculated. This type of discretization is referred to as a "staggered grid", Fig 4.1.

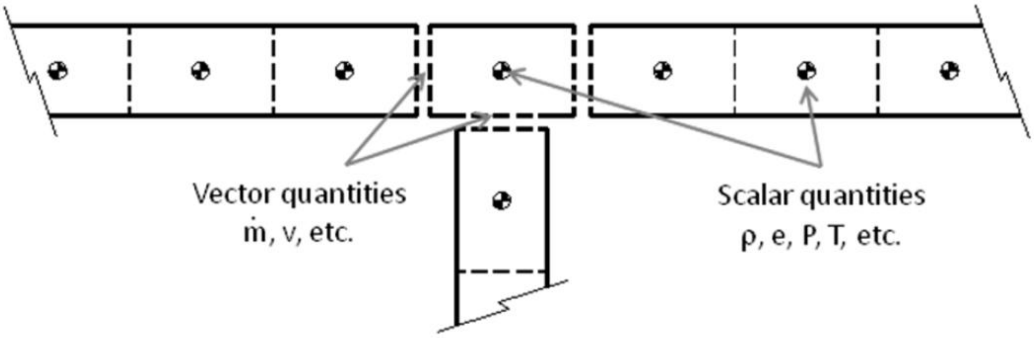

Figure 4.1 – Schematic of the staggered grid approach with scalar quantities at cell centres and vector quantities at boundaries.

4.2 Flow components and connections

To compute the mass flow and velocity in GT-Suite, components such as pipes, are linked together by connections. These connections are planes at which the momentum equation, Eq. (4.3), is solved and a number of different types of connections are available in the modelling program. When modelling a flow system, it is important to pay attention to any location where the area is changing since expansions and contractions represent a significant source of pressure drop. How the program is handling this together with a description of the different components and connections used in the modelling is presented below.

4.2.1 Pipe components

In pipes with a finite volume, the scalar equations (mass, energy) are solved at the centre of each computational cell, and the vector (mass flow) is solved at the boundaries between them. Depending on the desired geometry, several pipe templates are available in GT Suite. To take into account the effects of geometries there are some attributes that can be adjusted, i.e. the friction multiplier, heat-transfer multiplier, and the pressure loss coefficients. Since the heat transfer in the system is neglected, the heat-transfer multiplier is ignored in the simulation and will not be explained any further. Details about the friction multiplier and the pressure loss coefficient are presented below.

Friction multiplier

GT Suite calculates the flow losses in pipes due to friction between the fluid and the interior wall surface. The flow losses are calculated by a friction multiplier called the Fanning friction factor, C_f, as a function of Reynolds number, Re_D, based on the pipe diameter, D, and the wall surface roughness, ε.

To calculate the friction losses in the pipe there are three methods available in GT Suite: automatic, "simple" and "improved". These options offer trade-offs between speed and accuracy, where the "simple" method is the faster one and the "improved" method is the slower one. The automatic option is used in this work and is recommended by GT Suite for all models and it automatically chooses the best method.

In laminar flow regime, defined as $Re_D < 2000$, the friction factor is calculated similarly for both the “simple” and “improved” methods:

$$C_f = \frac{16}{Re_D} \qquad (laminar\ regime, Re_D < 2000) \qquad (4.4)$$

The differences between the “simple” and “improved” methods take place in the transition and turbulent regimes, and are further described in the following sections.

Simple Method:
In the turbulent flow regime, defined as $Re_D > 4000$, the “simple” method calculates the friction factor for smoothed walled pipes (roughness = 0) as:

$$C_f = \frac{0.08}{{Re_D}^{0.25}} \qquad (turbulentregime, Re_D > 4000) \qquad (4.5)$$

For pipes with a wall roughness > 0, the value of the friction factor is the larger of the factor given by Eq. (4.5) and that given by:

$$C_f = \frac{0.25}{(2 * log_{10}\left(\frac{1D}{2\varepsilon}\right) + 1.74)^2} \qquad (turbulent\ regime, Re_D > 4000) \qquad (4.6)$$

For the calculation of the friction factor in the transition regime, defined as $2000 < Re_D > 4000$, a linear interpolation between the laminar and “simple” turbulent value for the given Re_D is used.

Improved Method:
In turbulent flow regime the “improved” method calculates the friction factor as:

$$C_f = \frac{1}{4}\left(4.781 - \frac{(A - 4.781)^2}{B - 2A + 4.781}\right)^{-2} \ (turbulentregime, Re_D > 4000), \text{and all } \varepsilon/D \qquad (4.7)$$

where:

$$A = -2.0 log_{10}\left(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{12}{Re_D}\right)$$

$$B = -2.0 log_{10}\left(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51A}{Re_D}\right)$$

For the calculation of the friction factor in the transition regime, defined as $2000 < Re_D > 4000$, a linear interpolation between the laminar and “simple” turbulent value for the given $Re_D$is used.

Pressure loss coefficient

Pressure losses in pipes due to bends, tapers or an irregular cross-section are calculated with the pressure loss coefficient, C_p, defined as:

$$C_p = \frac{p_1 - p_2}{\frac{1}{2}\rho V_1^2} \tag{4.8}$$

Where p_2 is the total pressure at inlet, p_1 is the total pressure at outlet, ρ is the density of the fluid at inlet and V_1 is the inlet velocity.

4.2.2 Orifice connection

An Orifice connection is defined as a round hole where the diameter is fixed or variable/controllable, and is the link between most flow components. By setting the diameter of the orifice to be smaller than the diameter of two connected components a flow restriction can be specified.

The momentum equation, Eq. (4.3), is solved to calculate the flow rate through the orifice. The orifice accounts for pressure losses due to contraction, expansion, hole thickness friction and face friction, Fig. 4.2.

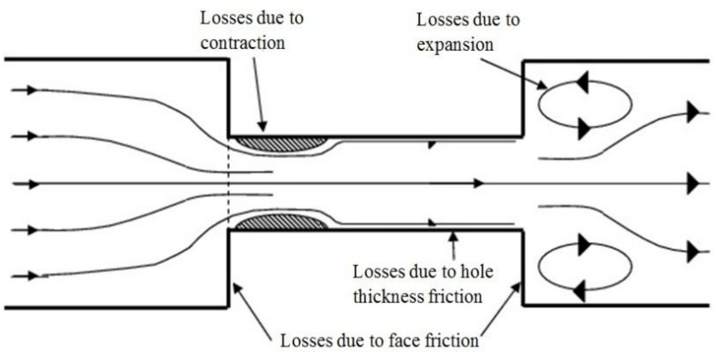

Figure 4.2– Different pressure losses that can occur in the orifice. The orifice is the smaller "pipe" in the middle of two components that are linked together.

4.2.3 Flowsplit components

When an object has several openings a conventional 1D treatment will not sufficiently capture the interaction of the flow through ports with arbitrary orientations. To account for conservation of momentum in these objects so called "flowsplits" are used. The geometry of the volume is thus taken into account, by considering the relative angle between the flows in and out of the volume. The lengths that a pressure wave must travel through the volume are also taken into account and as well as the geometry of the flow entering the chamber which can result in expansion or contraction losses.

The geometry of the flowsplit can be a cylinder, sphere, or any irregular volume, but no matter how large the volume is, a flowsplit is exactly one computational cell. The length and the cross-sectional area should always be conserved when creating a flowsplit, but this is not always possible. Conservation of volume should be maintained if the geometry is particularly irregular, and as for pipes, the friction multipliers, heat transfer multipliers and pressure loss coefficients can be adjusted to include the effect of irregular geometries.

The solution of the flowsplit is similar to the pipe where the scalars are calculated from the center of the volume. However, the momentum equation is solved for each of the volume openings (ports) separately. Each port is characterized by the port orientation, characteristic length and its expansion diameter. The port orientation is the relative angle of the port and the characteristic length is the distance the fluid will travel from the incoming port plane before its path is obstructed either by a wall or by the flow boundary at another port plane.

The expansion diameter is the maximum diameter the flow can expand into after entering a port to the flowsplit or contract from when leaving a port. The basic concept of the expansion diameter is that it is used to determine the pressure losses due to the contraction and expansion. It also determines the kinetic energy loss due to expansion for determining pressure recovery, and also the change in fluid properties due to changes in velocity resulting from a change in area (such as the temperature, pressure, density and speed of sound).

4.2.4 Pressure Loss Connection

In components where it is difficult to calculate/solve for the pressure loss it can be convenient to just impose a known pressure loss as a function of mass or volumetric flow rate. Instead of having an orifice placed between two components, a pressure loss connection can be used for this purpose. The pressure loss connection uses steady flow data and behaves as a quasi-steady component. This means that the momentum equation is not solved, and imposes limitations in the modelling if the model is to be extended to transient situations. If unsteady flow effects are important, the use of the pressure loss connection thus results in a reduced accuracy.

4.3 Description of complex components

The complex components were first modelled separately by using templates from the GT Suite library. The templates used to model each complex component were acquired from recommendations. Parameters in the template were chosen to achieve the best possible fit between the simulation results and the experimental results. Two different setups of parameters were fitted on each complex component for the purge process respectively the refuelling process.

A brief description of the modelling of each complex component is presented below together with an overview over the parameters used.

Carbon canister, air filter

The carbon canister and air filter was both modelled by the following templates: two flowsplits, two pipes, and one orifice. To compute for the geometry of the volume and to capture the changes in the flow direction when entering and leaving the canister and the air filter, flowsplits were used. The orifice linked the two flowsplits so that by changing the diameter of the orifice a flow restriction could be obtained and the desired pressure drop over the canister and air filter could be achieved. Each flowsplit characterize half of the canister’s respectively air filter’s volume. The nipples are represented by the pipes.

Purge valve, DMTL pump

The purge valve and the DMTL pump was both modelled by one orifice each, since they only represents a flow restriction in the pipe and the volume of these components are relatively small. The diameter in the orifice was changed in both cases until the pressure drop matched the lab results for each component.

Check valve

The check valve was first modelled the same way as the purge valve and DMTL pump, but the pressure drop in the simulation did not match the lab results. Therefore a pressure loss connection was used to just impose the pressure loss over the check valve.

4.4 Boundary conditions

An EndFlowInlet object was created to represent the boundary conditions at the inlet of the air filter. Both mass flow rate and temperature were imposed by using the same values as measured in the purge experiment (Appendix A). The initial fluid composition was set to “air2” which is a standard composition of air used in the GT Suite program.

The pressure in the engine, causing the vacuum pressure in the system, was modelled by creating an EndEnvironment object after the check valve.

The two processes, purge and refuelling, were modelled by using the same boundary conditions.

5 Sensitivity analysis of different parameters

The sensitivity analysis was done by performing six tests on the complete EVAP system. In each of these tests one specific parameter was changed. A description of each test follows below, which parameters that was changed and why it was of interest to investigate each parameter. Case 1 – Case 6 are the sensitivity analysis for the purge process, and Case 1* and Case 2* are for the refuelling process.

Case 1: In the current system pipes with an inner diameter of 6 mm and an outer diameter of 8 mm are used and the resulting pressure drops in these pipes are quite high. In Case 1 it was therefore investigated how an increase of the inner diameter from 6 to 10 mm would affect the pressure drop.

Case 1*: During refuelling, pipes with an inner diameter of 13 and 16 mm are used. In Case 1* it was investigated how the pressure drop would be affected if all the pipes had an inner diameter of 13 mm.

Case 2: The pipes used in the current system is longer than necessary to be able to fit with the other systems in the car, which means that the pipes cannot fit as straight pipes but need bends and curvatures. With new layouts and components to be considered in the future, it is important to see how new/extra pipe bends would affect the pressure drop in the system. For Case 2 bends was added on Pipe 5 (purge pipe) since this is the pipe with the most influence on the pressure loss during purge. Five bends were added with angles of 30, 45, 60, 70 and 90 degrees to evaluate the impact on the pressure drop.

Case 2*: Sometimes it is necessary to add some more bends to the pipes connected to the DMTL pump to make this part fit better under the car. Therefore the effects of adding bends for both pipes connected on each side of the DMTL pump have been investigated. Four 90 degree bends have been added to the pipes, two bends on the pipe connected to the canister and two bends on the pipe connected to the air filter, to see how it would affect the pressure drop in the system.

Case 3: Combination of Case 1 and Case 2. The diameter of the purge pipe was 10 mm (Case 1) combined with the extra bends in Case 2.

Case 4*:* The temperature in the system varies depending on if it is a hot or cold day. To investigate the influence of temperature, the gas temperature was varied from 283 to 323 K in Case 4. Heat transfer from the fluid to the walls was, however, still neglected.

Case 5*:* In Case 5 the composition of the working fluid was changed. The experiments and simulations have been done with pure air, but in reality the fluid from the canister to engine is a mixture of HC and air. In this case the amount of HC was added to the EVAP system. The composition of the fluid was changed from 100% air to a mixture of air and HC. Five scenarios were simulated with changed HC concentration starting at 10% up to 50% HC.

Case 6: The experiments showed a difference in pressure drop over the canister depending on if a refuelling or purge process was done. The canister has different sizes of the nipples at outflow for refuelling and purge, Fig. 2.3. In Case 6, the diameter of the nipple for purge was changed from 6 mm to 10 mm and the diameter of the purge pipe was changed to 10 mm.

6 Results

This section presents the results from the experiments and simulations of the purge and refuelling processes respectively. The sensitivity analyses for the two processes are presented in the end of this chapter where parameters have been changed to investigate the influence on the pressure drop.

6.1 Experiments

From the data obtained in the experiments, Appendix A, it can be seen that the highest flow rate measured for the purge process was around 62 l/min. It was not possible to achieve a higher flow rate through the system, which suggests that there is some flow restriction in the system. The highest flow rate measured for the refuelling process was around 97 l/min and the flow restriction in the system is caused by some of the components included in the purge process.

In Table 6.1 the pressure drop over each component (pipes and complex components) in the EVAP system measured at a flow rate of 42.46 l/min for the purge process and 40.24 l/min for the refuelling process are shown. For this specific purge process the total pressure drop was 25.16 kPa and for the refuelling process the total pressure drop was 0.872 kPa (measured data for all flow rates are presented in Appendix A). The pipes are, (see Fig. 2.1 for a schematic illustration of the pipes):

Pipe 5 – purge pipe between the canister and purge valve (PV)

Pipe 3 – pipe between the air filter and DMTL pump

Pipe 2 – pipe between the DMTL pump and canister (Can.)

Pipe 7 – pipe after the check valve (CV)

Pipe 1 – pipe between the fuel tank and canister

Table 6.1 – Pressure drop in each of the components in the EVAP system measured during a purge process with a flow rate of 42.46 l/min and during a refuelling process with a flow rate of l/min.

Process	$\dot{V}$ *[l/min]*	*Filter: [kPa]*	*DMTL: [kPa]*	*Can.: [kPa]*	*PV.: [kPa]*	*CV.: [kPa]*	*Pipe 1 [kPa]*	*Pipe 2 [kPa]*	*Pipe 3 [kPa]*	*Pipe 5 [kPa]*	*Pipe 7 [kPa]*
Purge	42.46	0.1	0.0617	1.717	2.637	1.557	-	0.0934	0.109	18.854	0.0301
Refuel	40.24	0.052	0.056	0.501	-	-	0.077	0.046	0.14	-	-

It can be seen that the pressure drop over the air filter and the canister is about 40 respectively 71% higher for the purge process than for the refuelling process. One way of explaining the difference in pressure drop between these two processes is the different flow directions of the gas, and the components included in each process. During purge the vacuum in the engine causes the flow through the system. The air is thus drawn through the air filter, the DMTL pump, the canister and the purge nipple of the canister, Section 2.1. The purge nipple has a somewhat smaller inner diameter (6 mm) compared to the fuel nipple (13.5 mm) used in the refuelling process and this creates a larger restriction of the flow during purge than during refuelling. The pipes included in the refuelling process have mainly an inner diameter of 16 mm, while the pipes in the purge process are 6/10 mm, which also explains differences in pressure drop during purge and refuelling.

For the purge process the results for other flow rates than of the one presented in Table 6.1 were more or less the same, apart for the check valve. The contribution of the check valve to the total pressure drop increased as the flow rate increased. For a flow rate around 56 l/min the check valve contributed more to the pressure losses than the canister. This could be because the maximal flow rate capacity of the check valve was reached and thus increasing the relative pressure drop.

The results for the specific refuelling process shown in Table 6.1 were similar for all the other flow rates, with the exception of flow rates below 35 l/min. For these flows Pipe 2 contributed with a slightly higher pressure loss than the DMTL pump. When looking at the measured results (Appendix A, Table A1.b), the results for the DMTL pump shows negative results for the first two flow rates. This is considered to be an error in the measured data due to the measurement uncertainty.

The data in Appendix A also shows that, for example, for the first flow rate (18.34 l/min) the vacuum pressure is set to 4.999 kPa. But when adding up all the pressure losses for each component in the system, the total pressure loss is shown to be 5.2 kPa, which is an error of 0.5%. This deviation can be explained by the extra pipe lengths that had to be included for the measurement, and also the small leakage that was noticed in the system (see section 3). For the other flow rates the deviation is less than 0.5%. These deviations are considered to be small and can be negligible.

The bar diagram in Fig. 6.1 and Fig 6.2 illustrates how much each of the components in the EVAP system contributes to the total pressure drop in percentage. In each diagram is a comparison between experiment data and simulated data. As shown is there some difference between the two. This can be explained by the impossibility to use the exact same measurement points in the experiment and in the simulation. Another explanation is the extra pipe length added to use the pressure gauges and modelling uncertainties.

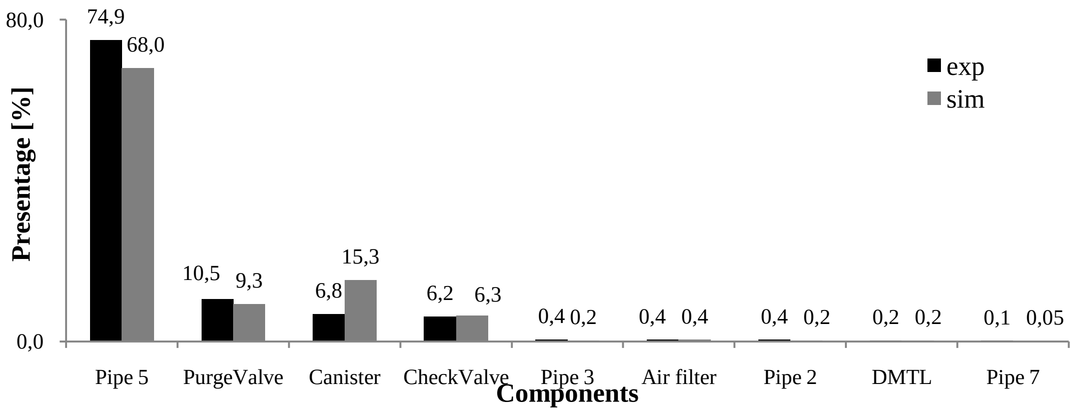

Figure 6.1 – Pressure drop during the purge process in each of the components in the system expressed as percentage of the total pressure drop of 25.16 kPa, measured at a flow rate of 42.46 l/min. A comparison between the experiment "exp" and simulation "sim" are shown.

As Fig. 6.1 shows, Pipe 5 contributes with 75% of the total pressure drop in the system (18.85 kPa) which is a large impact compared to the other components. Changes in this pipe would have a great influence on the pressure loss in the system, which means that changes in the pipe dimension are crucial for the total pressure drop in the system. It is also seen that Pipe 2, Pipe 3, Pipe 7, DMTL pump and air filter only have a small influence on the total pressure drop and changes of these components would not affect the pressure drop significantly. Due to their small influence it may be possible to neglect them in the modelling. During the experiment the pressure loss in Pipe 6 (the pipe between the purge valve and check valve, Fig. 2.2) was assumed to be very small, so only one measurement point was set between these two valves to get the pressure losses. The results above show that this assumption was reasonable, since Pipe 6 and Pipe 7 have the same dimension and shape.

The high pressure loss in Pipe 5 can be explained by looking at the expression for calculating pressure loss in a straight pipe (assuming steady, incompressible and single phase flow). The pressure loss are proportional to the length divided by the diameter of the pipe, times the square of the fluid velocity, which, assuming a constant volume flow, is proportional to the length divided by the diameter to the power of three [12]. This means that a long and small pipe will have a high pressure drop, especially the diameter has a strong influence on the pressure drop.

As can be seen in Table 2.1 the length and inner diameter of Pipe 5 is 5405 mm and 6 mm respectively. This is considered to be a long and small pipe that has a higher pressure drop compared to Pipe 3 (1574 mm, Ø13/16 mm), Pipe 2 (416 mm, Ø16 mm) and Pipe 7 (80 mm, Ø10 mm).

For the refuelling process the total pressure loss in the system is less than 1 kPa, and can be considered as a small pressure loss compared to the purge process. One explanation that imposes the higher pressure drop in the purge process is the larger number of components included. Another explanation is that the pipes included in the refuelling process all have larger or equal diameter compared to the purge process where Pipe 5 (not involved in the refuelling process) contributes to 75% of the pressure drop.

Figure 6.2 show that the canister has the greatest impact on the pressure loss during the refuelling process. The relative contribution of the canister to the total pressure prop decreases with increasing flow rate during the refuelling process.

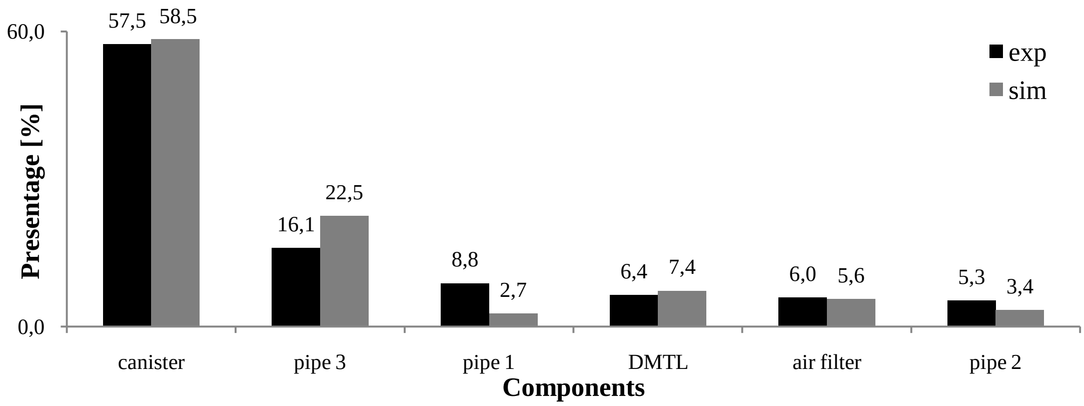

Figure 6.2 – A comparison between the experiment "exp" and simulation "sim" during the refuelling process with the pressure drop in each of the components in the system expressed as percentage of the total pressure drop of 0.872 kPa, measured at a flow rate of 40.24 l/min.

6.2 Comparison of experimental and simulated data

Figure 6.3 and Fig. 6.4 show a comparison of the experimental and simulated data of the whole system during the purge process and the refuelling process respectively, the pressure drop, ΔP, is presented on the y-axis and volumetric flow rate on the x-axis. As can be seen from the figures, the difference between the simulation and experiment is in general low, less than 2%, which can be regarded as acceptable.

The fitting of each of the complex components can be viewed in Appendix B for the purge process and Appendix C for the refuelling process. The fitting of the complex components are in overall good, except for the purge valve and canister during purge. As can be seen in the figure (Appendix B) there is a bad fit at the lowest and highest flow rate and the differences is more than the acceptable limit of 2%. Why there are such deviations at these two points when the rest of the data fits well, is not understood. But, even though there are some deviations when fitting each of the complex components, the simulation of the whole system matches the experiments well for both processes.

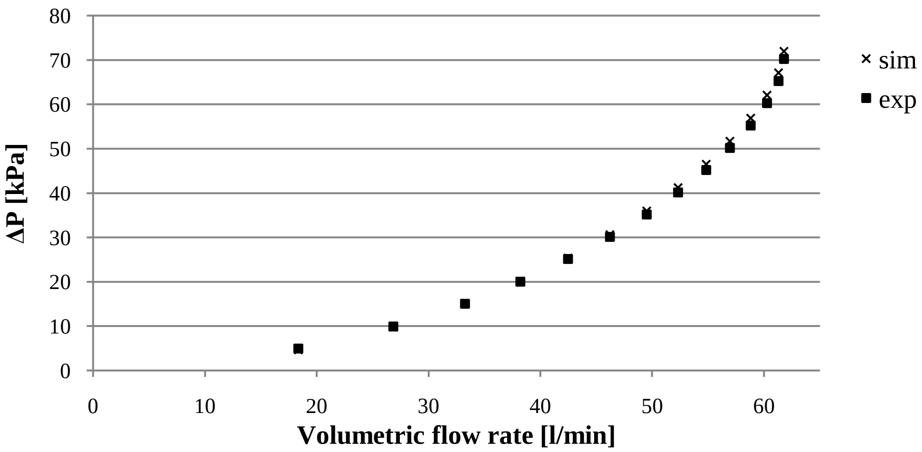

Figure 6.3 – Comparison of experimental and simulated data of the pressure drop for the whole system during purge, "exp" shorted for experiment and "sim" shorted for simulation.

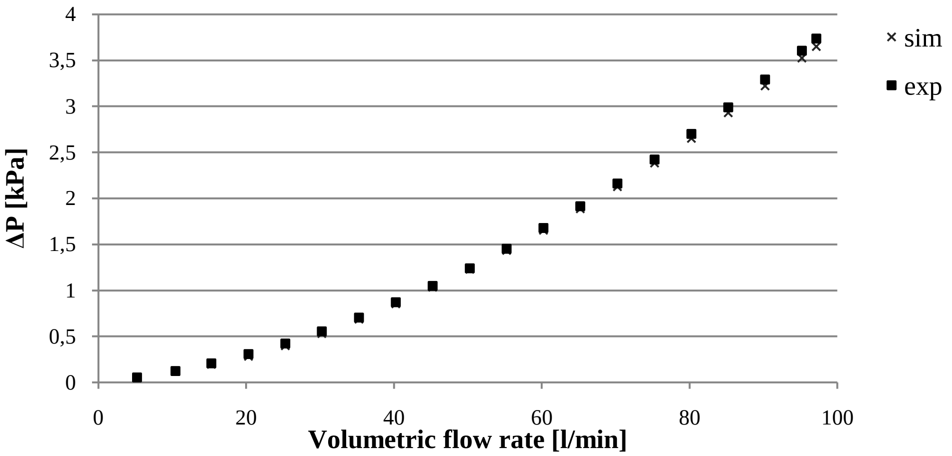

Figure 6.4 – Comparison of experimental and simulated data for the whole system during refuelling, "exp" shorted for experiment and "sim" shorted for simulation.

6.3 Sensitivity Analysis

6.3.1 Case 1

By changing the inner diameter from 6 mm to 10 mm in Pipe 5 in the model, the total pressure drop in the EVAP system during purge, decreases with 40-62% depending on the volumetric flow, Fig.6.5. This is a remarkable change of as much as 30 kPa for high flows. This strong influence is not unexpected as Pipe 5 accounts for 75% of the total pressure drop. The relation between the length and diameter has increased and therefore the pressure loss is decreased, and this is according to theory of pressure losses in pipes [12] and was discussed in Section 6.1.

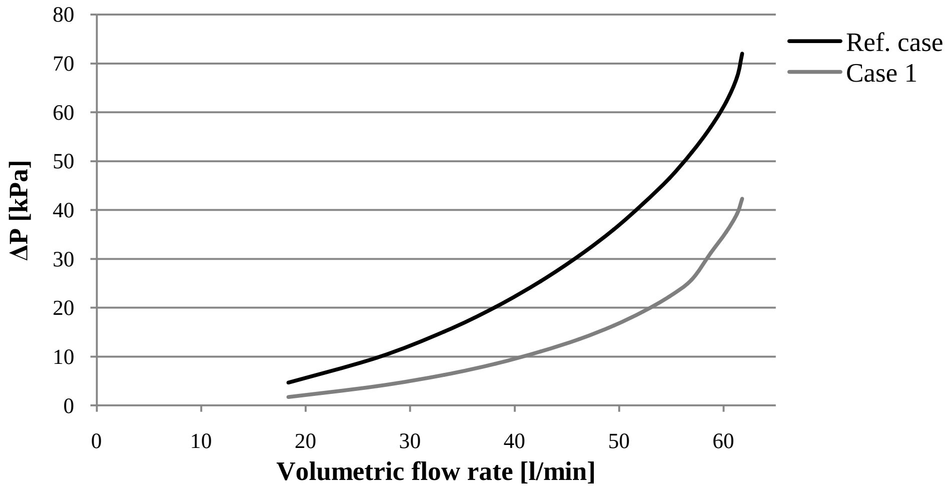

Figure 6.5 – Pressure drop in the whole system during purge for the reference case and for Case 1 where the inner diameter of Pipe 5 (purge pipe) was increased from 6 mm to 10 mm.

When increasing the diameter for Pipe 5, the connectors should be increased as well. The connectors was increased in the same magnitude as for Pipe 5, but this can only be considered to be an approximation of the dimension for the connectors.

6.3.2 Case 1*

Changing the inner diameter of the pipes included in the refuelling process, i.e. Pipe 1, 2 and 3, from 13 mm to 16 mm gave the results as shown in Fig. 6.6. The total pressure drop in the EVAP system did not show any significant change when increasing the pipe diameters. The change in the whole system varies from 5.3 to 6.4% depending on the volumetric flow, and this parameter can therefore be considered to have a small influence on the total pressure drop. For the same reason as mentioned above, the pressure loss will be increased with decreased diameter in pipes. Since the change in diameter for this case are for pipes that contribute with less than 16% of the total pressure loss of 0.872 kPa, changes here will not influence the pressure loss that much.

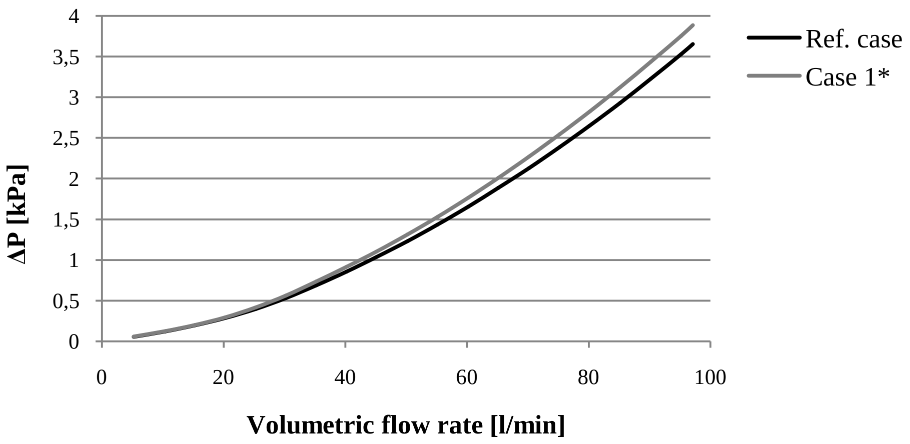

Figure 6.6 – Pressure drop in the whole system during refuelling for the reference case and for Case 1 where the inner diameter of Pipe 1, 2 and 3 was increased from 13 mm to 16 mm.*

6.3.3 Case 2

In this case a part of the purge pipe that had no bends is replaced with a pipe with bends. Figure 6.7 shows how the pressure drop is influenced when five bends are added with angles of 30, 45, 60, 70 and 90 degrees. The total pressure drop in the whole system is less than 0.04%, thus this parameter can be considered to have a negligible influence on the total pressure drop.

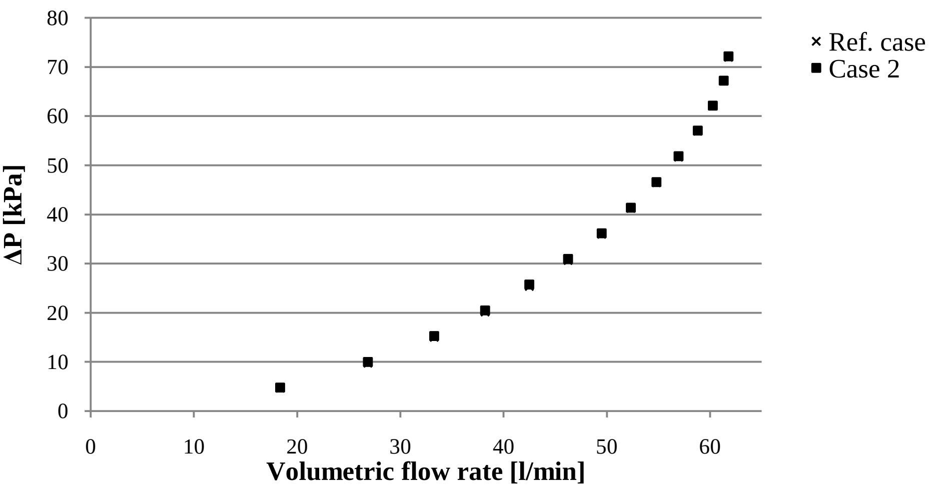

Figure 6.7 – Pressure drop in the whole system during purge for the reference case and for Case 2 where five bends are added to the purge pipe.

Sharp bends, angle of 90°, will have a greater impact on the pressure drop compared to bends with angle less than 90° [12]. The radius of the bend is another thing that will influence the pressure drop. The losses in bends depend on changes in flow direction due to flow separation [12]. However, the result showed in the figure above does not indicate a large influence of adding bends to the pipe. One reason could be that the comparison is not made to a straight pipe. The pipe in the reference case has many bends already and is one explanation that no difference could be deduced. Another thing could be the low pressure loss, the pressure loss in the system is low and therefore the change is not large enough to make a significant difference.

6.3.4 Case 2*

Adding more bends to both pipes connected on each side of the DMTL pump gave no change in the total pressure drop in the system during refuelling (Fig. 6.8), and this parameter can therefore be considered to have a small influence on the total pressure drop.

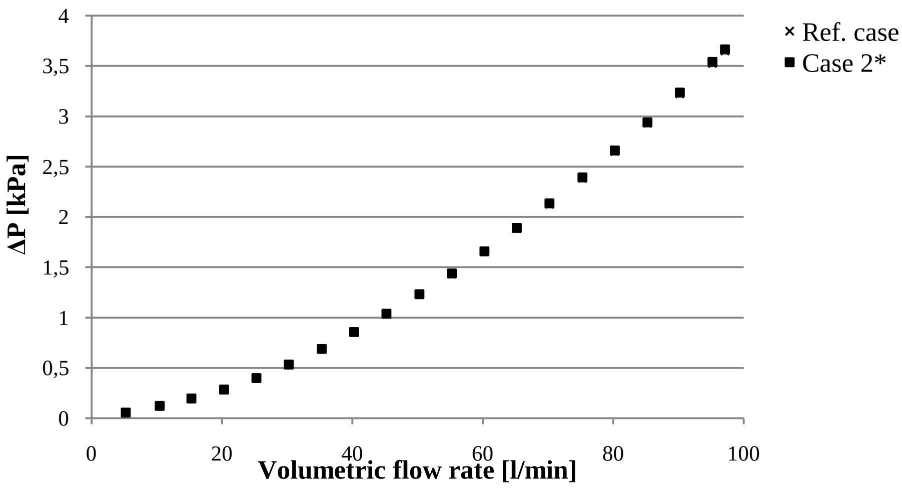

Figure 6.8 – Pressure drop in the whole system during refuelling for the reference case and for Case 2 where four bends are added to both pipes connected at each side of the DMTL pump.*

In the refuelling process the diameter of the pipes and the length could in this case have an impact, since no significant different in the pressure loss can be seen. The low pressure through the system will probably be the main reason that no change is seen.

6.3.5 Case 3

The combination of Case 1 and Case 2 can be seen in Fig. 6.9, together with the reference case. The diameter of Pipe 5 was increased from 6 mm to 10 mm (Case 1), and is shown by the dotted line. The grey line shows the result when both increasing the diameter of Pipe 5 combined with the extra bends added in Case 2. As seen in Case 1 the increase of the diameter of Pipe 5 has a significant influence on the pressure loss in the EVAP system. But adding five bends make almost no difference at all in the system. A reason for the small "knee" in the figure for Case 3 could not be found. A first consideration was that it could be an indication of transition from laminar flow to turbulent flow when the flow rate exceeds somewhere around 54 l/min, thus the pressure loss increases. But the simulation model shows a turbulent flow for all the flows, since the Reynolds number is higher than 2000 which indicates a turbulent region.

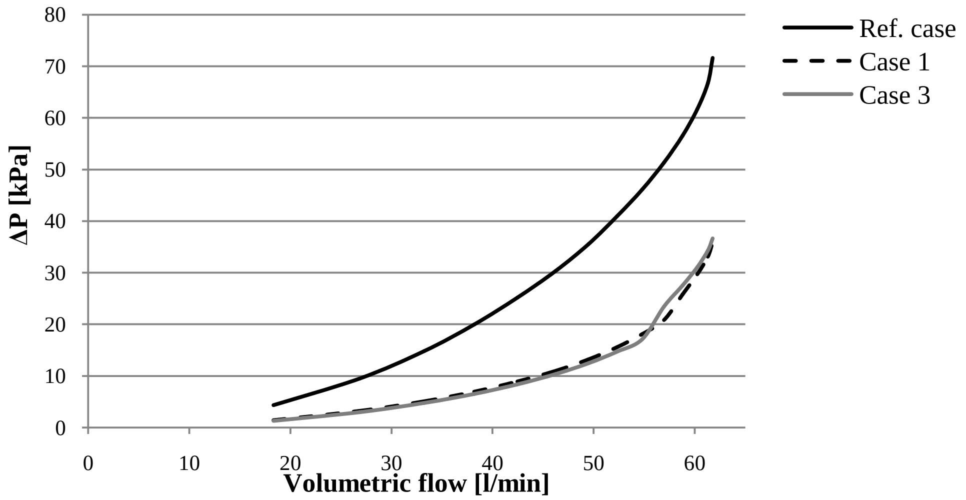

Figure 6.9 – Pressure drop in the whole system during purge for the reference case and Case 3. "Ref. case" is the reference case with no bends added. "Case 1" is where the diameter of Pipe 5 is increased from 6 to 10 mm, but no bends are added. "Case 3" is when five bends are added to Pipe 5 and the diameter is 10 mm.

6.3.6 Case 4

When increasing the temperature for the air from 20^{o}C to 50^{o}C during purge, the simulation shows a negligible decrease of the total pressure loss in the EVAP system, Fig 6.10. The change is less than 1.3 kPa and indicates that it is reasonable to neglect heat transfer in the modelling of the EVAP system. The thermodynamic state of a gas is described by its volume, temperature and pressure and by increasing the temperature the density will decrease [3]. The density and pressure are proportional, so when the temperature increases the pressure drop in the system decreases as well, but as seen the effect is very small.

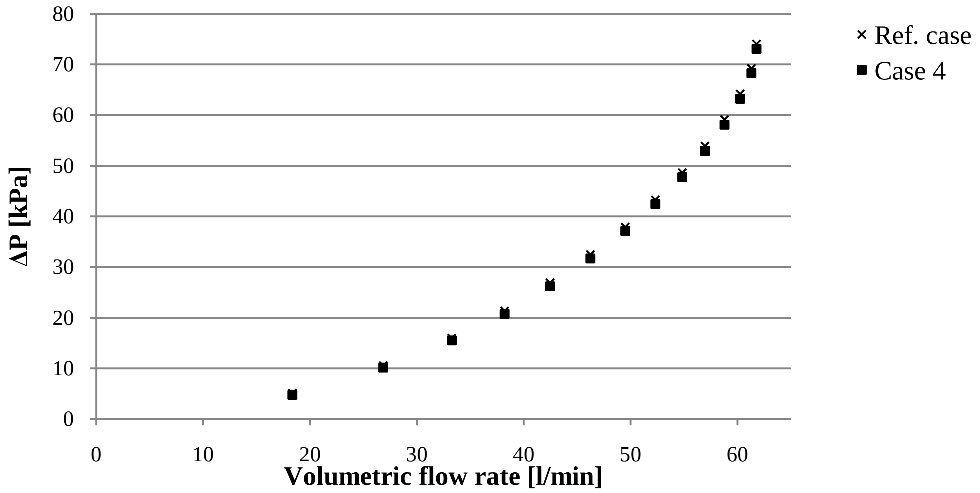

Figure 6.10 – Pressure drop in the whole system during purge for the reference case, with 20˚C and Case 4 where the temperature is changed to 50˚C.

6.3.7 Case 5

HC was added to the EVAP system and the composition of the working fluid was changed from 100% air to a mixture of HC and air. To simulate the HC, "indolene vapour" was used in simulation program. In Fig. 6.11 it can be seen how the composition of air and HC influences the pressure loss in the system. By having a HC concentration of 20% in the system, the total pressure loss changes between 5.6% for high flow rates and 0.7% for low flow rates compared to the reference case with air. This change is less than 0.5 kPa and is considered to be very small. When the HC concentration is set to be 50% in the system, the pressure loss changes between 2% for high flow rates and 16% for low flow rates compared to the reference case. These changes are less than 1.6 kPa, and can also be considered to be small.

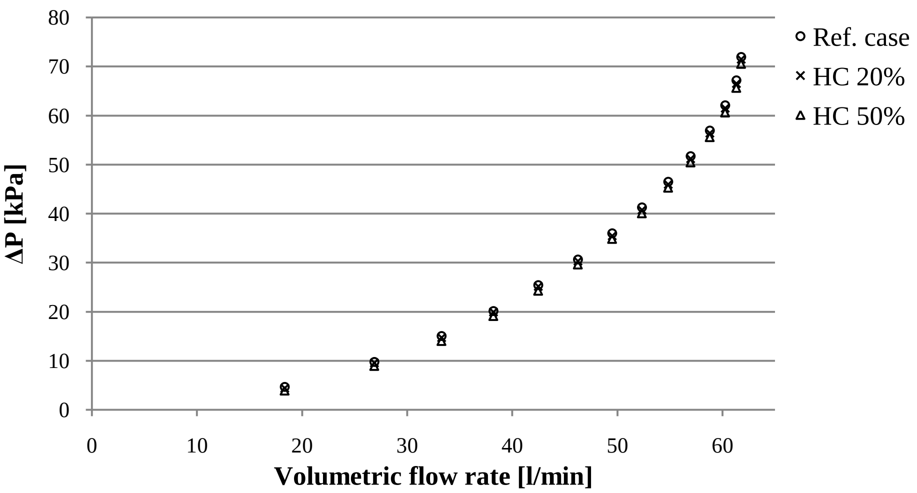

Figure 6.11 – Pressure drop in the whole system during purge for the reference case and two different cases: One case where the air is replaced with a mixture of air and HC, with an HC concentration of 20%, and one case where the air is replaced with a 50% mixture of air and HC.

This result shows that the differences between modeling the system with air or a mixture of air and HC are small, and modeling the EVAP system with 100% air will give sufficient results of the pressure loss in the system.

6.3.8 Case 6

The purge nipple for the canister is smaller than both the air and tank nipple. In Case 6 the nipple inner diameter has been increased from 6 mm to 10 mm. Together with this change the inner diameter of Pipe 5 has been increased from the original 6 mm to 10 mm. Figure 6.12 shows the comparison between the original case (Ref. case) with Case 1, with increased purge pipe diameter and Case 6, increased nipple diameter and purge pipe diameter.

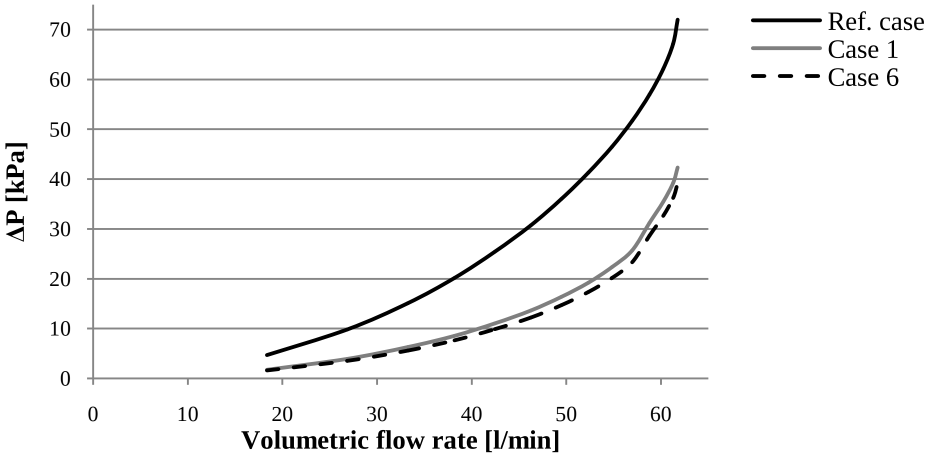

Figure 6.12 – Pressure drop in the whole system during purge for the reference case, Case 1 and Case 6 where the diameter of the purge nipple of the canister and the diameter of the purge pipe both are increased from 6 to 10 mm.

When increasing both the purge nipple and the purge pipe diameter the total pressure loss in the system is decreased with 7-11% compared to Case 1, where only the purge pipe diameter is increased. Compared to the reference case this is a total decrease of 46-69%. This shows that the dimension of the nipple is important for the pressure loss, but has a much smaller influence than the purge pipe diameter.

7 Discussion

Although the modeled EVAP system was a simplification of the real system and the complex components were fitted to match the experimental results, the comparison between the total pressure loss in the simulation and the experiment are matching quite well. If there is not enough information to obtain about the full internal geometry and physical behaviors of more complex components, the imposing procedure of modeling these is sufficient enough. As long as the simulation results match the characteristics of the complex components, it is acceptable to model it in this way. The modeled system can thus be used for predictive analyses for the specific system tested. It is important to point out that as long as the complex components are not modeled by their full internal geometry and physical behaviors, changes on these components cannot be made in the modeling. If some of the complex components are to be replaced by other components, for example a larger canister is to be tested in the system, new pressure loss measurements data needs however to be implemented. The measured data should then be fitted to match the modeled system.

In this thesis, the pressure loss measurements were executed on the whole system at once and the model was then fitted to the experimental data obtained. In the experiments the highest possible flow rate measured for the purge process was around 62 l/min. It was argued by Volvo that the purge valve would cause this restriction, and therefore one additional experiment of the purge valve was done by Volvo [10]. This experiment showed that the maximal capacity was around 120 l/min, which shows that the purge valve was not causing any flow restriction in the system. So, some interesting questions thus follow: Would it have been possible to do single pressure loss measurements on individual complex components, and then implement this data into the modelled system? Would then the results have been the same as shown here? If tests had been done for each complex component, and then used for fitting the model, the knowledge of these components flow restriction would already exist.

The EVAP system was analysed at steady state conditions, but in reality the purge valve constantly open and closes causing the system to fluctuate. A vibrant system provides greater pressure variations. When doing the experiments the purge valve was first set to be active, causing a pulsation of the gas in the system. However, the pressure loss results showed unreasonable outcomes and it was therefore decided to only investigate a steady state system. To model the system at unsteady conditions, the complex components need to be modelled by knowing more about their physical behaviour.

When the CAD drawings were implemented in the GT Suite, circular pipes were created even though some of the pipes have an elliptical cross-sectional area. This should however not be a problem in a 1D simulation like this, where boundary layer effects are not taken into account and only the cross-sectional area of the pipes is of importance. When the elliptic cross-sectional area pipes are converted to round pipes in the program, the program is creating a pipe with a diameter which matches the cross-sectional area of the original elliptic pipe.

When looking at the pressure drop for each component during purge, Pipe 5 shows a significantly higher pressure loss compared to the other components. By increasing the inner diameter of the pipe from 6 to 10 mm in the simulation, the total pressure drop in the system was decreased between 40 and 62%, and this is the single most efficient measure to reduce the pressure drop during purge. The pressure drop over the canister shows a significant variation between the purge and the refuelling process, which is explained by the smaller inner diameter of the purge nipple. By increasing both Pipe 5 and the purge nipple in the simulation, the total pressure loss in the system was shown to decrease between 46 and 69%, which is an additional of 7 - 11% compared to only increasing the diameter of Pipe 5 and is thus an additional measure to reduce the pressure drop.

The increase in pressure drop over the air filter due to an accumulation of particles was not considered in this study. The simulation results shows a negligible pressure drop over the air filter. Since the volume of the air filter is relatively small, an accumulation of particles would probably not be causing any significant increase in the pressure drop. This assumption is thus considered to be reasonable.

For the experiments in the lab, the pressure gauges used and the small pipe lengths that had to be added to the EVAP system caused some errors in the measurement. The deviation of the measurement in the experiments was however small, and was calculated to be around 0.5%. Even though this is considered to be an error of the measurement data, these errors are minor and do not have a significant influence on the modelling results. There is one thing to be cautious about though when this type of fitting to measured data is done, and that is to be careful about where the pressure gauges were placed in the measurement. In some modelled systems there can be a noticeable pressure drop through a pipe (in addition to an orifice), so it is thus important to make sure that the drop in the simulation is measured consistently with the test bench.

8 Future work

If the complex components are to be modified, a more accurate modeling of these components needs to be executed or new experimental date is required to for fitting of the pressure drop. These tasks will be essential to make it possible to model other EVAP system.

A factor that could be of great importance for the pressure drop is the open/close cycle of the purge valve that has not been considered in this work. With a more detailed description of this component it can be possible to account for these pulsations instead of steady state assumption used in the model today. By doing this it will be possible to simulate the real system behaviour and how it is affected by different frequencies of the opening/close cycle.

How the HC concentration varies in the system and are adsorbed in the canister should be investigated and implemented in the modeling.

9 Conclusions

A model of the EVAP system has been developed using the simulation program GT Suite to simulate and identify pressure losses in the system. Although the simulation model is a simplification of the real system, the model can be used for predictive analyses for the specific system tested as long as the simulation results match the characteristics of the complex components. Changes on these components cannot be made in the modeling given that the complex components are not modeled by their full internal geometry and physical behaviors. If some of the complex components are to be replaced by other, new pressure loss measurements data needs to be implemented and fitted to match the modeled system.

To decrease the pressure loss in the system significantly (during purge), it is recommended to use a Pipe 5 with a larger diameter than what is used in the current system. And it is also recommended to increase the diameter of the purge nipple on the canister from 6 mm to 10 mm. Bends were shown to only have a small influence on the total pressure drop.

Having a model that can simulate how changes on the EVAP system will influence the pressure loss, tests can be run in advanced and more tests on the system can be accomplished in shorter times. This will save both time and money.

10 References

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Appendix A – Measured Data

The measured data from the experiment (flow test) are shown in the following three tables. Table A.1a and b shows the measured data from the purge test for complex components. The vales from the refuelling test are shown in Table A.2.

Table A.1a – Measured values from the purge flow test for the complex components

Vacuum P: [kPa]	$\dot{V}$ *[l/min]*	*ρ [kg/ m³]*	*T [°C]*	*Filter ΔP: [kPa]*	*DMTL ΔP: [kPa]*	*Canister ΔP: [kPa]*	*Purge V. ΔP: [kPa]*	*Check V. ΔP: [kPa]*
4.999	18.34	1.2026	19.9	0.021	0.011	0.398	0.48	0.317
9.956	26.84	1.2027	19.9	0.041	0.0245	0.752	0.975	0.647
15.025	33.25	1.2027	19.92	0.061	0.0378	1.094	1.507	0.963
20.018	38.19	1.2026	19.94	0.081	0.0497	1.412	2.053	1.258
25.099	42.46	1.2025	19.96	0.1	0.0617	1.717	2.637	1.557
30.114	46.22	1.2025	19.98	0.117	0.0715	2	3.26	1.83
35.145	49.49	1.2024	20	0.133	0.0834	2.264	3.936	2.125
40.159	52.31	1.2023	20.02	0.148	0.0929	2.506	4.677	2.439
45.174	54.81	1.2022	20.04	0.161	0.1014	2.725	5.508	2.777
50.171	56.95	1.2022	20.06	0.173	0.1089	2.926	6.454	3.143
55.231	58.79	1.2021	20.08	0.184	0.1156	3.102	7.596	3.56
60.249	60.25	1.202	20.1	0.193	0.1209	3.247	9.047	4.026
65.245	61.3	1.202	20.12	0.199	0.124	3.347	11.172	4.549
70.202	61.77	1.2019	20.13	0.202	0.1242	3.393	14.439	5.136
75.303	61.84	1.2018	20.15	0.202	0.1236	3.399	18.649	5.878
80.302	61.88	1.2018	20.16	0.203	0.1233	3.399	22.654	6.873
85.321	61.95	1.2017	20.18	0.202	0.1217	3.399	26.191	8.358

Table A.1b- Measured values from the purge flow test for the pipes

Vacuum P: [kPa]	$\dot{V}$*: [l/min]*	*ρ [kg/ m³]*	*T [°C]*	*Pipe2 ΔP: [kPa]*	*Pipe3 ΔP: [kPa]*	*Pipe5 ΔP: [kPa]*	*Pipe7 ΔP: [kPa]*
4.999	18.34	1.2026	19.9	0.0118	0.029	3.743	0.0118
9.956	26.84	1.2027	19.9	0.0332	0.052	7.455	0.0237
15.025	33.25	1.2027	19.92	0.0535	0.074	11.26	0.0253
20.018	38.19	1.2026	19.94	0.0738	0.092	15.023	0.0245
25.099	42.46	1.2025	19.96	0.0934	0.109	18.854	0.0301
30.114	46.22	1.2025	19.98	0.1109	0.127	22.627	0.0294
35.145	49.49	1.2024	20	0.1267	0.141	26.363	0.0271
40.159	52.31	1.2023	20.02	0.1412	0.156	30.03	0.0311
45.174	54.81	1.2022	20.04	0.1504	0.169	33.61	0.0278
50.171	56.95	1.2022	20.06	0.1603	0.18	37.053	0.0272
55.231	58.79	1.2021	20.08	0.1705	0.191	40.339	0.0271
60.249	60.25	1.202	20.1	0.1788	0.199	43.261	0.0237
65.245	61.3	1.202	20.12	0.1832	0.206	45.492	0.0272
70.202	61.77	1.2019	20.13	0.1846	0.208	46.535	0.0198
75.303	61.84	1.2018	20.15	0.1846	0.209	46.677	0.0192
80.302	61.88	1.2018	20.16	0.1846	0.209	46.677	0.0209
85.321	61.95	1.2017	20.18	0.185	0.208	46.675	0.0187
90.273	62.03	1.2017	20.19	0.1848	0.209	46.674	0.0182

Table A.2 – Measured values from the refuelling test for the all components in the system

$\dot{V}$: [l/min]	ρ [kg/ m^3]	T [°C]	Pipe 1 [kPa]	Canister ΔP: [kPa]	Pipe2 [kPa]	DMTL ΔP: [kPa]	Pipe3 [kPa]	Filter ΔP: [kPa]
5.22	1.2026	19.9	0.002	0.042	0.005	-0.003	0.008	0.002
10.42	1.2027	19.9	0.006	0.09	0.009	-0.001	0.017	0.004
15.28	1.2027	19.92	0.013	0.142	0.013	0.003	0.029	0.009
20.28	1.2026	19.94	0.022	0.202	0.017	0.01	0.043	0.014
25.26	1.2025	19.96	0.032	0.267	0.023	0.019	0.062	0.021
30.22	1.2025	19.98	0.045	0.338	0.029	0.029	0.085	0.03
35.25	1.2024	20	0.06	0.417	0.037	0.041	0.111	0.04
40.24	1.2023	20.02	0.077	0.501	0.046	0.056	0.14	0.052
45.2	1.2022	20.04	0.095	0.591	0.055	0.072	0.171	0.065
50.22	1.2022	20.06	0.114	0.689	0.064	0.091	0.205	0.079
55.2	1.2021	20.08	0.136	0.79	0.076	0.111	0.244	0.095
60.22	1.202	20.1	0.16	0.899	0.087	0.133	0.287	0.113
65.19	1.202	20.12	0.185	1.01	0.1	0.157	0.331	0.132
70.19	1.2019	20.13	0.211	1.124	0.112	0.183	0.381	0.151
75.25	1.2018	20.15	0.24	1.245	0.123	0.21	0.432	0.173
80.21	1.2018	20.16	0.271	1.368	0.137	0.24	0.489	0.196
85.19	1.2017	20.18	0.303	1.496	0.151	0.271	0.549	0.22
90.19	1.2017	20.19	0.337	1.629	0.166	0.303	0.611	0.245
95.18	1.2017	20.19	0.371	1.766	0.182	0.338	0.677	0.271

Appendix B –Fitting of complex component, purge

The fitting of the complex components, during purge, are here shown in graphs, with ΔP on the y-axis and volumetric flow rate on the x-axis. The fitted results are compared with measured values from the experiments.

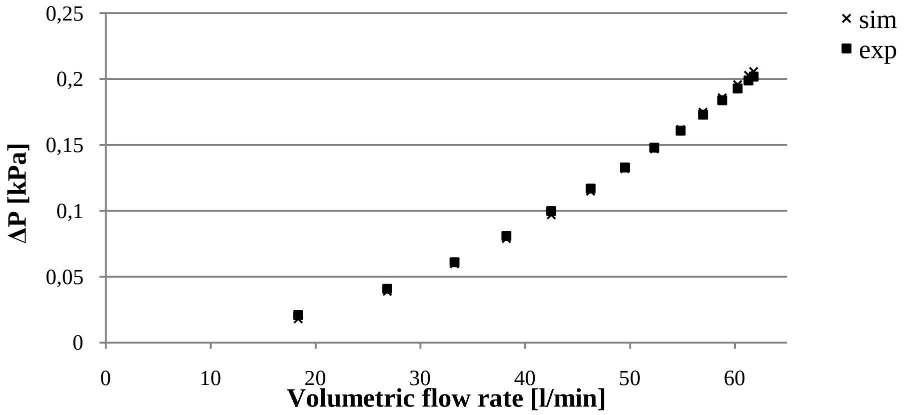

Figure B.1 – The fitting of the air filter, during purge.

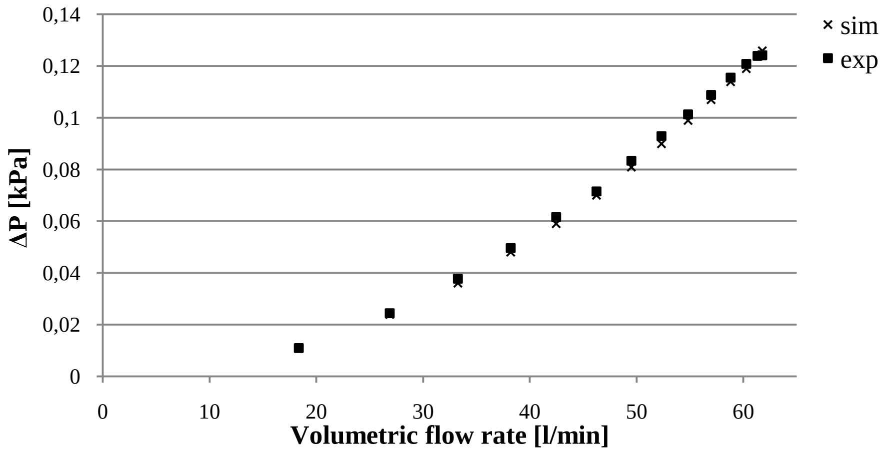

Figure B.2 – The fitting of the DMTL, during purge.

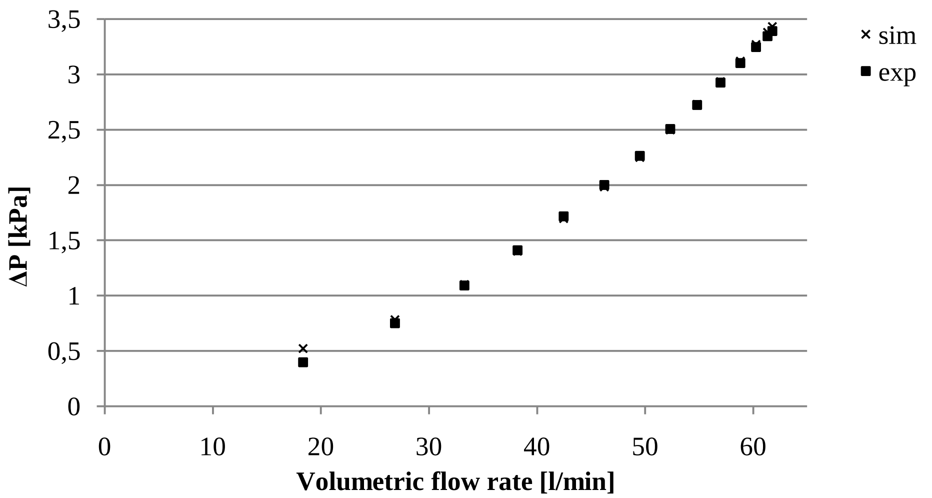

Figure B.3 – The fitting of the canister, during purge.

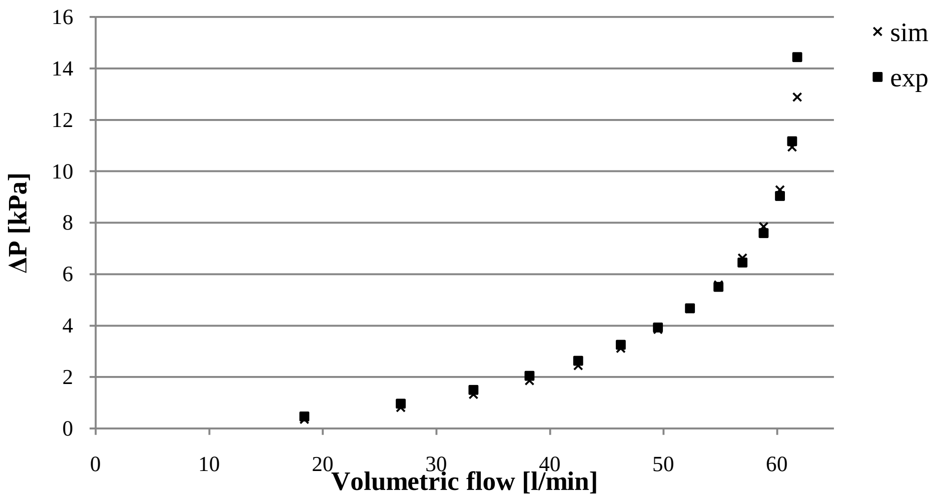

Figure B.4 – The fitting of the purge valve, during purge.

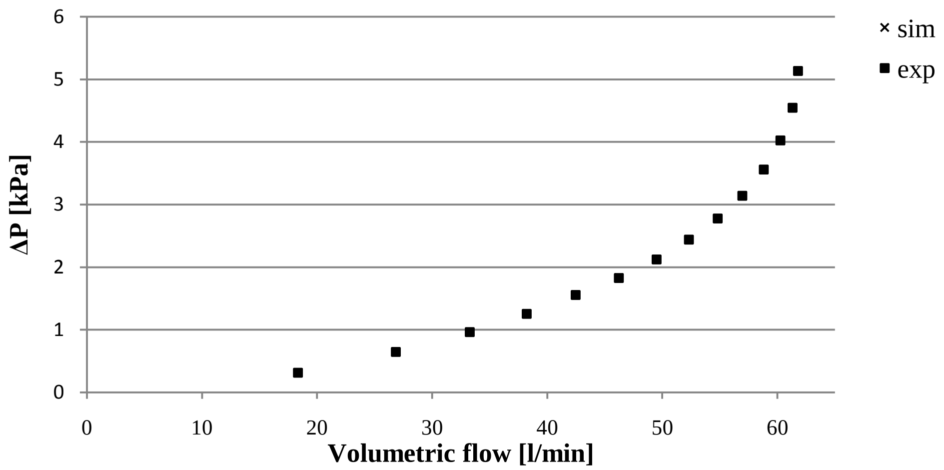

Figure B.5 – The fitting of the check valve, during purge

Appendix C–Fitting of complex component, refuelling

The fitting of the complex components, during refuelling, are here shown in graphs, with ΔP on the y-axis and volumetric flow on the x-axis. The simulated results are compared with measured values from the experiments.

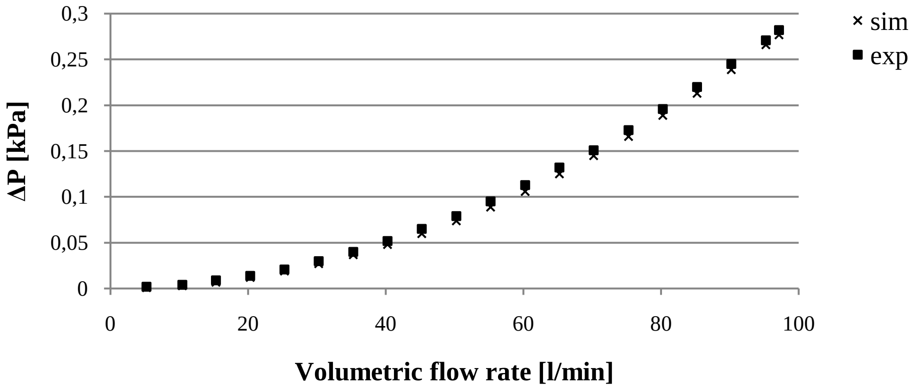

Figure C.1 – The fitting of the air filter, during refuelling.

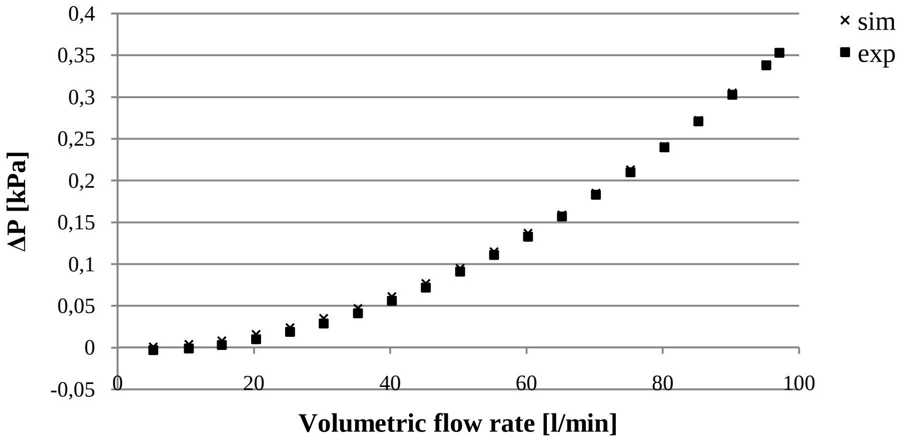

Figure C.2 – The fitting of the DMTL, during refuelling.

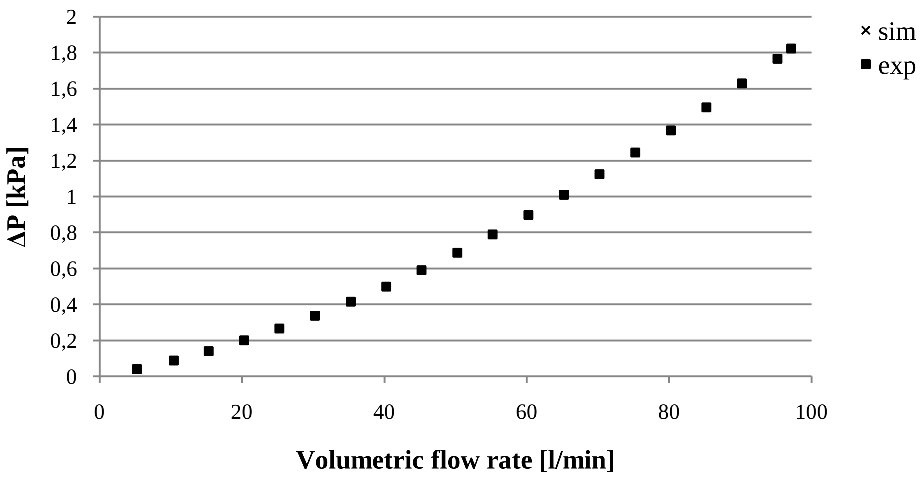

Figure C.3 – The fitting of the canister, during refuelling

Appendix D – The main System

Here the model of the EVAP system in GT Suite is shown.

The main system, during purge

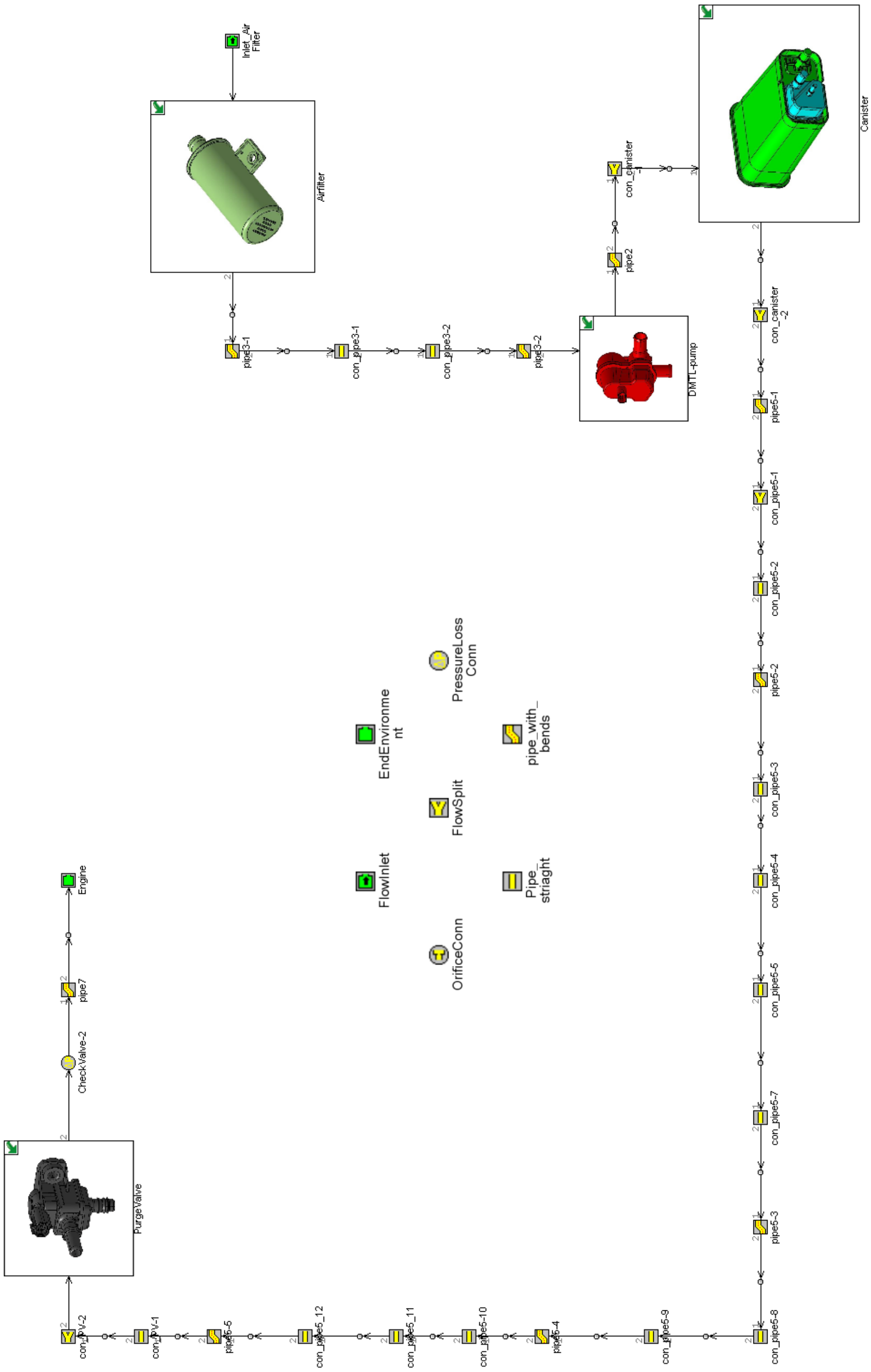

Figure D.1– An illustration of how the main system is modelled in GT Suite, during purge.”con” is shorted for connector and the pipes are named according to Fig. 2.1.

The main system, during refuelling

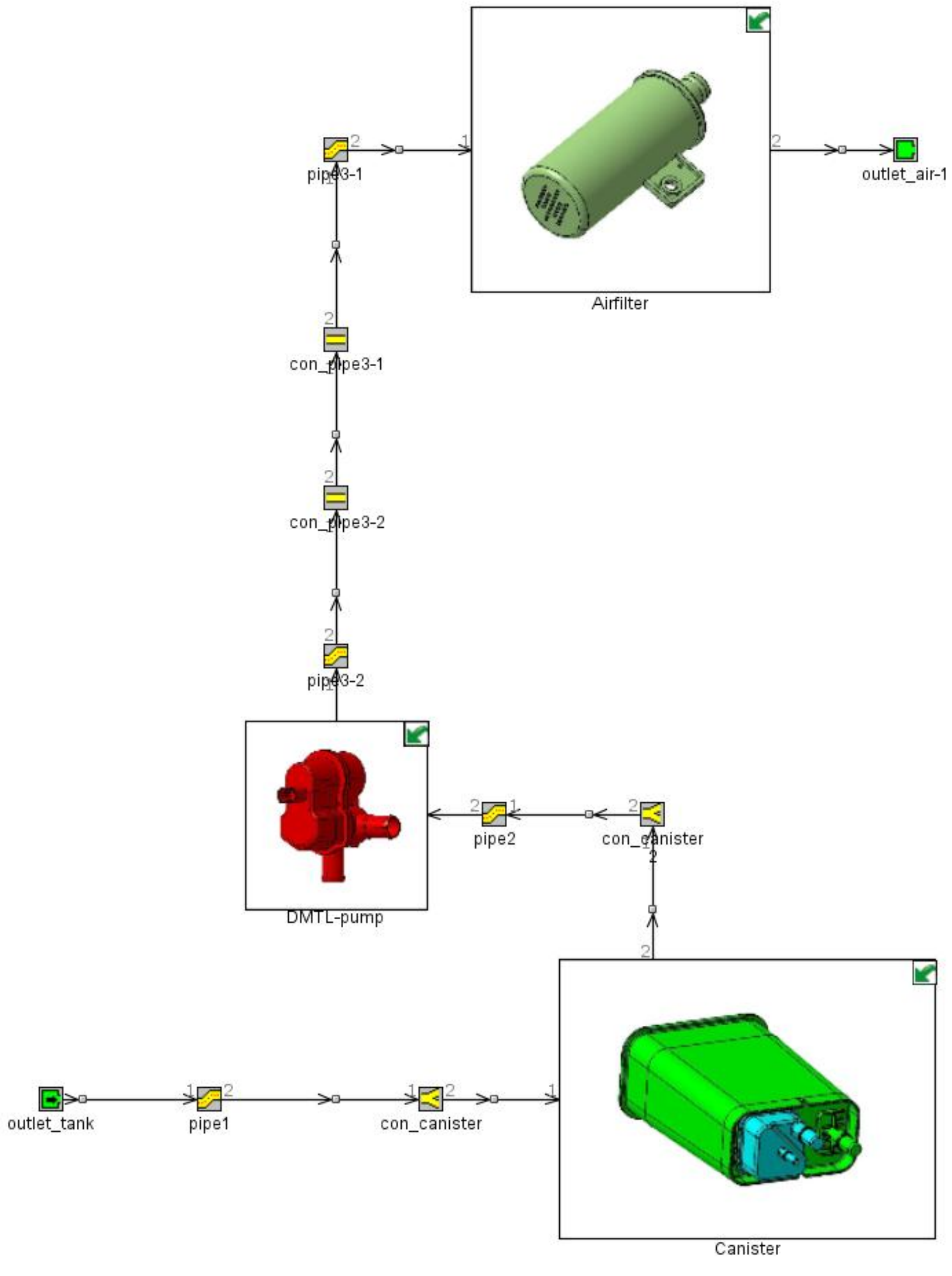

Figure D.2 - An illustration of how the main system is modelled in GT Suite, during refuelling. "con" is shorted for connector and the pipes are named according to Fig. 2.1.

Complex components

Figure D.3 – An illustration of how the air filter is modelled in GT Suite.

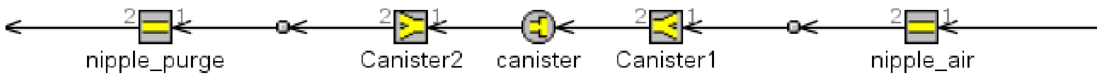

Figure D.4– An illustration of how the canister is modelled in GT Suite, during purge.

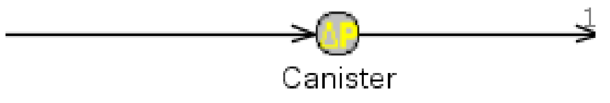

Figure D.5 – An illustration of how the canister is modelled in GT Suite, during refuelling.

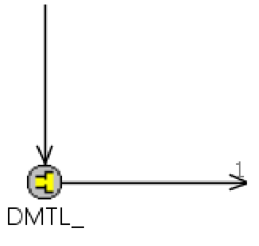

Figure D.6 – An illustration of how the DMTL is modelled in GT Suite.

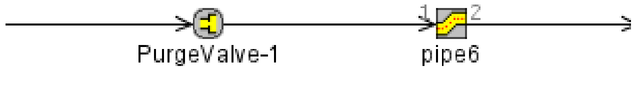

Figure D.7 – An illustration of how the purge valve is modelled in GT Suite.