Experimental investigation of automotive fuel tank filling.

Maurizio Mastroianni
University of Windsor

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EXPERIMENTAL INVESTIGATION OF AUTOMOTIVE FUEL TANK FILLING

by

Maurizio Mastroianni

A Thesis
Submitted to the Faculty of Graduate Studies and Research through Mechanical - Automotive and Materials Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada

2000

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ABSTRACT

A transparent rectangular fuel tank approximately 30.5 cm x 30.5 cm x 91.5 cm (12” x 12” x 36”) was designed, constructed and fitted with a standard filler pipe with a constant inside diameter of 1.6 mm (1/16”) for the roll-over valve. The experimental protocol required the refueling of the fuel tank system for the purpose of flow visualization and measurement of pressure and temperature. A fuel-conditioning cart which has the capabilities of conditioning the fuel at a constant temperature of 19 °C (67 °F) and providing fuel at the desired fuel-dispense flow rate was used. The following were varied in the tests:

Vent tube diameter: 9.5 mm (3/8”), 6.4 mm (1/4”) and 3.2 mm (1/8”)

Fuel-dispense flow rate: 38 L/min (10 GPM) and 45 L/min (12 GPM)

Fuel Reid Vapour Pressure (RVP): 83 kPa (12 psi) and 55 kPa (8 psi)

It was found that for all test, the smallest diameter vent tube caused pre-mature shut-off whereas the larger diameters did not. The vent tube diameter is therefore, a critical parameter in determining premature shut-off. The pressure-time curves for the case of normal shut-off demonstrated the classic, three-phase, characteristic previously noted in the literature.

A sudden drop in the filler pipe pressure followed by a rise to a value higher than before the drop occurred at each shut-off for both premature shut-off or normal shut-off. This was found to be associated with spill-back which occurred in every test condition.

Increase in fuel RVP and fuel-dispensing rates tended to increase the maximum pressures recorded, however, these did not always lead to premature shut-off.
It was noted that, on a relative basis, the fuel RVP is more effective in increasing the tank dome pressure than an increase in the fuel-dispense rate. In addition, the effects of RVP, $d_m$, and $Q_{Lin}$ on PSO are conveniently shown on a dimensionless plot.
Dedicated To:

Mom, Dad, Pino, Roberto
and
Layla
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>CAD/CAE</td>
<td>Computer-Aided Design and Computer Aided Engineering</td>
</tr>
<tr>
<td>CARB</td>
<td>California Air Resources Board</td>
</tr>
<tr>
<td>CCR</td>
<td>California Code of Regulations</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamic</td>
</tr>
<tr>
<td>CFR</td>
<td>Code of Federal Regulations</td>
</tr>
<tr>
<td>GPM</td>
<td>U.S. Gallons Per Minute</td>
</tr>
<tr>
<td>HDPE</td>
<td>High-density Polyethylene</td>
</tr>
<tr>
<td>NPT</td>
<td>National Pipe Thread</td>
</tr>
<tr>
<td>NSO</td>
<td>Normal Shut-off</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>ORVR</td>
<td>Onboard Refueling Vapour Recovery</td>
</tr>
<tr>
<td>PETG</td>
<td>Polyethylene Terephthalate</td>
</tr>
<tr>
<td>PSO</td>
<td>Premature Shut-off</td>
</tr>
<tr>
<td>ROV</td>
<td>Roll-over Valve</td>
</tr>
<tr>
<td>RVP</td>
<td>Reid Vapour Pressure</td>
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NOMENCLATURE

\[ P_T = \text{tank dome pressure (kg m}^{-1}\text{ sec}^{-2}) \]
\[ P_F = \text{filler pipe pressure (kg m}^{-1}\text{ sec}^{-2}) \]
\[ Q_{\text{L,n}} = \text{fuel-dispensing nozzle flow rate (m}^3\text{/sec)} \]
\[ d_{\text{h}} = \text{internal diameter of the filler hose fitting (m)} \]
\[ Q_{\text{V,in}} = \text{vapour flow rate entering in the filler pipe (m}^3\text{/sec) } \]
\[ \rho_L = \text{density of liquid fuel (kg/m}^3\text{)} \]
\[ \rho_V = \text{density of fuel vapour (kg/m}^3\text{)} \]
\[ g = \text{gravitational constant (9.81 m/sec}^2\text{)} \]
\[ \nu_v = \text{kinematic viscosity of the vapour (m}^2\text{/sec)} \]
\[ \nu_L = \text{kinematic viscosity of the liquid (m}^2\text{/sec)} \]
\[ t = \text{time (sec)} \]
\[ P_{\text{atm}} = \text{atmospheric pressure (kg m}^{-1}\text{ sec}^{-2}) \]
\[ L_n = \text{length of the filler tube (m)} \]
\[ V = \text{volume of the tank (m}^3\text{)} \]
\[ \text{RVP} = \text{Reid vapour pressure (kg m}^{-1}\text{ sec}^{-2}) \]
\[ d_{\text{vt}} = \text{internal diameter of the vent tube orifice (m)} \]
\[ d_{\text{rov}} = \text{internal diameter of the roll over valve orifice (m)} \]
\[ L_{\text{vt}} = \text{length of the vent tube orifice (m)} \]
\[ L_{\text{rov}} = \text{length of the roll over valve orifice (m)} \]
Chapter 1

INTRODUCTION

1.1 Background

Original Equipment Manufacturers (OEMs) are challenging automotive fuel system suppliers to design and manufacture fuel tank systems for smaller available pockets in the underbody of vehicles. In addition, higher safety standards require that fuel tanks not be located in crash zones of the vehicle. In some cases, a more complicated fuel filler tube design must be used. Potential problems exist during the refueling process due to the configuration of the fuel system, complexity of the fuel characteristics and fuel tank geometry. Problems that occur during refueling include fuel-dispensing nozzle premature shut-off (PSO), fuel spitting (spit-back) and fuel spilling out of the filler pipe (well-back). The safety of the consumer is at risk when the consumer experiences the latter two difficulties during refueling of the vehicle. Also, the escape of liquid fuel or hydrocarbon vapours out of the fuel tank system during refueling is a source of air pollution. In the United States of America, provisions of Title 40, Code of Federal Regulations (CFR), Part 86 regulate the evaporative emissions of hydrocarbon vapour into the atmosphere during refueling.

Designing a fuel tank system to operate in accordance with all requirements set by the customer and regulatory agencies is a challenge faced by fuel system suppliers. They are continually being required to supply a more technically advanced product at a reduced cost in a shorter period of time. Subsequently, suppliers are depending on computer-aided design and computer-aided engineering (CAD/CAE) tools to reduce development time and costs. As a result, fuel system suppliers are investigating the
possibility of using Computational Fluid Dynamic (CFD) software to determine the fill quality of fuel tank systems. The current state of the art of CFD is such that experimental validation is required.

The little information that is available in the open literature regarding the physical processes occurring during the refueling of an automotive fuel tank and the lack of available experimental data were the reasons for conducting the experiments described and discussed in this thesis.

1.2 Concept

The goal of this project is to develop an understanding of the factors that influence the quality of the refueling process and to obtain quantitative information. An experimental study was performed to determine how vent tube diameter, fuel Reid Vapour Pressure (RVP), and fill rate affect the occurrence of PSO, spit-back and spill-back. The experiments were restricted to the consideration of a simple tank shape, one type of fuel-dispensing nozzle with an optimum alignment of the fuel-dispensing nozzle with the filler pipe.

This study is part of a larger effort which has the objective of predicting the occurrence of PSO using a simple lumped parameter model as well as a CFD technique. The results of the present experiments will be used to validate these methods.
Chapter 2

LITERATURE REVIEW

2.1 Introduction

Fuel tank systems are more complicated than an average person realizes. Fuel systems are designed to manage multi-phase (liquid/vapour) and multi component (gasoline/air) fluids over a wide range of ambient temperatures, pressures, vehicle grades and fuel-dispensing nozzle types. This literature review is structured such that the following topics are considered:

- the processes in refueling an automotive fuel tank,
- the operation of a fuel-dispensing nozzle,
- numerical simulations by others,
- related considerations such as premature shut-off mechanisms, vapour management applied to fuel systems and hydrocarbon emission standards.

2.2 Fuel Tank Filling

A general schematic of the automotive fuel tank system during the filling process is illustrated in Figure 1.
Figure 1. Schematic diagram of an automotive fuel tank system.

Sinha et al [1] described the fueling events as follows: Filling a fuel tank creates a two-phase compressible mixture. Fuel is pumped through the fuel-dispensing nozzle, through the filler pipe and into the fuel tank. During this phase, (Phase I), the pressure in the tank vapour dome increases as indicated in Figure 2. As the two-phase mixture enters the tank, phase separation occurs where the fuel vapour occupies the vapour space and liquid deposits at the bottom of the tank. The liquid level continues to rise, which displaces the air/fuel vapor mixture from the tank via several venting paths. Due to venting, a constant pressure is maintained throughout the major portion of the refueling (Phase II).

After some time, the fuel level rises and enters the vent tube opening (Phase III). Now the air/vapour mixture in the tank is essentially trapped. After continued filling, the pressure in the tank increases, which reduces the rate at which fuel enters the fuel tank. The nozzle however, continues to dispense fuel, therefore increasing the level of fuel in the filler pipe until it covers the sensing port on the fuel-dispensing nozzle. At this point the fuel-dispensing nozzle shuts off. This is the mechanism of normal shut-off (NSO).
If the fuel-dispensing nozzle shuts off before the fuel tank has been filled up to the level of the vent tube, PSO has occurred.

![Diagram of tank pressure over time with phases labeled]

**Figure 2.** Typical fuel tank dome pressure profile during refueling.

During Phase II, one venting path is through the line that leads to the upper part of the filler pipe and the air/vapour mixture following this route eventually exhausts out into the atmosphere and/or is entrained into the fuel that is being dispensed. The other venting path, through the roll-over valve (ROV), carries the vapours to a carbon canister. The carbon canister adsorbs the hydrocarbons and prevents them from entering the atmosphere. During engine operation, the purge valve opens, allowing the vacuum manifold to draw fresh air through the carbon canister to desorb the hydrocarbons and carry them into the engine for combustion [2].

Garrett [2] found similar events during the refueling of the fuel tank. In addition, it was indicated that a ball-valve (check valve) is used at the lower end of the filler pipe to ensure that the sudden increase in back-pressure during Phase III does not cause spill-back.
2.3 Fuel-dispensing Nozzle

Consumers expect the fuel-dispensing nozzle to shut-off automatically when the tank is full. Many brands of fuel-dispensing nozzles are used at pumping petrol stations.

Figures 3 (a) and 3 (b), which are modification of figures from Holloway [4], illustrate the mechanical components of one type of fuel-dispensing nozzle during the refueling of a vehicle in the “on” and “off” position respectively.

The operation of a fuel-dispensing nozzle can be explained as follows[3]. When the dispensing handle is engaged, fuel passes through the nozzle forcing the “venturi check valve” open and continues through the fuel-dispensing nozzle spout. As the fluid passes through the “venturi check valve”, a reduced pressure is caused, which draws air/fuel vapour into the sensing port which is located on the outer surface of the spout near the outlet. The air/fuel vapour entering the sensing port becomes entrained in the liquid being dispensed through the spout. The liquid level rises in the filler pipe of the vehicle eventually covering the sensing port which blocks the flow of air. The lack of airflow through the sensing port causes the pressure at the “venturi check valve” to reduce which causes the diaphragm to move upward. The motion of the diaphragm releases a trip mechanism in the fuel-dispensing nozzle that drops a poppet to halt the liquid flow through the nozzle as indicated in Figure 3 (b).
2.4 Numerical Investigations

Sinha et al in 1998 [1] concluded that it is possible, but not practical to numerically simulate a complete fuel system with a single mesh of elements simultaneously. Initially small time and length scales are important until the tank begins to fill uniformly. Until the fuel level rises close to its shut-off height, large time and length scales are possible. Once the vent tube is covered by the rising fuel level, small time and localized length scales are required again.

Stoneman [5] stated that “in terms of fluid dynamics, the flow of liquid fuel is one of the most complex one could meet in engineering.” He reports that there are two methods by which fuel is ejected upward from the filler pipe. The first is when small drops of fuel are carried out by vapour (spit-back). The second is when a large slug of
fuel is displaced from the filler pipe (well-back) due to the back-pressure developed in the vapour space of the fuel tank. Most often the term well-back is also referred to as spill-back.

Although not directly applicable to this study, literature pertaining to the filling of non-automotive fuel storage tanks was also found. In Germany, it is not permitted for petrol stations to release hydrocarbon vapours into the atmosphere (except in emergency situations). Petrol stations are required to collect displaced fuel vapours by a gas recovery system and then transfer them to the delivery system [6].

2.5 Premature Shutoff Mechanisms

Premature shut-off can be attributed to a number of factors. Each of the following subsections gives a description of one of these factors:

2.5.1 Misalignment of Fuel-dispensing Nozzle with the Filler Pipe

Poor design of the filler pipe, which results in a misalignment of the fuel-dispensing nozzle relative to the filler pipe, can lead to PSO. If the fuel-dispensing nozzle is directed towards the wall of the filler pipe the fuel could be deflected off the wall towards the fuel-dispensing nozzle. This situation increases the probability that the sensing port will be covered by fuel and that the fuel dispenser will shut off. Figure 4 shows an example of a fuel-dispensing nozzle that is not properly aligned.
2.5.2 Restrictions to the Flow in the Filler Pipe

Any geometrical feature that tends to restrict the flow in the filler pipe could cause PSO. Once the flow is restricted, fuel accumulates in the filler pipe and the fuel level rises. If the liquid level continues to rise, it will eventually cover the sensing port on the fuel-dispensing nozzle, causing the fuel flow to shut off. Factors that would affect the restriction in the filler pipe are the radii of the bends and any reduction in area throughout the path in the filler pipe. The latter is an issue with blow moulded filler pipes, due to seams which protrude into the flow path [5].

2.5.3 Air/Vapour Space Venting Restrictions

During refueling, the liquid entering the fuel tank forces the air/vapour mixture in the tank into an increasingly smaller region. This has the affect of increasing the tank pressure. The top of the tank is vented to relieve this pressure. The amount of venting is controlled by a combination of the leakage space for the vapour around the fuel-dispensing nozzle, the size and length of the lines connecting components of the fuel
tank, the flow resistance of the roll-over valve, and the adsorption and resistance characteristic of the carbon canister. The tank back-pressure is both an undesirable feature and a necessity. Too much back-pressure for too long of a duration, will cause PSO and/or poor fill quality. Overfilling the fuel tank can occur if not enough back-pressure is generated when the tank is full.

Sinha et al [1] simulated the vapour/air flow ahead of the liquid column in the vent pipe. They showed that the composition of the air and fuel vapour mixture can drastically reduce the speed of sound resulting in an increase pressure in the tank due to the large pressure waves created. Eventually, the result of this could be a PSO.

2.8 Vapour Management

Modern fuel tank systems are becoming more complicated as new emission regulations take effect. All fuel storage tank systems serve the same purpose, they come in a variety of shapes and sizes, subsequently leading to many different vapour management systems. Vapour management in a fuel system is critical for vehicle functionality, customer interface and most importantly, safety for the environment and consumers. The purpose of vapour management systems is to manage the generation, venting, adsorption and purging of hydrocarbon vapours.

Many design criteria need to be considered for each fuel system. If not designed properly, vapour management techniques can interfere with the filling process and increase the risk of PSO, spit-back and/or spill-back.

An approach to control vapour emissions during refueling has been mandated by the California Code of Regulations (CCR). The legislation requires that the hydrocarbon
vapours generated during refueling must be managed by an on-board refueling vapour recovery (ORVR) system [7]. ORVR systems are being implemented on fuel systems in phases based on different vehicle classes.

2.6.1 On-board Refueling Vapour Recovery Design

An ORVR design must manage all vapours generated during refueling and vehicle operation. It also, from a design standpoint, must not cause PSO, spill-back or spit-back, over-filling the fuel tank or over-pressurizing the fuel tank. Currently, there are two types of ORVR systems. The first type is a mechanical ORVR system, which contains a leak tight physical connection between the fuel-dispensing nozzle and the filler pipe. The leak tight seal prevents the vapours from escaping out of the filler pipe during refueling. The seal is located in the area where the fuel-dispensing nozzle is inserted into the filler pipe. The second type of system is a liquid or dynamic seal. The fuel flow during refueling is used to create a dynamic seal (liquid seal) within the fuel filler pipe to prevent the hydrocarbon vapours from entering the atmosphere through the filler pipe opening. To the consumer, refueling a vehicle equipped with an ORVR system should be no more difficult than filling a vehicle with a conventional fuel tank system.

2.6.2 Refueling Emission Standard

The California Air Resources Board (CARB) has regulated the amount of hydrocarbons that can be emitted during vehicle refueling. Title 13, California Code of Regulations, § 1978 [7] states that:
“Vehicle refueling emissions for 1998 and subsequent model gasoline-fueled, alcohol-fueled, diesel-fueled, fuel-flexible, and hybrid electric passenger cars, light-duty trucks, and medium-duty vehicles with a gross vehicle weight rating less than 8501 pounds, shall not exceed the following standards: . . . Hydrocarbons 0.20 grams per gallon of fuel dispensed [4].”

In addition, Title 40 - Protection of the Environment, Code of Federal Regulations (CFR), Part 86, Subparts A, B, and S regulate spit-back to a maximum of 1.0 gram of hydrocarbon per test [8] for all States in the United States of America.

With these requirements, fuel system suppliers are required to change current designs of fuel systems to ORVR designs. The ORVR model year phase-in schedule is listed in Table 1.

<table>
<thead>
<tr>
<th>Class of Vehicle</th>
<th>40% Fleet</th>
<th>80% Fleet</th>
<th>100% Fleet</th>
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<td>Passenger Cars</td>
<td>1998</td>
<td>1999</td>
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<tr>
<td>Light-Duty Trucks</td>
<td>2001</td>
<td>2002</td>
<td>2003</td>
</tr>
<tr>
<td>Medium Duty Trucks</td>
<td>2004</td>
<td>2005</td>
<td>2006</td>
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Table 1. ORVR model year phase-in schedule [7].

2.7 Factors Affecting Spit-back and Spill-back

A malfunctioning fuel-dispensing nozzle or a poor design of the filler pipe could cause fuel to spill or spit out of the filler neck.

A fuel-dispensing nozzle that does not shut-off automatically when the liquid level in the filler pipe has been sensed will cause spill-back. Also, if the fuel-dispensing nozzle is malfunctioning such that the response time taken to halt the liquid flow is too long, spill-back of fuel will occur. Additionally, there could be cases, at petrol stations, where the pumps used to dispense fuel from the underground storage tank to the vehicle
are adjusted to a very high rate of flow. If the flow rate is too great the liquid level in the filler pipe can rise so fast that the delay between the sensing and actual shut-off causes overflow of fuel – spill-back.

Spit-back may be caused by droplets of fuel becoming entrained in the air/vapour which enters the atmosphere from the filler tube. This is more evident during cases of generation of high fuel vapours.
Chapter 3

EXPERIMENTAL PROTOCOL

This chapter includes a description of the equipment that was employed during the experimentation and the procedures that were used in obtaining the experimental results. The experimental equipment consisted of the test fuel tank, filler tube and vent tube as well as the fuel-dispensing nozzle which is part of the dispensing cart. The data acquisition arrangement details are also given.

3.1 Experimental Fuel Tank

A transparent rectangular fuel tank with dimensions 30.5 cm x 30.5 cm x 91.5 cm (12” x 12” x 36”); as seen in Figure 5 was vacuum formed from polyethylene terephthalate (PETG). Detailed drawings of the fuel tank system will be presented in Section 3.1.1.

![Vacuum formed tank](image)

**Figure 5.** Vacuum formed tank.

Visual observation of the filling process was accomplished by having the fuel tank and the filler tube made of transparent material. PETG was chosen as the tank
material because of its chemical resistivity to gasoline and its transparent characteristics. Current production plastic fuel tanks are blow molded using high-density polyethylene (HDPE). Components such as the ROV, fill spud, vent tube, etc. can be "welded" onto the fuel tank, provided that the weld pads of both the fuel tank and components are made of HDPE. Unfortunately, this is not the case with PETG. Therefore, special fixtures were designed and machined in order to attach the components onto the experimental fuel tank. Plastic fittings with ¼” NPT threaded ports were constructed to hold the pressure transducer and temperature sensor. One of these fittings is shown in Figure 6 (a). A plastic fitting with a "barbed" tube connector was also constructed to be used for connection to the vent tube. This fitting is shown in Figure 6 (b). The aluminum retaining ring used to hold these onto the tank is shown in Figure 6 (c). To ensure that the components were assembled such that they were leak free, o-ring seals and fuel resistant sealant (DOW CORNING® 730 Solvent Resistant Sealant) were used. The final assembly of a sealed plastic fitting with ¼” NPT port and aluminum fixture is illustrated in Figure 6 (d).
Figure 6. Fuel tank components. (a) Plastic fitting with $\frac{1}{8}$" NPT port. (b) Vent tube configuration. (c) Aluminum retainer. (d) Assembly.

A detailed drawing is given in Figure 7 which includes the overall dimensions of the vent tube fitting and illustrates the inside diameter (d) which was changed from one fitting to another.
Figure 7.  Vent tube fitting.

To determine if the fuel tank set-up had any air leaks, the fuel tank was submerged under water for thirty (30) seconds and subjected to a gauge pressure of approximately 20 kPa (3 psi). Visible bubbles indicated leaks. Sealant was applied to leaking joints until the tank passed the "bubble test".

3.2 Fuel Tank, Filler Pipe and Vent Tube Arrangement

The configuration of the fuel tank, filler pipe and vent tube is shown in Figures 8, 9, and 10. This arrangement was fixed for the duration of the experiments in order to have repeatable tests.
Figure 8.  Front view of the fuel tank system.

Figure 9.  Top view of the fuel tank system.  $P_F$ = filler pipe pressure location, $P_T$ = tank dome pressure location, $T$ = temperature sensor and ROV = roll-over valve locations.
Figure 10. Right side view of the fuel tank system.

3.3 Fuel-dispensing Nozzle Fixture

To reduce variability in the results due to differences in the fuel-dispensing nozzle location, a fixture with a locator pin was fabricated. This fixture ensured repeatability of setup for every refueling test. The fixture arrangement is shown in Figure 11.
3.4 Fuel Conditioning Cart

A fuel-conditioning cart (Model FCD100) designed and manufactured by Richmond Instruments and Systems Incorporation was used to dispense the fuel. The fuel cart was set to condition the fuel at the desired temperature (21.1 °C (70 °F)) and
dispensing the fuel at the required flow rate (37.9 or 45.4 L/min (10 or 12 GPM)). The fuel cart has a storage capacity of approximately 200 litres and is illustrated in Figure 12.

Figure 12. The fuel-conditioning cart.

3.5 Fuel Tank Instrumentation

The arrangement of the pressure transducers and thermocouple is illustrated on the schematic diagram of the fuel tank system shown in Figure 13. The pressure and
temperature values were collected and recorded at a sampling rate of 10 samples per second during the experiment.

Figure 13. Schematic diagram of the instrumented fuel tank system.

3.6 Data Acquisition System

The program used for collecting and storing data was written using LabVIEW™ (Version #5.01) and the data acquisition system is indicated schematically in Figure 14.
Figure 14. Data acquisition system layout

The data acquisition board is a National Instruments™ 16-bit resolution I/O DAQ board (Model # AT-MIO-16XE-50). A set of SCXI low noise cables (Model #1349) which guarantees reliable communication and signal integrity, links the DAQ board to the SCXI-1100 chassis. The SCXI-1100 chassis is a low-noise chassis house that routes analog and digital signals and powers and controls the SCXI-1120 module. The signal conditioning is accomplished by using the SCXI-1120 Module. Three (3) channels were
utilized on the SCXI-1120 module each of which includes an isolated amplifier and a lowpass filter [9]. The terminal block (Model # SCXI-1328) includes isothermal construction that minimizes errors caused by thermal gradients between terminals and the high-precision cold-junction sensor. Between the sensors and the terminal block are the Pepperl+Fuchs® shunt zener diode barriers (Model numbers Z960 & Z787). Model number Z960 was used for the temperature sensor, while the Z787 was used for the two (2) 4-20 mA pressure transducers. Two pressure transducers manufactured by Druck, Model PTX 610, were used during testing. The accuracy of these transducers including non-linearity, hysteresis and repeatability was ±0.08% full scale. A type K thermocouple with an accuracy ±1°C was used to record fuel temperature during refueling.

The zener diode barriers act as safety interfaces between intrinsically safe and non-intrinsically safe circuits. They are designed to limit the amount of energy that can be transferred from a safe to a hazardous area in the event of fault conditions occurring in the safe area [10].

The safe area is considered to be located within the purge cabinet. All the hardware mentioned above (excluding the sensors) is enclosed within the purge cabinet as illustrated in Figure 14. Since the hardware requires a source of electricity, which could lead to sparking, the purge cabinet must maintain a positive pressure of approximately 60 mbar. Should the purge cabinet (safe area) not maintain its positive pressure, the source of electricity would be cut-off, subsequently an immediate shutdown occurs. In addition, if in the purge cabinet a fault condition occurs (voltage increase relative to the reference voltage), a fuse will open isolating the safe and hazardous area.
Safety is a concern when handling gasoline. Testing was done in the Kautex Textron laboratory, which is in compliance with the regulations of the Ministry of Labour, Ministry of Environment and Energy, and the Fire Marshall’s Office (enforcing the fire and building codes).

The pressure measurement system, (i.e. A/D converters and transducers combination) was calibrated using a Druck Incorporated pressure calibrator (Model DPI603) which supplied known pressures and had an accuracy of ±0.075% full scale. Twelve (12) points from −5.2 kPa (−0.75 psig) to 13.8 kPa (2.0 psig) inclusive were used for calibration.

The overall test set-up including the data acquisition and fuel conditioning cart is illustrated in Figure 15.

![Figure 15. Overall experimental arrangement. (1 = Fuel Cart, 2 = Test Fuel Tank, 3 = Fuel-dispensing Nozzle, 4 = Purge Cabinet, 5 = Fuel-dispensing Nozzle Fixture)]
3.7 Experimental Conditions

The conditions tested can most easily be represented in the form of a matrix. The matrix shown in Table 2, is the summary of the tests completed. Three (3) parameters were changed throughout the tests:

1. fuel RVP,
2. fuel flow rate, and
3. inside diameter of the vent tube.

<table>
<thead>
<tr>
<th>TEST NUMBER</th>
<th>VENT ID (d,v) mm (inches)</th>
<th>FLOW RATE (Q,v) L/min (gpm)</th>
<th>RVP kPa (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.5 (3/8)</td>
<td>38 (10)</td>
<td>83 (12)</td>
</tr>
<tr>
<td>2</td>
<td>9.5 (3/8)</td>
<td>45 (12)</td>
<td>83 (12)</td>
</tr>
<tr>
<td>3</td>
<td>9.5 (3/8)</td>
<td>38 (10)</td>
<td>55 (8)</td>
</tr>
<tr>
<td>4</td>
<td>9.5 (3/8)</td>
<td>45 (12)</td>
<td>55 (8)</td>
</tr>
<tr>
<td>5</td>
<td>6.4 (1/4)</td>
<td>38 (10)</td>
<td>55 (8)</td>
</tr>
<tr>
<td>6</td>
<td>6.4 (1/4)</td>
<td>45 (12)</td>
<td>55.2 (8)</td>
</tr>
<tr>
<td>7</td>
<td>6.4 (1/4)</td>
<td>38 (10)</td>
<td>83 (12)</td>
</tr>
<tr>
<td>8</td>
<td>6.4 (1/4)</td>
<td>45 (12)</td>
<td>83 (12)</td>
</tr>
<tr>
<td>9</td>
<td>3.2 (1/8)</td>
<td>38 (10)</td>
<td>83 (12)</td>
</tr>
<tr>
<td>10</td>
<td>3.2 (1/8)</td>
<td>38 (10)</td>
<td>55 (8)</td>
</tr>
<tr>
<td>11</td>
<td>3.2 (1/8)</td>
<td>45 (12)</td>
<td>55 (8)</td>
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<tr>
<td>13</td>
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<td>45 (12)</td>
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</tr>
<tr>
<td>14</td>
<td>3.2 (1/8)</td>
<td>38 (10)</td>
<td>7 (1)</td>
</tr>
</tbody>
</table>

Table 2. Test matrix indicating experimental conditions.
The parameters that remained constant throughout each test were the following:

1. relative position of the vapour line, filler pipe and fuel-dispensing nozzle (constant to within ± 5 mm),
2. fuel temperature (19 °C ± 1°C = 67 ± 2°F),
3. simulated ROV orifice diameter (1.6 mm ± 0.1 mm),
4. vent tube length (37.1 mm ± 0.1 mm), and
5. room temperature (21 °C ± 2°C = 67 °F ± 3°F).

The first fueling test conducted on a tank is referred to as the green test due to the fact that the tank has never been in contact with fuel. In order to eliminate the green tank effect the tank was initially refueled several times. For each test number, three (3) repetitions were performed. The tank dome pressure, filler pipe pressure and tank temperature were monitored throughout.

Calibration fluid (Trade Name: MS-4957 Calibration Fluid) available from Gage Products Company, located in Ferndale Michigan, was used in test numbers 13 and 14. Calibration fluid has similar properties to gasoline, except that is not as volatile as gasoline. The purpose of this test was to further investigate the importance of changes in fuel volatility over a wide range.

3.8 Experimental Procedure

The following steps were followed in conducting the experiment.

1) The fuel cart was completely drained of any fuel stored in it.

2) Approximately 150 L (40 US gallons) of test fuel was placed in the fuel cart.
3) The fuel was conditioned to a temperature of 19 °C ± 1°C (67 ± 2°F) and the fuel-dispense flow rate set to the desired value.

4) The video recorder was positioned to capture the fuel sloshing during the filling of the fuel tank.

5) Power was supplied to the purge cabinet and data acquisition equipment.

6) A one (1) litre glass jar was filled with a representative sample of the conditioned fuel according to ASTM D 5191 [11] procedures prior to the start of each test.

7) The Reid-equivalent vapour pressure was determined for test trial using the MINIVAP VPS manufactured by GRABNER INSTRUMENTS in Vienna.

8) Detailed test set-up information was documented in the pre-notes section of the data acquisition program and on paper. The detailed information included vent size opening, flow rate used and the fuel RVP.

9) The fuel-dispensing nozzle was placed into the filler pipe utilizing the locator pin from the fuel-dispensing nozzle fixture.

10) The fuel-dispensing nozzle was triggered in order to dispense the fuel flow at the desired rate. The test proceeded until the fuel tank was filled or PSO occurred. In either case, the fill volume was recorded at the end of each fill.

11) If PSO occurred, a time period of 10 seconds passed before attempting to fill again. This step was repeated several times. Fill volumes were recorded at each attempt.

12) When the test was completed, the data acquisition was stopped and post comments recorded.
13) The clear tube portion of the filler pipe was disconnected from the filler spud on the fuel tank. The vacuum line from the fuel-conditioning cart was then placed into the fuel tank, through the filter spud, and the tank completely drained.

From test to test there was a period of approximately twenty minutes before the next test could start. When the vent tube was required to be changed, the test would commence the next day due to the time required for the sealant to dry and to verify that no leaks existed.
Chapter 4

ANALYSIS OF EXPERIMENTAL RESULTS

Three quantities were varied during these experiments. They were the fuel Reid vapour pressure, RVP, the fuel-dispensing rate, \( Q_{\text{in}} \), and the vent tube diameter, \( d_v \). The raw data consisted of tank dome and filler tube pressures versus time.

The analysis includes comparisons of the data to determine the influence of varying one (1) experimental variable at a time while maintaining the remaining variables constant. For simplicity, only examples of the dimensional data are presented in the text to show the affects of the variables mentioned above. The entire set of raw data is presented in Appendix A. Certain features of the raw data were then extracted and analyzed. A dimensional analysis was also completed and the extracted information plotted non-dimensionally. In the following, it should be noted that the RVP values shown are actual measured RVP values although they will be referred to by their nominal values.

4.1 Variability of Pressure-time Data

In the case of normal shut-off, the experiments were repeated three (3) times for each set of experimental condition. Plotting all three (3) data sets for each experimental condition on one graph indicates the variability in the results. For comparison purposes, the data for tank dome pressure and filler tube pressure are plotted in Figures 16 and 17 respectively for one set of experimental conditions. Please note that the symbols in Figures 16 and 17 are used for distinguishing the curves and reflect only a sampling of data points.
Figure 16. Variability of tank dome pressure-time data for $d_{vt} = 9.5$ mm, $Q_{Lin} = 45$ L/min and nominal RVP = 83 kPa.

Figure 17. Variability of filler pipe pressure-time data for $d_{vt} = 9.5$ mm, $Q_{Lin} = 45$ L/min and nominal RVP = 83 kPa.
Conditional variation is noticed from one test run to the next. This is primarily due to the difficulty experienced in maintaining the RVP at a constant value. The longer the fuel is left open to the atmosphere, the lower the value of the fuel RVP. For this reason the fuels are kept in sealed containers, however, the RVP still changed from one run to the next. From these plots the variation in the peak pressure during Phase I is approximately ± 0.5 kPa.

4.2 Pressure-time Data

Figures 18, 19, and 20 are plots of the time history of the tank dome and filler pipe pressures with identical experimental conditions except for vent tube diameter. Note that the time scale in Figure 20 is not the same as in Figures 18 and 19.

![Graph showing pressure-time data for tank dome and filler pipe](image)

**Figure 18.** Typical pressure-time history of the tank dome and filler pipe for the case where \(d_r = 9.5\) mm, \(Q_{\text{in}} = 45\) L/min and RVP = 56 kPa.
Figure 19. Typical pressure-time history of the tank dome and filler pipe for the case where $d_{vt} = 6.4$ mm, $Q_{in} = 45$ L/min and RVP = 53 kPa.

Figure 20. Typical pressure-time history of the tank dome and filler pipe for the case where $d_{vt} = 3.2$ mm, $Q_{in} = 45$ L/min and RVP = 58 kPa.
While maintaining the fuel-dispense rate constant at 45 L/min and the nominal RVP at approximately 55 kPa, it can be seen that by reducing the inside diameter of the vent tube fitting, the tank dome and filler pipe pressure values increase. The pressure-time profiles in Figures 18 and 19 clearly demonstrate the existence of the three (3) phases of refueling as reported by previous investigators and illustrated in Figure 2. It is interesting to note that the Phase II portion of the pressure-time profile in Figure 19 is of higher value as compared to Figure 18.

The pressure-time profile in Figure 20 clearly does not show the three (3) phases of refueling. The 3.2 mm (1/8") inside diameter vent tube caused PSO in all test combinations regardless of the fuel-dispensing rate and fuel RVP conditions including the calibration fluid which had a fuel RVP of approximately 7 kPa (1.0 psi). Therefore, the pressure-time profile does not pass the Phase I portion of the expected three (3) phases of refueling of a NSO pressure-time profile.

The filler pipe pressure-time profiles, shown in Figures 18, 19 and 20 have similar trends as the tank pressure profile albeit with more noise. With this fuel system, however, the filler pipe experiences lower pressures compared to the tank pressure and the Phase I peak is not as pronounced.

Figures 21 and 22 are plots similar to those in Figures 18 to 20 except that the fuel-dispense flow rate is changed while all other tank conditions are held constant.

The pressure values in the tank and filler pipe are seen to increase while increasing the fuel-dispense flow rate and maintaining the fuel RVP and the inside diameter of the vent tube constant.
Figure 21. Typical pressure-time history of the tank dome and filler pipe for the case where \(d_v = 9.5\, \text{mm} \), \(Q_{\text{LL}} = 38 \, \text{L/min}\) and \(RVP = 54 \, \text{kPa}\).

Figure 22. Typical pressure-time history of the tank dome and filler pipe for the case where \(d_v = 9.5\, \text{mm} \), \(Q_{\text{LL}} = 45 \, \text{L/min}\) and \(RVP = 56 \, \text{kPa}\).
Figure 23 contains the pressure-time histories for identical tank conditions as those in Figure 22 except for an increase in the RVP. It is seen that by increasing the fuel RVP the pressure values in the tank and filler pipe increase, especially during the first peak.

![Pressure-time history graph](image)

Figure 23. Typical pressure-time history of the tank dome and filler pipe for the case where \(d_{r1} = 9.5\) mm, \(Q_{F1} = 45\) L/min and RVP = 72 kPa.

Figures 24, 25 and 26 show the effect of decreasing the fuel RVP in the case where PSO occurred.
Figure 24. Typical pressure-time history of the tank dome and filler pipe for the case where $d_{rt} = 3.2$ mm, $Q_{Lm} = 45$ L/min and RVP = 82 kPa.

Figure 25. Typical pressure-time history of the tank dome and filler pipe for the case where $d_{rt} = 3.2$ mm, $Q_{Lm} = 45$ L/min and RVP = 58 kPa.
Figure 26. Typical pressure-time history of the tank dome and filler pipe for the case where \( d_{rt} = 3.2 \, \text{mm} \), \( Q_{LM} = 45 \, \text{L/min} \) and \( RVP = 7 \, \text{kPa} \).

As the RVP is decreased, the peak pressure at shut-off also decreased and the time to shut-off increased. However, it can be seen that the peak pressure at shut-off remains approximately constant for low values of fuel RVP and increases at higher fuel RVP.

Although Figure 26 indicates that fuel was dispensed for a longer period of time, it is still considered a PSO due to the fact that the fuel tank was not filled to the proper volume on its first attempt. Realistically, the fuel RVP used in actual vehicles will never be as low as the calibration fluid used in this experiment. It is, therefore, clearly seen that fuel evaporation is a factor (up to a point) in determining the pressure in the tank and causing PSO to occur in a shorter period of time.
Pressure-time histories where PSO occurred for identical tank conditions but different flow rates are given in Figures 27 and 28. Comparisons indicate that by increasing the fuel-dispense flow rate, the tank and filler pipe pressure increases while the time to shut-off decreases. Obviously, more fuel is initially forced into the tank in the case of the higher fuel-dispensing flow rate, and this leads to a faster build-up in pressure and a quicker PSO.

Figure 27. Typical pressure-time history of the tank dome and filler pipe for the case where \( d_{rt} = 3.2 \) mm, \( Q_{LA} = 38 \text{ L/min} \) and \( RVP = 83 \text{ kPa} \).
Figure 28. Typical pressure-time history of the tank dome and filler pipe for the case where \( d_{rt} = 3.2 \text{ mm}, Q_{km} = 45 \text{ L/min} \) and RVP = 82 kPa.

Spill-back was expected and did occur at the end of each and every refueling test. This can be explained by looking at the pressure-time profile for the filler pipe pressure \( (P_F) \). Figure 29 highlights the area where PSO occurred. It can be seen that the filler pipe pressure experienced a quick drop (Point 1 to Point 2) followed with a sudden increase in pressure (Point 2 to Point 3). This was due to the fuel-dispensing nozzle being deactivated at Point 1, which caused the filler pipe pressure to decrease to Point 2 due to the momentum of the slug of fuel travelling through the filler pipe. The slug is decelerated due to the higher pressure in the tank, and the lower pressure upstream in the filler pipe. From Point 2 to Point 3 the fuel slug is accelerated up the filler pipe causing an increase in pressure and the liquid fuel to exit from the filler pipe. To prevent this
practical fuel systems employ a check valve at the location where the filler pipe connects to the fuel tank.

![Graph showing pressure-time history with labeled points 1, 2, and 3.]

Figure 29. Typical pressure-time history of the filler pipe highlighting the sequence for spill-back ($d_{rt} = 3.2$ mm, $Q_{Lat} = 38$ L/min and RVP = 83 kPa).

4.3 Peak Pressure Data in Phase I

The peak tank dome pressures in Phase I were extracted from the pressure-time curves and are presented for comparison in Figure 30 plotted against the area of the vent tube. Each data point is the average of three (3) tests with the same conditions. The RVP values shown are nominal values. In the case where PSO occurred the peak pressure at PSO was taken. Therefore, the peak pressures at which PSO occurred are compared with the peak pressures of the Phase I region where NSO occurred.
Figure 30. Average peak tank dome pressures during Phase I versus the area of the vent tube.

On a relative basis for the case of NSO, the increase in tank dome pressure due to an increase in RVP is equal or greater than the increase in tank dome pressure due to an increase in \( Q_{\text{in}} \). For the case of PSO, the trend is reversed.

On a relative basis for all shut-off types, the sensitivity of tank dome pressure to RVP increases with increasing fuel-dispensing rate.

In addition, Figure 30 shows that the peak pressures under PSO conditions (8 mm\(^2\) vent tube area) can be less than the Phase I peak pressures under NSO conditions (\( \geq 32 \) mm\(^2\) vent tube area).

Figure 31 illustrates plots similar to those of Figure 30, except that the pressure values are recorded from the filler pipe. Similar observations to those made in Figure 30
can be seen here except in the region where the vent tube area is approximately between 35 mm² and 72 mm². It can be seen that at a vent tube area of approximately 48 mm², the curves which have a fuel-dispense rate at 45 L/min intersect the curve which have a lower fuel-dispense rate. It is reasonable to expect this to occur because at the higher flow rate (45 L/min as compared to 38 L/min), an increase in the velocity would be expected in the upper region of the filler pipe. This increased velocity would result in a decrease in pressure due to the Bernoulli effect. At smaller vent tube areas the flow in the vent tube is restricted, lowering the velocity and resulting Bernoulli effect.

![Graph showing pressure vs. vent tube area](image)

**Figure 31.** Average peak filler pipe pressures during Phase I versus area of the vent tube.

The apparent increase in filler pipe pressure for the case of 38 L/min and 55 kPa is well within the uncertainty of ± 500 Pa and therefore not significant. The recorded
values for the tank dome pressure ($P_T$) and the filler pipe pressure ($P_F$) does contain a reasonable amount uncertainty in the measurements that is explained in Appendix B.

4.4 Dimensional Analysis

Dimensional analysis was used to reduce the large number of variables to fewer non-dimensional parameters. The following list includes all the variables that influence the tank dome pressure, $P_T$, of the automotive fuel tank considered in this study. The same variables influence the filler pipe pressure, $P_F$.

\[
\begin{align*}
Q_{\text{Lin}} &= \text{fuel-dispensing nozzle flow rate (m}^3/\text{sec)} \\
d_h &= \text{internal diameter of the filler hose fitting (m)} \\
Q_{\text{Vin}} &= \text{vapour flow rate entering in the filler pipe (m}^3/\text{sec)} \\
\rho_L &= \text{density of liquid fuel (kg/m}^3) \\
\rho_V &= \text{density of fuel vapour (kg/m}^3) \\
g &= \text{gravitational constant (9.81 m/sec}^2) \\
\nu_v &= \text{kinematic viscosity of the vapour (m}^2/\text{sec)} \\
\nu_L &= \text{kinematic viscosity of the liquid (m}^2/\text{sec)} \\
t &= \text{time (sec)} \\
P_{\text{atm}} &= \text{atmospheric pressure (kg m}^{-1}\text{ sec}^{-2}) \\
L_R &= \text{length of the filler tube (m)} \\
V &= \text{volume of the tank (m}^3) \\
RVP &= \text{Reid vapour pressure (kg m}^{-1}\text{ sec}^{-2}) \\
d_v &= \text{internal diameter of the vent tube orifice (m)} \\
d_{rov} &= \text{internal diameter of the roll over valve orifice (m)} \\
L_v &= \text{length of the vent tube orifice (m)} \\
L_{rov} &= \text{length of the roll over valve orifice (m)}
\end{align*}
\]

The matrix method [12] was used for cases of $P_T$ and $P_F$ to determine the dimensionless groups with $d_v$, $Q_{\text{Lin}}$ and $P_{\text{atm}}$ used as repeating variables. In order to
simplify the dimensional analysis the following list of assumptions and conditions were used.

1) The temperatures of the fuel tank, fuel and ambient air are the same temperatures (isothermal) and remain constant.

2) The tank is a rigid system.

3) There is no liquid in the vapour lines.

4) The ratio of vapour flow rate to the total volume flow rate in the fuel-dispensing nozzle is always constant.

The fifteen independent dimensionless variables were found and given below:

\[ \pi_{14} = \frac{P_r}{P_{am}} \quad \pi_{1B} = \frac{P_r}{P_{am}} \]

\[ \pi_2 = \frac{t \cdot Q_{lm}}{d_{\pi}^3} \quad \pi_3 = \frac{RVP}{P_{am}} \quad \pi_4 = \frac{\rho_r \cdot Q_{lm}}{P_{am} \cdot d_{\pi}^4} \]

\[ \pi_5 = \frac{Q_{ra}}{Q_{lm}} \quad \pi_6 = \frac{g \cdot d_{\pi}^5}{Q_{lm}} \quad \pi_7 = \frac{\nu_r \cdot d_{\pi}}{Q_{lm}} \quad \pi_8 = \frac{v_L \cdot d_{\pi}}{Q_{lm}} \]

\[ \pi_9 = \frac{\rho_r \cdot Q_{lm}}{P_{am} \cdot d_{\pi}^4} \quad \pi_{10} = \frac{L_{\pi}}{d_{\pi}} \quad \pi_{11} = \frac{\hat{V}}{d_{\pi}^3} \quad \pi_{12} = \frac{L_{cor}}{d_{\pi}} \]

\[ \pi_{13} = \frac{d_{rh}}{d_{\pi}} \quad \pi_{14} = \frac{L_{\pi}}{d_{\pi}} \quad \pi_{15} = \frac{d_{cor}}{d_{\pi}} \]

The values of dimensionless maximum filler pipe pressure, \(\pi_{1B}\), versus dimensionless RVP, \(\pi_3\), are plotted in Figure 32.
Figure 32. **Dimensionless maximum filler pipe pressure versus the dimensionless RVP.**

Two (2) distinctive regions are noticed in Figure 32. Above the critical line is the PSO region and below the critical line is the NSO region.

The four (4) \( \pi_0 \) lines below the critical line in Figure 32 can be extrapolated to converge at Point A.

Figure 32 is useful in predicting when PSO would occur under various conditions. In the case where \( \pi_0 = 2.6 \), i.e. constant \( Q_{LIQ} \) and \( d_{in} \), if the RVP of the fuel were increased, it is predicted that PSO would occur.

As discussed earlier, the fuel-dispensing nozzle automatically shuts-off when the liquid level covers the sensing port. Therefore, it is the filler pipe pressure that is more significant in our analysis. This was demonstrated by Figure 33. The tank dome pressure
gave inferior fit to the non-dimensional experimental data than using the filler pipe measurements.

Figure 33 is a plot of dimensionless maximum tank dome pressure versus dimensionless RVP.

![Graph showing data points and labels](image)

**Figure 33.** Dimensionless maximum tank dome pressure versus the dimensionless RVP.

The two (2) distinctive regions that were noticed in Figure 32 do not exist in Figure 33. The curve where $\pi_9 = 2.6$ consists entirely of data points that experienced normal shut-off. Therefore, having some of the NSO data points located in the “region” of PSO does not allow a clean separation of PSO and NSO regions as in Figure 32.
Chapter 5

CONCLUSIONS

All refueling events that did not experience premature shut-off demonstrated the classic three (3) phase pressure-time profile similar to that previously noted in the literature. When premature shut-off resulted, it would not go further than the Phase I section of the pressure-time profile.

It was observed that the vent tube with an inside diameter of 3.2 mm caused the fuel-dispensing nozzle to shut-off prematurely at all conditions which were tested, while no premature shut-off was detected for vent tubes with a diameter of 9.5 mm or 6.4 mm. The inside diameter of the vent tube, is therefore, a critical parameter for premature shut-off. In addition, it can be said that higher fuel RVP and fuel-dispense rate resulted in higher tank dome pressures, but not necessarily a premature shut-off. It was noted that, on a relative basis, the fuel RVP is more effective in increasing the tank dome pressure than an increase in the fuel-dispense rate.

In the cases of both premature shut-off and normal shut-off, a sharp decrease in the filler pipe pressure followed by a large pressure rise to a value greater than before the drop was noted at shut-off.

In addition, it was observed that the effects of RVP, $d_v$, and $Q_{lim}$ on PSO are conveniently shown on a dimensionless plot.
Chapter 6

RECOMMENDATIONS

Recommendations for future work include:

To further distinguish the premature shut-off and normal shut-off regions, additional experiments should be conducted to determine if a vent tube between diameters of 3.2 mm (1/8”) and 6.4 mm (1/4”), say 4.8 mm (3/16”) would cause PSO and NSO for experimental conditions in this study.

Test apparatus should be incorporated in the region of the filler pipe and fuel-dispensing nozzle such that the velocity and vapour to liquid ratio can be measured and recorded. This information may confirm the theory about why the higher of the two fuel-dispense flow rates would cause a reduction of filler pipe pressure. This information can also validate the velocity and void fraction ratio determined by computational fluid dynamic computations. In addition, it could help determine better design practices to reduce the hydrocarbon vapours exiting the filler pipe.
REFERENCES


Figure A-1. Test #1, Trial #1: \(d_{xt} = 9.5 \text{ mm} \) - \(Q_{LIn} = 38 \text{ L/min} \) - RVP = 61 kPa

Figure A-2. Test #1 - Trial #2: \(d_{xt} = 9.5 \text{ mm} \) - \(Q_{LIn} = 38 \text{ L/min} \) - RVP = 88 kPa
Figure A-3.  Test #1 - Trial #3: $d_{rt} = 9.5$ mm – $Q_{Lh} = 38$ L/min – RVP = 71 kPa

Figure A-4.  Test #2 - Trial #1: $d_{rt} = 9.5$ mm – $Q_{Lh} = 45$ L/min – RVP = 82 kPa
Figure A-5. Test #2 - Trial #2: $d_{rt} = 9.5\, \text{mm} - Q_{in} = 45\, \text{L/min} - RVP = 70\, \text{kPa}$

Figure A-6. Test #2 - Trial #3: $d_{rt} = 9.5\, \text{mm} - Q_{in} = 45\, \text{L/min} - RVP = 72\, \text{kPa}$
Figure A-7. Test #3 - Trial #1: \( d_{rt} = 9.5 \text{ mm} \) – \( Q_{Lm} = 38 \text{ L/min} \) – RVP = 81 kPa

Figure A-8. Test #3 - Trial #2: \( d_{rt} = 9.5 \text{ mm} \) – \( Q_{Lm} = 38 \text{ L/min} \) – RVP = 57 kPa
Figure A-9. Test #3 - Trial #3: \( d_{rt} = 9.5 \text{ mm} \) – \( Q_{\text{Lb}} = 38 \text{ L/min} \) – RVP = 54 kPa

Figure A-10. Test #4 - Trial #1: \( d_{rt} = 9.5 \text{ mm} \) – \( Q_{\text{Lb}} = 45 \text{ L/min} \) – RVP = 49 kPa
Figure A-11. Test #4 - Trial #2: $d_{rt} = 9.5$ mm – $Q_{LH} = 45$ L/min – RVP = 56 kPa

Figure A-12. Test #4 - Trial #3: $d_{rt} = 9.5$ mm – $Q_{LH} = 45$ L/min – RVP = 54 kPa
Figure A-13. Test #5 - Trial #1: \(d_{eff} = 6.4 \text{ mm} \) – \(Q_{LH} = 38 \text{ L/min} \) – RVP = 52 kPa

Figure A-14. Test #5 - Trial #2: \(d_{eff} = 6.4 \text{ mm} \) – \(Q_{LH} = 38 \text{ L/min} \) – RVP = 50 kPa
Figure A-15. Test #5 - Trial #3: $d_{rt} = 6.4$ mm - $Q_{In} = 38$ L/min - RVP = 51 kPa

Figure A-16. Test #6 - Trial #1: $d_{rt} = 6.4$ mm - $Q_{In} = 45$ L/min - RVP = 49 kPa
Figure A-17. Test #6 - Trial #2: $d_r = 6.4$ mm - $Q_{in} = 45$ L/min - RVP = 53 kPa

Figure A-18. Test #6 - Trial #3: $d_r = 6.4$ mm - $Q_{in} = 45$ L/min - RVP = 55 kPa
Figure A-19. Test #7 - Trial #1: \( d_{rt} = 6.4 \text{ mm} \) - \( Q_{LM} = 38 \text{ L/min} \) - RVP = 78 kPa

Figure A-20. Test #7 - Trial #2: \( d_{rt} = 6.4 \text{ mm} \) - \( Q_{LM} = 38 \text{ L/min} \) - RVP = 74 kPa
Figure A-21. Test #7 - Trial #3: \(d_{\text{i}} = 6.4 \text{ mm} - Q_{\text{L,bs}} = 38 \text{ L/min} - \text{RVP} = 82 \text{ kPa}\)

Figure A-22. Test #8 - Trial #1: \(d_{\text{i}} = 6.4 \text{ mm} - Q_{\text{L,bs}} = 45 \text{ L/min} - \text{RVP} = 70 \text{ kPa}\)
Figure A-23. Test #8 - Trial #2: \( d_{rt} = 6.4 \text{ mm} \) - \( Q_{Lm} = 45 \text{ L/min} \) - RVP = 71 kPa

Figure A-24. Test #8 - Trial #3: \( d_{rt} = 6.4 \text{ mm} \) - \( Q_{Lm} = 45 \text{ L/min} \) - RVP = 80 kPa
Figure A-25. Test #9 - Trial #1: \( d_{rt} = 3.2 \) mm – \( Q_{in} = 38 \) L/min – RVP = 83 kPa

Figure A-26. Test #9 - Trial #2: \( d_{rt} = 3.2 \) mm – \( Q_{in} = 38 \) L/min – RVP = 79 kPa
Figure A-27. Test #10 - Trial #1: $d_{rt} = 3.2\text{mm} - Q_{Lh} = 38 \text{ L/min} - \text{RVP} = 58 \text{ kPa}$

Figure A-28. Test #11 - Trial #1: $d_{rt} = 3.2\text{mm} - Q_{Lh} = 45 \text{ L/min} - \text{RVP} = 58 \text{ kPa}$
Figure A-29. Test #12 - Trial #1: \( d_{rt} = 3.2 \text{mm} \) – \( Q_{in} = 45 \text{ L/min} \) – \( RVP = 82 \text{ kPa} \)

Figure A-30. Test #13 - Trial #1: \( d_{rt} = 3.2 \text{ mm} \) – \( Q_{in} = 45 \text{ L/min} \) – \( RVP = 7 \text{ kPa} \)
Figure A-31. Test #13 - Trial #2: $d_{rt} = 3.2 \text{ mm} - Q_{L,M} = 45 \text{ L/min} - RVP = 7 \text{ kPa}$

Figure A-31. Test #14 - Trial #1: $d_{rt} = 3.2 \text{ mm} - Q_{L,M} = 38 \text{ L/min} - RVP = 7 \text{ kPa}$
Figure A-31. Test #14 - Trial #2: $d_{ct} = 3.2$ mm – $Q_{L,in} = 38$ L/min – RVP = 7 kPa
APPENDIX B

UNCERTAINTY ANALYSIS
The following are estimates of the uncertainty (W_x) for the variables indicated in the subscript X:

\[ W_{p_{\text{atm}}} = \pm 2 \text{kPa} \quad W_{d_{\text{vt}}} = \pm 0.0001 \text{m} \quad W_{RVP} = \pm 2 \text{kPa} \]

\[ W_{\rho_{\text{L}}} = \pm 10 \text{kg/m}^3 \quad W_{Q_{\text{in}}} = \pm 0.00001 \text{m}^3/\text{sec} \quad W_{P_{\text{vt}}} = \pm 0.5 \text{kPa} \]

The value given to P_{\text{atm}} was 101,300 Pa. Although P_{\text{atm}} was measured, the day to day fluctuation with P_{\text{atm}} ranged according to W_{P_{\text{atm}}}.

The uncertainty for \( \pi_{\theta} \), knowing that,

\[ \pi_{\theta} = \frac{\rho_{\text{L}} \cdot Q_{\text{in}}^2}{P_{\text{atm}} \cdot d_{\text{vt}}^4} \]

is determined from the following equation:

\[ W_{\pi_{\theta}} = \pi_{\theta} \cdot \sqrt{\left( \frac{W_{\rho_{\text{L}}}}{\rho_{\text{L}}} \right)^2 + \left( \frac{2W_{Q_{\text{in}}}}{Q_{\text{in}}} \right)^2 + \left( \frac{-W_{P_{\text{atm}}}}{P_{\text{atm}}} \right)^2 + \left( \frac{-4W_{d_{\text{vt}}}}{d_{\text{vt}}} \right)^2} \]

Since the experiments consist of three (3) orifice sizes for the vent tube (d_{\text{vt}}) and two (2) fuel-dispense flow rates (Q_{\text{in}}), six (6) \( W_{\pi_{\theta}} \) can be calculated. Table B-1 lists the uncertainty for \( W_{\pi_{\theta}} \):

<table>
<thead>
<tr>
<th>Q_{\text{in}} [L/min]</th>
<th>d_{\text{vt}} [mm]</th>
<th>\pi_{\theta}</th>
<th>W_{\pi_{\theta}}</th>
</tr>
</thead>
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<tr>
<td>37.9</td>
<td>9.5</td>
<td>0.35</td>
<td>0.02</td>
</tr>
<tr>
<td>45.4</td>
<td>9.5</td>
<td>0.51</td>
<td>0.03</td>
</tr>
<tr>
<td>37.9</td>
<td>6.4</td>
<td>1.8</td>
<td>0.13</td>
</tr>
<tr>
<td>45.4</td>
<td>6.4</td>
<td>2.6</td>
<td>0.18</td>
</tr>
<tr>
<td>37.9</td>
<td>3.2</td>
<td>28.6</td>
<td>3.65</td>
</tr>
<tr>
<td>45.4</td>
<td>3.2</td>
<td>41.7</td>
<td>5.20</td>
</tr>
</tbody>
</table>

**Table B-1. Uncertainty Analysis for \( W_{\pi_{\theta}} \).**

The maximum relative uncertainty on \( W_{\pi_{\theta}} \) is 13%.
The uncertainties for $\pi_3$ and $\pi_{1B}$, knowing that,

$$\pi_3 = \frac{RVP}{P_{am}}$$

and

$$\pi_{1B} = \frac{P_{Fam}}{P_{am}}$$

are determined from the following respective equations:

$$W_{\pi_3} = \pi_3 \sqrt{\left(\frac{W_{RVP}}{RVP}\right)^2 + \left(\frac{-W_{P_{am}}}{P_{am}}\right)^2}$$

and

$$W_{\pi_{1B}} = \frac{P_{Fam}}{P_{am}} \cdot \frac{P_F}{P_{Fam}} \sqrt{\left(\frac{W_{P_F}}{P_F}\right)^2 + \left(\frac{W_{P_{am}}}{P_{am}}\right)^2}$$

For $\pi_3$ and $\pi_{1B}$ the maximum (RVP = 55 kPa and $P_F = 0.5$ kPa) and minimum (RVP = 83 kPa and $P_F = 7$ kPa) uncertainties can be determined and are shown in Table B-2.

<table>
<thead>
<tr>
<th></th>
<th>MAX</th>
<th>MIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{\pi_3}$</td>
<td>0.0225</td>
<td>0.0255</td>
</tr>
<tr>
<td>$W_{\pi_{1B}}$</td>
<td>0.0049</td>
<td>0.0051</td>
</tr>
</tbody>
</table>

Table B-2. The uncertainty values for $\pi_3$ and $\pi_{1B}$ at maximum and minimum conditions.

The maximum relative uncertainty on $\pi_3$ and $\pi_{1B}$ are 4% and 0.5% respectively.
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