# Construction of The Digital Shadow of A Fuel Supply Testbed

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**April 2023**

# Abstract

This coursework analyses the fuel supply testbed in the C103a laboratory, with an in-depth analysis of the system under healthy and faulty conditions. This is to help understand how the system behaves when it is working under the right conditions and distinguish it from the faulty conditions. Data was gathered from the testbed at the different operating conditions. The different failure modes, clogged filter, degraded pump, leaking pipe, stuck valve, and clogged nozzle were closely analysed and characterised against the healthy conditions. A model was built to predict the flow rate of the pump, based on different pump speeds and differential pressure, to build a foundation for a digital shadow that will be used to create a digital twin. Prior to that, a literature review on the different failure modes was conducted.

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# Chapter One

# Introduction

## 1.0 Introduction

The fuel supply system which is also called the fuel injection system is a very important part of a mechanical system. It ensures the delivery of the right amount fuel to the engines under optimum conditions. It is made up of fuel filters, fuel pump, fuel lines (pipes), valves and an injector.

The filter performs the duty of ensuring a clean fuel reaches the engine, by removing all impurities from the fuel, to ensure optimum performance of the engine and prevent the nozzle from failing. The pipes which are the fuel lines in the system, are a medium for transporting the fuel from one component to another before it reaches its destination, the engine. The injector has the job of delivering fuel to the combustion chamber of the engine either directly or indirectly. The injector is positioned in such a way that the fuel is either spayed at the inlet valve of the engine or straight into the cylinder. The valves have the task of regulating the flow of fuel to the engine and must be capable of opening and closing when needed. The pressure of the fuel and the flow rate must be maintained and meet the engine requirements, this is the duty of the fuel pump.

Just like any system involved in the workings of a larger system, components can lose their optimal capabilities. There are different failure modes that affect the fuel system, from a clogged filter which can lead to reduced engine optimization, a degraded gear pump leads to poor flow rate, a sticking valve, a leaking pipe reduces the volume and flow rate of fuel to the engine and other components in the system, to a clogged injector which reduces the flow rate.

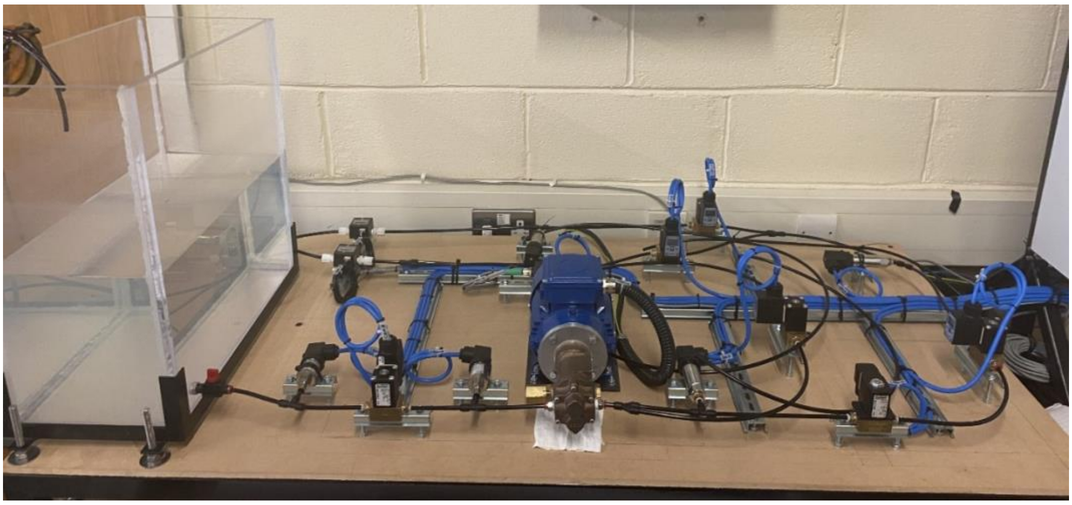


*Figure 1: The Fuel System Testbed*

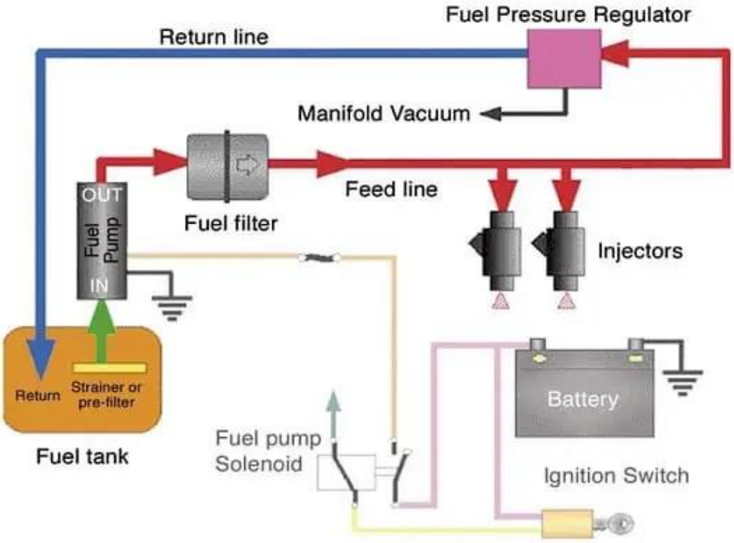


*Figure 2: Schematic Diagram of a Fuel Supply System*

## 1.1 Aim

To understand the concept of digital twins and demonstrate that understanding by creating the elements of a digital risk twin for a fuel system testbed.

## 1.2 Objectives

I. Compilation of a literature review on the five failure modes affecting five different components (clogged filter, degraded gear pump, mid-range position stuck valve, leaking pipe, and clogged injector) in the fuel supply system.

II. Analysing and characterising the healthy conditions of the fuel system at a specific operating point.

III. Analysing and characterising the faulty conditions that have the potential to affect the system.

**IV.** Comparison of the pump test data against the Original Equipment Manufacturer’s (Oberdorfer N999R) datasheet and construction of the pump model.

**V.** Explanation of how the digital shadow constructed can be used to design a digital twin of the fuel system.

# Chapter 2

## 2.0 Literature Review

This chapter focuses on reviewing past journals and projects published on the fuel supply system, with a focus on the failure modes that affect the five different components that are in a fuel supply system. It is a review of the five failure modes that affects the different components.

The review is focused on the physical degradation that can be mimicked on the fuel system. The five components are the clogged filter, degraded gear pump, mid-range position stuck valve, leaking pipe, and the clogged nozzle.

### 2.1 Clogged Filter

The removal of contaminants from fuel is a very key part of the engineering processes in industries. A clogged filter is one of the most common failure modes in many application areas, which results in a drop in performance and poor efficiency (Skaf et al, 2017). The type of fuel passing through the filter also constitutes to how fast it gets clogged and degraded over time (Komariah et al., 2018).

In the journal Filter Clogging of a UAV Fuel System by Skaf *et al* (2017) the authors proposed a model-based approach to predict clogging of filter by monitoring the health parameters of the system. Methods aimed at predicting when filters are clogged where developed, leading to a preventive approach maintenance focused on reducing the impact of clogging on the performance of a system.

Biodiesel Effects on Fuel Filter: Assessment of Clogging Characteristics by Komariah *et al* (2018) focuses on how fuel filters clog when used with conventional diesel fuel and biodiesel, checking the impact of biodiesel on the performance and shelf life of filters. The study gives useful information into clogged filters in biodiesel powered systems, pointing out the importance of ongoing research and development in the area. Strategies that predict filter clogging and prevent it are important to the performance of biodiesel fuel systems.

If filter clogging can be predicted, knowing how to reduce the effects will go a long way. Filter Clogging Data Collection for Prognostics by Eker *et al* (2013) focuses on that. Prognostics is a type of science that helps predict an event that will happen, helping the engineer involved to prevent it before it happens. This journal helps in building an experimental rig to collect data for the clogging of a filter. However, the writers realized that the process of collecting data can be better improved. It still stands that analysing sensor data from pressure drop and flow rate, will help detect changes in the filter performance and forecast the shelf life of the filter.

## 2.2 Degraded Gear Pump

The pump unit in a fuel supply system is an important part of the system, as it delivers a smooth pulse-free fuel at a higher pressure on its discharge side. It is exposed to different factors like wear and tear, temperature, among others, which can result in the degradation of the pump, which in turn will have a dire effect on the system as a whole (Guo *et al.*, 2020).

Research on Identification Method of Wear Degradation of External Gear Pump Based on Flow Field Analysis by Guo *et al* (2020) is a paper that focuses on wear degradation in external gear pumps. The factors that contribute to the degradation and how to identify the wear and tear using flow field analysis were discussed in this research paper. Computational Fluid Dynamics (CFD) simulations is the method used to check the flow field and note the difference in flow rate that indicate wear. The paper verifies the method used with an experiment, demonstrating the effectiveness in recognising wear in a gear pump. It also provides a clear understanding into the degradation of gear pumps and offers a useful approach for pinpointing wear using flow field analysis.

The journal Degradation Detection for Internal Gear Pumps using Pressure Reduction Time Maps by Pichler *et al* (2021) compares two methods for detecting and monitoring the degradation of internal gear pumps namely, Pressure Reduction Time Maps Volume (PRTMV) and Pressure Holding Speed (PHS). It also discusses abrasion, erosion, and fatigue as the different types of wear that can occur in a pump and what leads to their growth. The workings of PRTMV are described in this journal, it involves analysing the pressure output of a pump to note the difference in flow rate, pressure and other factors that are associated with degradation. It is noted in this article that PRTMV is more superior to PHS as a tool for monitoring the health and preventing failures in a gear pump.

Lamoureux *et al* (2012) in An Approach to the Health Monitoring of a Pumping Unit in an Aircraft Engine Fuel System provides an advance for health monitoring of gear pumps over an early detection of failure modes premises. They developed five proposed development methods: health monitoring perimeter definition, data analysis, system and degradation modelling, simulation results and statistical validation and prognostics issue(Lamoureux, Massé and Mechbal, no date). They defined a component health indicator to monitor the state of the pump. The journal generated different system and degradation modelling to check the gear pump behaviour, the fuel system, and the degradation modelling to simulate the influence of all the potential faults. An algorithm for fault detection was also developed, using key performance indicators, statistical validation is performed. A degradation severity indicator is defined, and prognostic is performed based on the monitoring. The paper concluded on improving fault detection and prognostics algorithms to extend PHM to the whole aircraft engine fuel system.

## 2.3 Mid-Range Position Stuck Valve

Over the years, detecting and diagnosing faults in fuel supply systems is a growing issue in the industry. The sticking valve is a failure mode that commonly occurs in fuel supply systems. A sticking valve refers to a valve that becomes partially open or closed position and does not respond to control signals Liu et al., (2021). This leads to poor performance of the engine and reduced efficiency Hiltz et al., (2002).

Hiltz *et al* (2002) in Diesel Engine Valve Failures conducted research on different diesel engine generators to check what causes valve to fail. The authors documented that system integration, different lubrications and fuels, oversight in design and varied maintenance along with operational environments affect the reliability of diesel. The failed components can be evaluated, which will provide a better understanding into the conditions that occurred before the component failed, which will in turn lead to changes that will reduce the probability of the same problems reoccurring. The failures that occur in valves are characterized by deposits forming on them. The paper concluded that control of lubrication oil dilution by uncombusted and partially burned fuel is quite key to valve deposit formation than the oxidative stability of the lubrication oil. It is integral to maintain a problem free equipment by preventing lubrication oil contamination, adjusting air intake, fuel supply and coolant flow, component supply and design.

Liu *et al* (2021) in A Machine Learning Based Clustering Approach to Diagnose Multicomponent Degradation of Aircraft Fuel Systems used machine learning and clustering techniques to present an innovative approach to diagnosing multicomponent degradation in aircraft fuel systems. The authors of the journal introduced with routine maintenance costing airlines a lot of money in the modern aviation industry. The paper introduces a new test rig to replicate the multi-component degradation of an aircraft fuel system. A machine learning-based clustering approach was used, k-means to be precise, identifying the location and severity of the fault. The journal used data from multiple sensors in the fuel system, to detect the performance of the system and level of degradation caused by a sticking valve.

## 2.4 Leaking Pipes

A pipeline rupture leading to a leak may significantly impact the environment and have a negative impact on the company operating the pipeline Korlapati et al., (2022). Pipes in a fuel supply system has the role of transporting the medium between different components that make up the system. It is difficult to avoid the probability of leakage in a pipeline system, before it needs to be replaced (Lambert *et al.*, 2001).

Korlapati *et al* (2022) in Review and Analysis of Pipeline Leak Detection Methods compared different leak detection methods, evaluating their advantages and limitations. The journal starts with listing the different types of pipes in the industry and what causes leaks in pipes. Furthermore, it discusses the dangers of leaks and how important it is to detect it early. The authors discuss different leak detection methods including physical methods, acoustic methods, statistical methods, and machine learning techniques. The different methods are compared in regard to the advantages and disadvantages, accuracy, how reliable each method is, the cost and how easy it is to implement. Additionally, the strengths and weaknesses are also compared. The journal concludes the need for further research and how advanced technique can improve the accuracy and reliability of pipeline leak detection.

Lambert *et al* (2001) in Leak Detection in Pipeline Systems and Networks: A Review surveyed different leak detection methods, classifying them into four groups, namely, Offline observation and surveillance, online pig-based methods, acoustic methods, and hydraulic methods. The paper featured the advantages and disadvantages, accentuating the appropriate panacea for different pipeline systems. The authors considered the inverse transient method most importantly. The paper concluded that all the detection methods must be used in conjunction with conventional leak detection methods. Additionally, transient-based inverse leak detection is more promising in integrity monitoring, however, it is still in the early stages.

Sarwar and Lu (2018) wrote a journal Leak Detection, Localization and Prognosis of High-Pressure Fuel Delivery System that discusses how important it is to detect and localize leaks in modern engines. The authors discuss different ways to detect leak in high-pressure fuel delivery system and various approaches to localizing leaks once detected. The authors discuss how important prognosis is for high-pressure fuel delivery systems.

## 2.5 Clogged Nozzle

Neto *et al* (2015) in Failure in Fuel Injector Nozzles Used in Diesel Engines conducted a study of the problems associated with the wear of the needles and nozzles used in fuel injection of diesel engines. The authors associated the degradation to impurities in the fuel and micro cavitation due to high pressure during air compression for combustion of the combustible fluid. AN experiment was conducted by the authors on an injection unit, and they concluded that, the wear on the nozzles was caused by the fuel contamination. The journal concluded that more study must be done about the fuel properties, such as high viscosity, low volatility, and reactivity of unsaturated hydrocarbon chains.

Liu *et al* (2021) conducted an experiment in A Machine Learning-based Clustering Approach to Diagnose Multi-component Degradation of Aircraft Fuel Systems to accurately predict fault and prognosis, to reduce maintenance costs, increase the safety and availability of engineering systems that have become more complex. The authors set up an experiment rig and injected fault to simulate a sticking valve, a clogged nozzle, blocked flow meter and a clogged filter. The journal utilised the clustering approach, k-means to group faults identified in the test rig. The authors concluded that their approach is limited as it only works on stationary systems and the level of degradation does not change with time, they advised future studies should focus on dynamical systems.

# Chapter 3

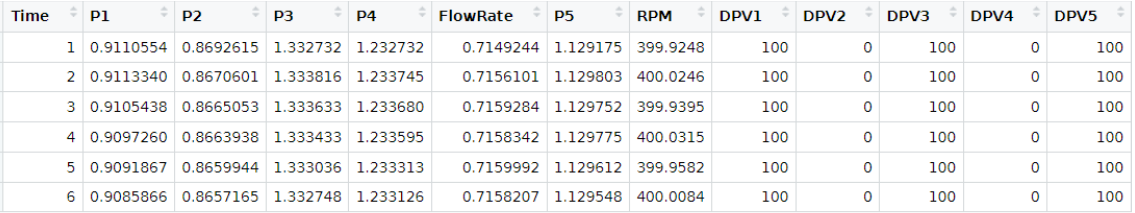
## 3.0 Analysis of the System

The fuel testbed being examined in this work is in the C103a laboratory at GCU.  It has been used to conduct different experiments , both at the undergraduate and postgraduate level. The testbed operates initially at healthy conditions before faults is injected into it using Direct Proportional Valves (DPV).

There are five pressure sensors, P1, P2, P3, P4, and P5. They monitor the pressure before the filter, before the pump, after the pump, after the valve and before the tank respectively. The sensors monitor the pressure levels at different operating conditions.

### 3.1 Analysis of the Healthy Conditions

The different DPVs are used to mimic the different faults. DPV1 represents a clogged filter, the valve is 100% open, signifying no fault in the filter. DPV2 represents a degraded pump and is fully closed, to represent a fully functioning pump.



| Time | P1 | P2 | P3 | P4 | FlowRate | P5 | RPM | DPV1 | DPV2 | DPV3 | DPV4 | DPV5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.9110554 | 0.8692615 | 1.332732 | 1.232732 | 0.7149244 | 1.129175 | 399.9248 | 100 | 0 | 100 | 0 | 100 |
| 2 | 0.9113340 | 0.8670601 | 1.333816 | 1.233745 | 0.7156101 | 1.129803 | 400.0246 | 100 | 0 | 100 | 0 | 100 |
| 3 | 0.9105438 | 0.8665053 | 1.333633 | 1.233680 | 0.7159284 | 1.129752 | 399.9395 | 100 | 0 | 100 | 0 | 100 |
| 4 | 0.9097260 | 0.8663938 | 1.333433 | 1.233595 | 0.7158342 | 1.129775 | 400.0315 | 100 | 0 | 100 | 0 | 100 |
| 5 | 0.9091867 | 0.8659944 | 1.333036 | 1.233313 | 0.7159992 | 1.129612 | 399.9582 | 100 | 0 | 100 | 0 | 100 |
| 6 | 0.9085866 | 0.8657165 | 1.332748 | 1.233126 | 0.7158207 | 1.129548 | 400.0084 | 100 | 0 | 100 | 0 | 100 |

*Table 1: Healthy Dataset*

DPV3 represents a blocked shut-off valve, it is 100% open when there is no fault in the valve. DPV4 is fully closed and represents the leaking pipe further down the testbed and is 0% open to show no fault. Finally, DPV5 represents a clogged injector, it is fully open at 100%, with fault severity at 0%. The pump is operating at a fixed pump speed of 400 RPM. The conditions under which the system operates as a healthy system, had to be defined, to note the baseline for the degradation of the system.

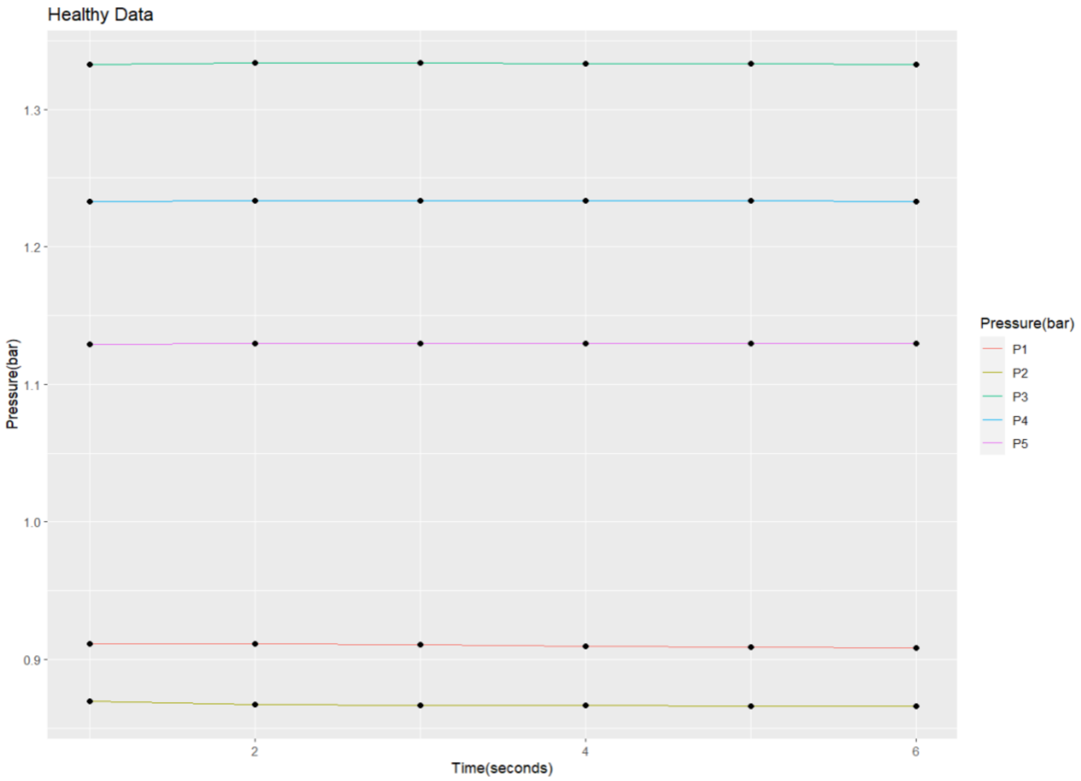


*Figure 3: Pressure Against Time in Healthy Condition*

At the healthy conditions stated earlier, the data generated from the testbed, which has been in operation over 5 years was plotted in RStudio. The pressure of the pump was plotted against different variables, to set a standard against which the failure modes will be compared. The first chart, figure 3 is a chart of pressure against time. P1 is the pressure before the filter, P2 is the pressure after the filter, P3 is the pressure after the pump, P4 is the pressure after the shut-off valve and P5 is the pressure after the nozzle. The pressure in the fuel testbed is unchanging throughout the time the testbed ran at healthy conditions.

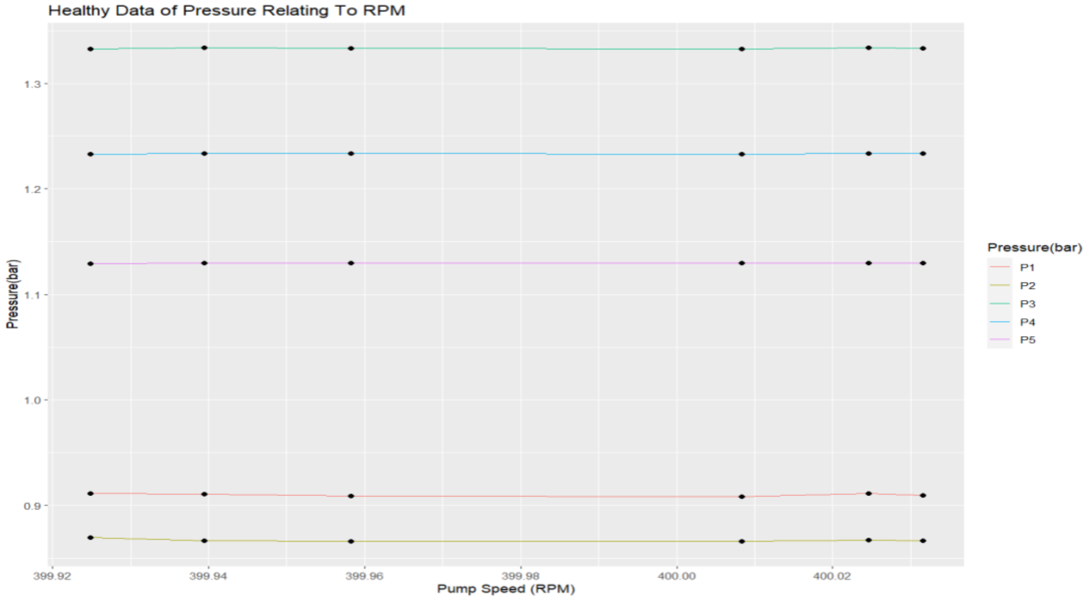


*Figure 4: Pressure Against Pump Speed*

Figure 4 is a graph of the pressure at healthy conditions against the pump speed in the range of 399.95 to 400.04, despite the minute RPM range, the pressure remains unchanged at the optimal operating conditions of the testbed.

The third chart below, relates the pressure against flow rate. The chart shows no change in the pressure at the different components, which reiterates the pump is operating at healthy conditions.

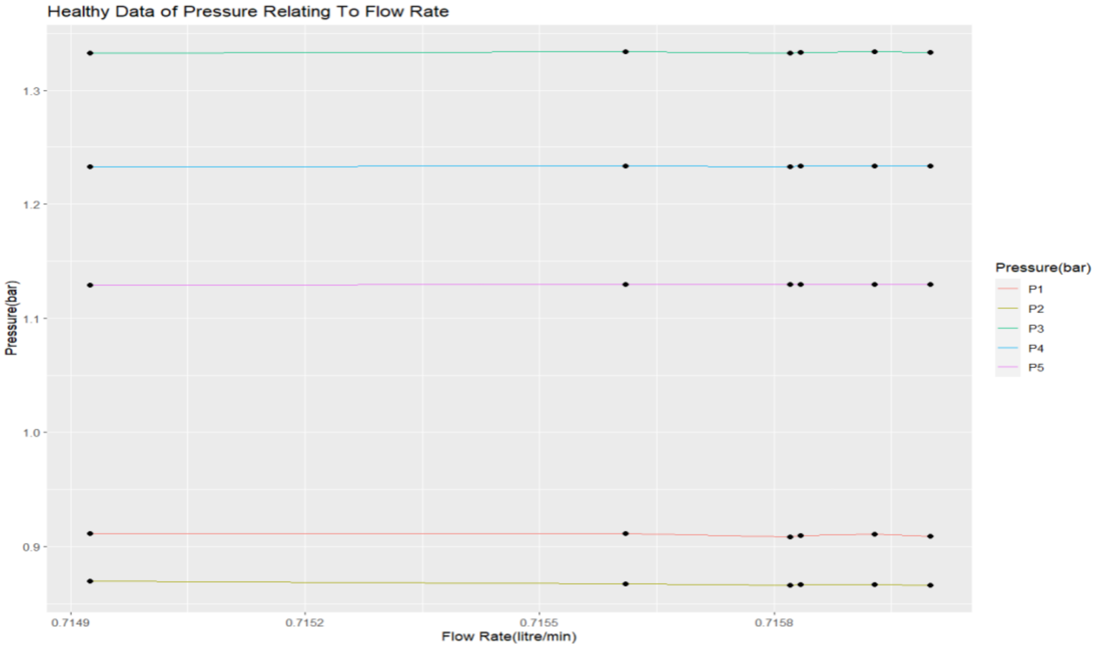


*Figure 5: Pressure Against Flow Rate*

# Chapter 4

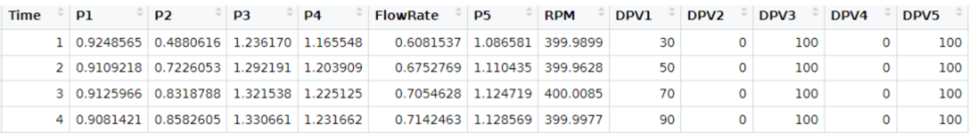
## 4.0 Analysis of the Faulty Conditions

The different failure modes, clogged filter, degraded pump, stuck valve, leaking pipe, and clogged nozzle are injected into the system, using their respective DPVs. The level of severity is varied with the different valve openings at 30%, 50%, 70% and 90%, the pressure at the different components is recorded in respect to their valve openings.

The failure mode, clogged filter is the only fault that is injected before the pump, unlike the other faults that are injected downstream of the pump.

## 4.1 Clogged Filter

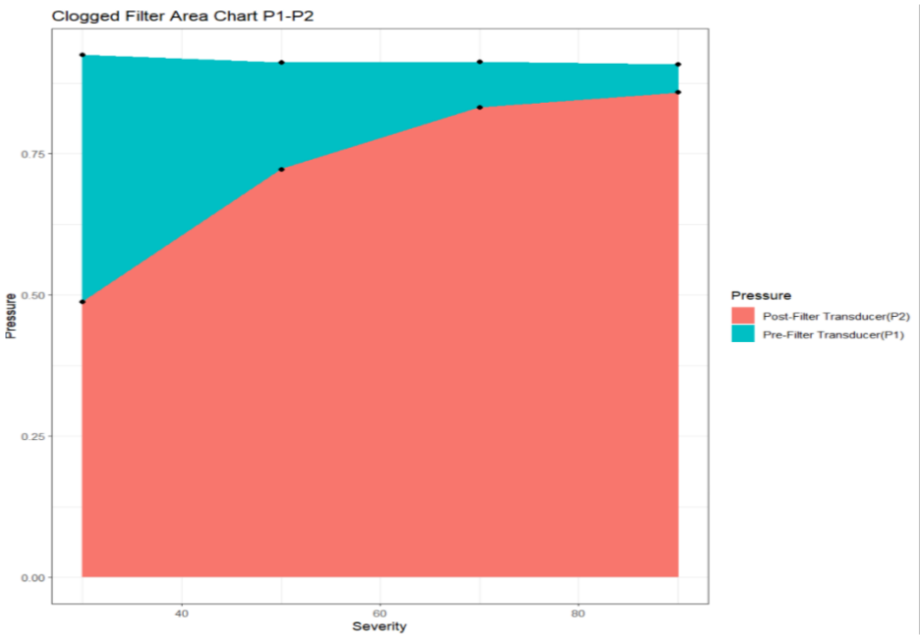
The filter is the only component in the testbed that precedes the pump, the failure mode, clogged filter, is the only fault that is injected before the pump. The clogging of a filter can go undetected, even at high level of severity, as the degradation has little effect on the pump (Bardakis, Niculita and Wallace, 2020).



| Time | P1 | P2 | P3 | P4 | FlowRate | P5 | RPM | DPV1 | DPV2 | DPV3 | DPV4 | DPV5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.9248565 | 0.4880616 | 1.236170 | 1.165548 | 0.6081537 | 1.086581 | 399.9899 | 30 | 0 | 100 | 0 | 100 |
| 2 | 0.9109218 | 0.7226053 | 1.292191 | 1.203909 | 0.6752769 | 1.110435 | 399.9628 | 50 | 0 | 100 | 0 | 100 |
| 3 | 0.9125966 | 0.8318788 | 1.321538 | 1.225125 | 0.7054628 | 1.124719 | 400.0085 | 70 | 0 | 100 | 0 | 100 |
| 4 | 0.9081421 | 0.8582605 | 1.330661 | 1.231662 | 0.7142463 | 1.128569 | 399.9977 | 90 | 0 | 100 | 0 | 100 |

*Table 2: Clogged Filter*

The filter is at the intake part of the pump, its clogging influences how much liquid goes in the pump. The clogged filter up to a severity of 50% has little effect on the amount of liquid flowing into the pump. However, even as the severity increases and there is no more flow into the pump, as the pressure loss across DPV1 is the same as the differential pressure between the atmospheric pressure of the tank and the pump intake is the same, a phenomenon called "line stripping" occurs, where all the liquid trapped in the line is suddenly flushed out (Bardakis, Niculita and Wallace, 2020). Table 1 shows the flow rate change over the increased severity, with 90% representing a near healthy filter and 30% the highest severity and the lowest flow rate recorded.



The area chart above clearly depicts the difference in the pressure before and after the filter.

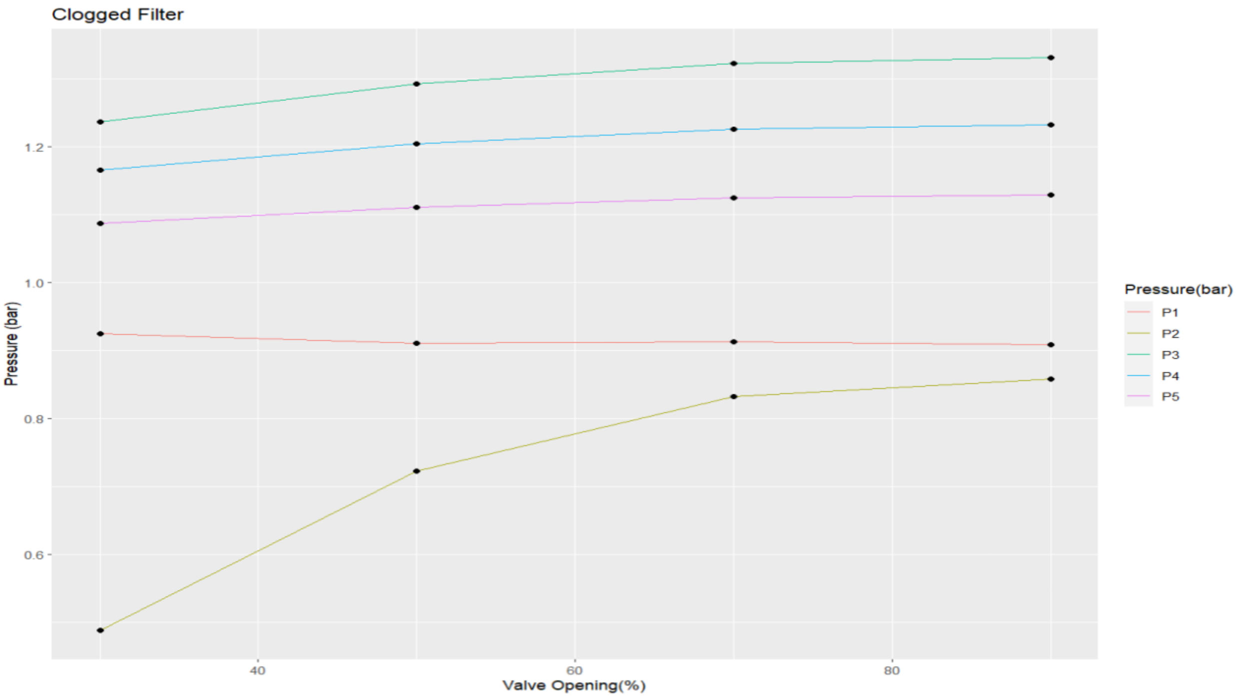
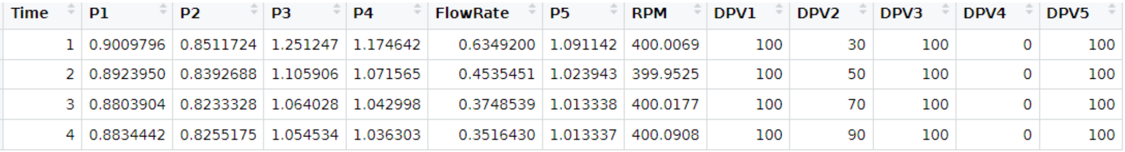


*Figure 6: Chart of the Clogged Filter Pressure Against Severity*

Figure 6 is a chart of the pressure against the severity, P2 and P3 records the most significant drop at the highest level of severity at 30% and 50%, while P1 has an increased pressure at the high level of severity. The pressure returns to normal as the severity reduces to 90%.

## 4.2 Degraded Pump

The failure mode, degraded pump is simulated with DPV2, it is initially closed and opened gradually to increase the severity of the leakage at the pump outlet. In the table below, a sharp drop of the flow rate is noticed as the leakage at the pump outlet is increased, which is due to a drop in pressure at P3.



| Time | P1 | P2 | P3 | P4 | FlowRate | P5 | RPM | DPV1 | DPV2 | DPV3 | DPV4 | DPV5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.9009796 | 0.8511724 | 1.251247 | 1.174642 | 0.6349200 | 1.091142 | 400.0069 | 100 | 30 | 100 | 0 | 100 |
| 2 | 0.8923950 | 0.8392688 | 1.105906 | 1.071565 | 0.4535451 | 1.023943 | 399.9525 | 100 | 50 | 100 | 0 | 100 |
| 3 | 0.8803904 | 0.8233328 | 1.064028 | 1.042998 | 0.3748539 | 1.013338 | 400.0177 | 100 | 70 | 100 | 0 | 100 |
| 4 | 0.8834442 | 0.8255175 | 1.054534 | 1.036303 | 0.3516430 | 1.013337 | 400.0908 | 100 | 90 | 100 | 0 | 100 |

*Table 3: Degraded Pump*

The graph below is a representation of the table, plotting the pressure against the valve opening simulating the failure mode. The pressure after the pump and at all other components rapidly declines as the valve opening is increased. The fault is noticed most at P3, the differential pressure P3-P2 decreases as the pump leakage increases.

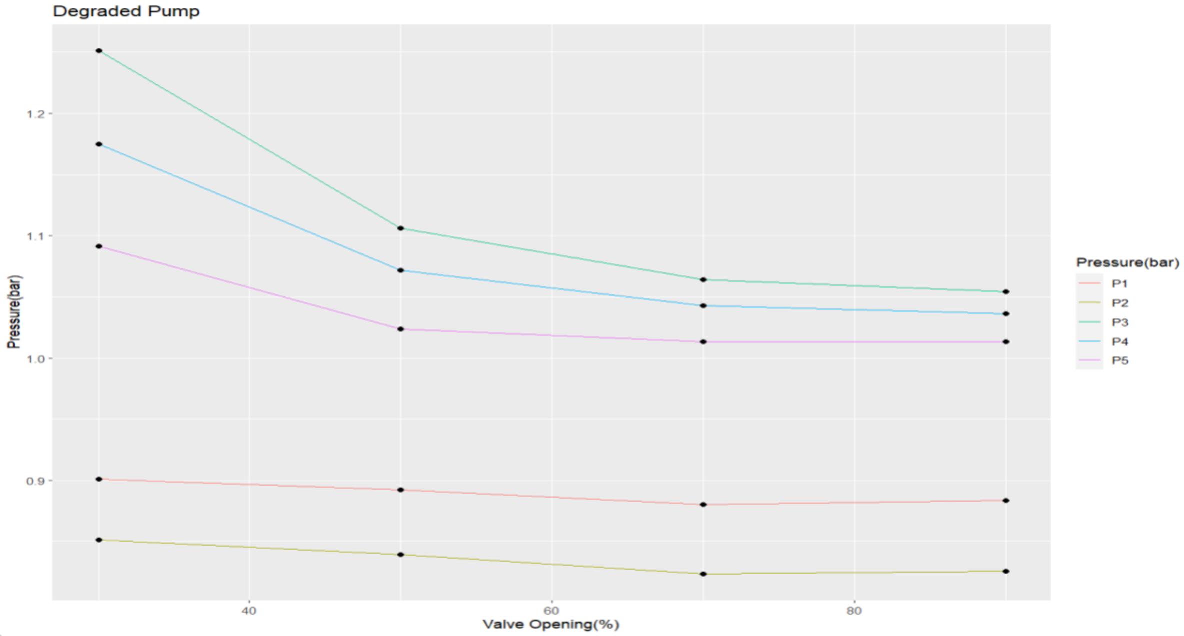
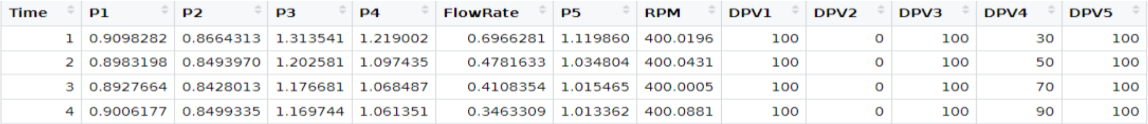


*Figure 7: Degraded Pump*

It can also be noticed on the graph, that as the severity increases, the testbed recovers its flow rate and pressure, this is due to the fluid dynamics, which restores the equilibrium of the testbed. This can also be noticed in P5, where the pressure tends to become the same at 70% and 90% severity.

## 4.3 Leaking Pipe

The leaking pipe failure mode is like the degraded pump, as they both represent pipe leakages, however, the leaking pipe is further away from the pump outlet. The severity of the pipe is emulated with DPV4, with the valve opening increasing from 30% to 90% for a fully leaking pipe. Table 3 shows the flow rate rapidly declining as the DPV fully opens.



| Time | P1 | P2 | P3 | P4 | FlowRate | P5 | RPM | DPV1 | DPV2 | DPV3 | DPV4 | DPV5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.9098282 | 0.8664313 | 1.313541 | 1.219002 | 0.6966281 | 1.119860 | 400.0196 | 100 | 0 | 100 | 30 | 100 |
| 2 | 0.8983198 | 0.8493970 | 1.202581 | 1.097435 | 0.4781633 | 1.034804 | 400.0431 | 100 | 0 | 100 | 50 | 100 |
| 3 | 0.8927664 | 0.8428013 | 1.176681 | 1.068487 | 0.4108354 | 1.015465 | 400.0005 | 100 | 0 | 100 | 70 | 100 |
| 4 | 0.9006177 | 0.8499335 | 1.169744 | 1.061351 | 0.3463309 | 1.013362 | 400.0881 | 100 | 0 | 100 | 90 | 100 |

*Table 4: Leaking Pipe*

As earlier stated, the degraded pump and leaking pipe both have some similarities, in the case of the degraded pump, the flow rate and pressure drop earlier as it is near the point of great pressure, compared to the leaking pipe which is farther away from the pump. The testbed fully recovers its pressure in the leaking pipe scenario, this is also due to its distance away from the pump.

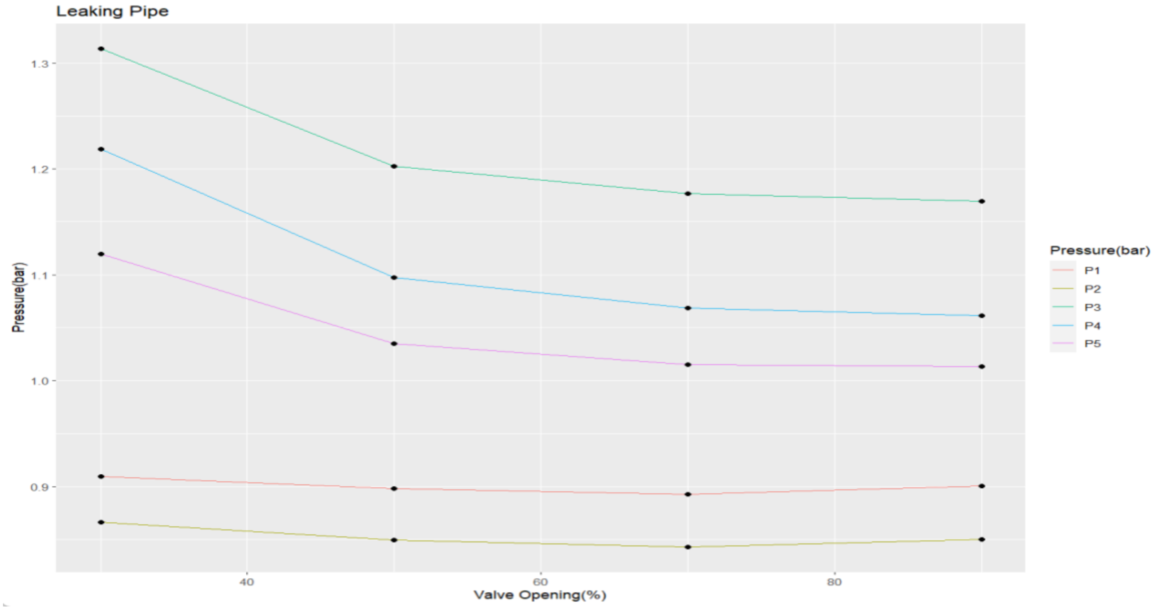
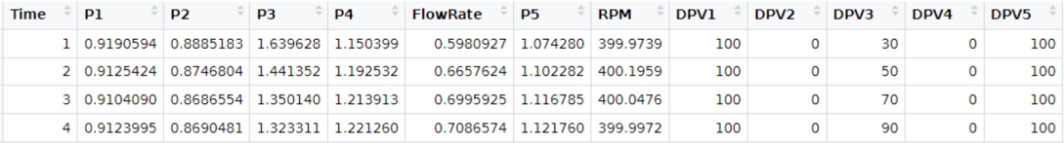


*Figure 8: Leaking Pipe*

To note the fault in the testbed is coming from either the pump or a leaking pipe, a drop in pressure and flow rate is the signature to look out for. As can be noted in the graph, the pressure before the pump, P1 and P2 do not suffer great pressure drop, compared to the pressure after the pump and at other components, as in P4 and P5.

## 4.4 Stuck Valve

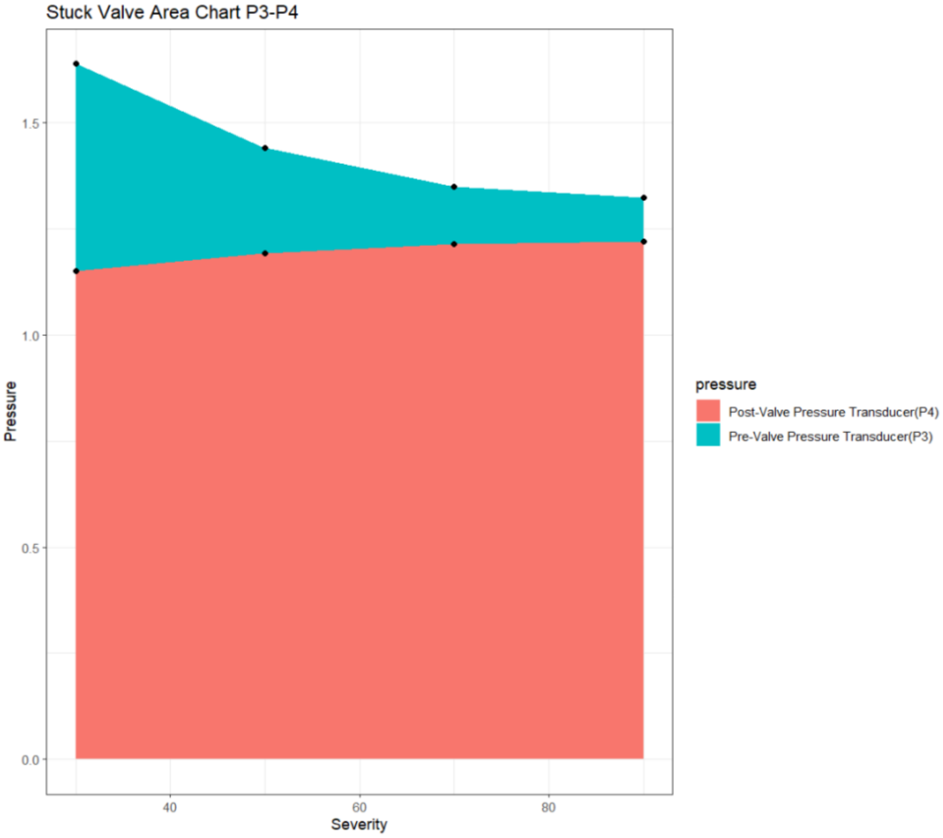
The failure mode, stuck valve is one of the failure modes that showcase a blockage after the pump. The DPV3 is initially open at 100% to show no fault and gradually closed till 30%, which initiates a blockage of the valve. The flow rate steadily declines as the valve gets blocked and stuck. There is a build-up of pressure after the pump, as the liquid has no way to go. The pressure after the valve increases as DPV3 gradually opens, the effect of the valve opening is also noticed in the pressure after the nozzle.



| Time | P1 | P2 | P3 | P4 | FlowRate | P5 | RPM | DPV1 | DPV2 | DPV3 | DPV4 | DPV5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.9190594 | 0.8885183 | 1.639628 | 1.150399 | 0.5980927 | 1.074280 | 399.9739 | 100 | 0 | 30 | 0 | 100 |
| 2 | 0.9125424 | 0.8746804 | 1.441352 | 1.192532 | 0.6657624 | 1.102282 | 400.1959 | 100 | 0 | 50 | 0 | 100 |
| 3 | 0.9104090 | 0.8686554 | 1.350140 | 1.213913 | 0.6995925 | 1.116785 | 400.0476 | 100 | 0 | 70 | 0 | 100 |
| 4 | 0.9123995 | 0.8690481 | 1.323311 | 1.221260 | 0.7086574 | 1.121760 | 399.9972 | 100 | 0 | 90 | 0 | 100 |

*Table 5: Stuck Valve*

In the graph below of the pressure against the valve opening, the build-up of pressure after the pump is quite noticeable, this is because the liquid has no way to go. The pressure before the pump is in no way affected, as the filter has no blockage. The differential pressure at the pump, P3-P2, is ever increasing as the valve gets blocked. This is due to the pump working extra hard trying to get the liquid through it, as the liquid gets pushed back. If the pump was working at a different RPM, the differential pressure will be much higher, as Newton's law states "for every action, there is an opposite reaction".



The area chart shows the pressure level before and after the valve at different levels of severity.

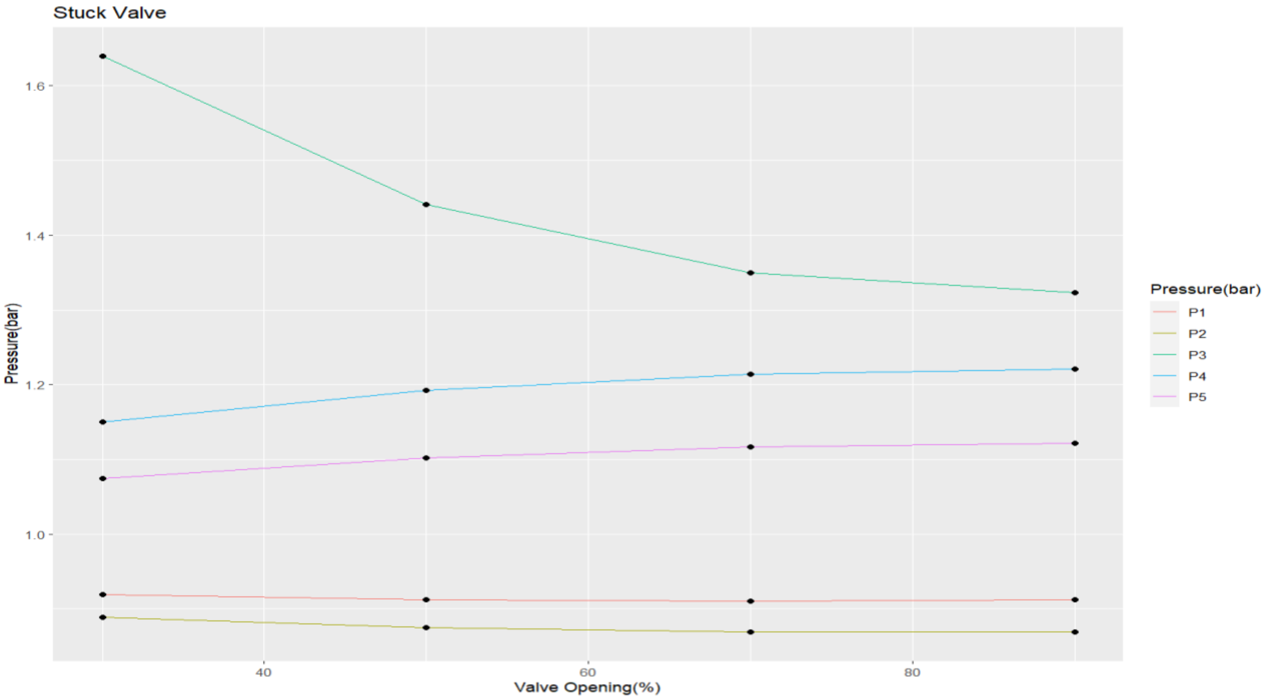
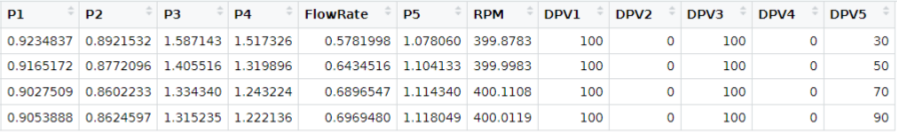


*Figure 9: Stuck Valve Pressure against Valve Opening*

To detect the fault at this component, the change from healthy conditions should be noted and the pressure before the pump, as the change is little.

## 4.5 Clogged Nozzle

The clogged nozzle is another failure mode that features a blockage downstream of the pump. The nozzle is fully open at 100% and severity of the nozzle increases as it closes to 30%. The flow rate increases as DPV5 opens fully at 100%, also the pressure after the nozzle increases.



| P1 | P2 | P3 | P4 | FlowRate | P5 | RPM | DPV1 | DPV2 | DPV3 | DPV4 | DPV5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.9234837 | 0.8921532 | 1.587143 | 1.517326 | 0.5781998 | 1.078060 | 399.8783 | 100 | 0 | 100 | 0 | 30 |
| 0.9165172 | 0.8772096 | 1.405516 | 1.319896 | 0.6434516 | 1.104133 | 399.9983 | 100 | 0 | 100 | 0 | 50 |
| 0.9027509 | 0.8602233 | 1.334340 | 1.243224 | 0.6896547 | 1.114340 | 400.1108 | 100 | 0 | 100 | 0 | 70 |
| 0.9053888 | 0.8624597 | 1.315235 | 1.222136 | 0.6969480 | 1.118049 | 400.0119 | 100 | 0 | 100 | 0 | 90 |

*Table 6: Clogged Nozzle*

The pressure after the valve decreases as the nozzle goes from a state of high severity to low severity, as the nozzle opens to relieve the build-up of pressure after the valve. The pressure after the pump is also high as the nozzle gets blocked.

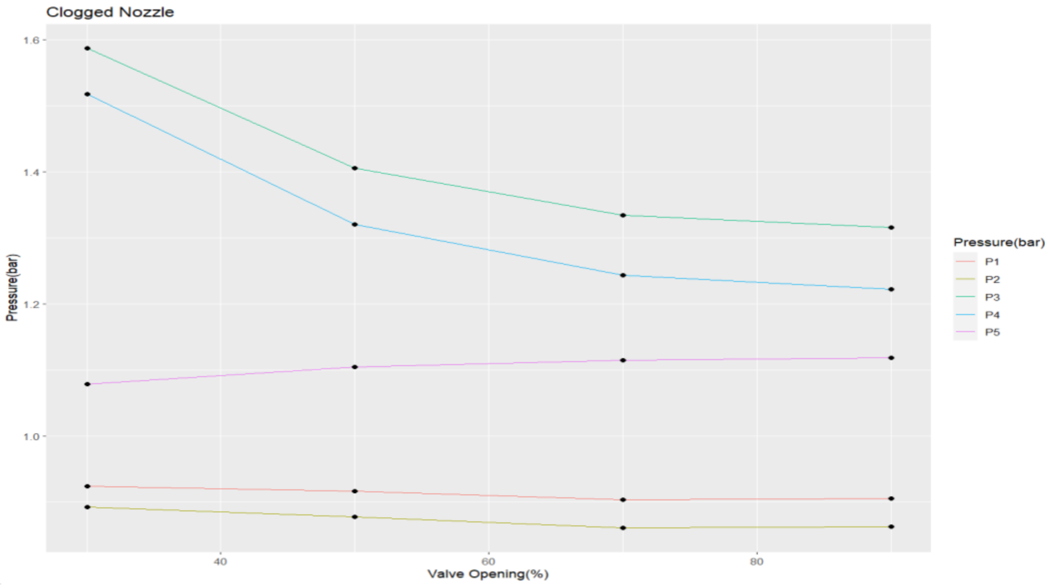
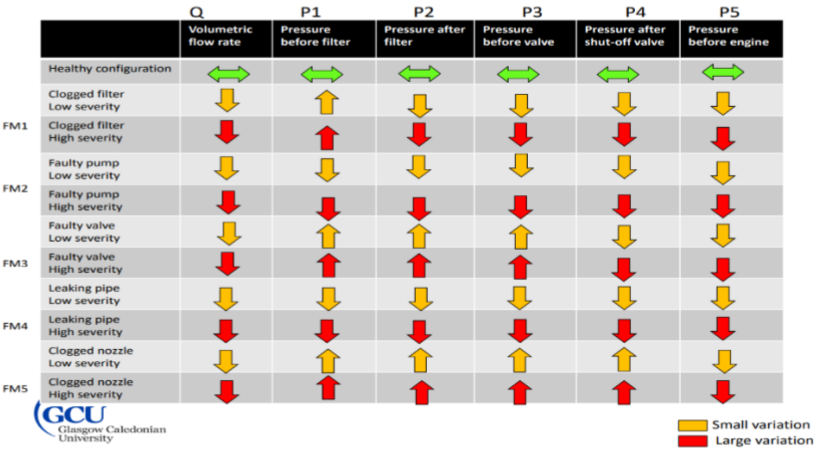


*Figure 10: Chart of Nozzle Pressure against Valve Opening*

The chart is much like that of the stuck valve, except for the pressure after the valve, which takes the same shape as the pressure after the pump. The fault detection is similar as well, only in this case the deviation of the pressure after the valve from the healthy conditions should also be noted.

## 4.6 Diagnostic Trees

To diagnose the exact location of the fault in the fuel supply testbed, a diagnostic tree is very important. The table below shows exactly how each pressure sensor located in the testbed behaves in relation to each failure mode. When the system starts to underperform, it is best to be able to pinpoint exactly where the deterioration is. A diagnostic tree is a type of decision tree that is used to move from one branch to another to diagnose a problem (Young, 2019).



| | | Q<br>Volumetric flow rate | P1<br>Pressure before filter | P2<br>Pressure after filter | P3<br>Pressure before valve | P4<br>Pressure after shut-off valve | P5<br>Pressure before engine |
|---|---|---|---|---|---|---|---|
| | Healthy configuration | ↔ | ↔ | ↔ | ↔ | ↔ | ↔ |
| FM1 | Clogged filter<br>Low severity | 🟧↓ | 🟧↑ | 🟧↓ | 🟧↓ | 🟧↓ | 🟧↓ |
| | Clogged filter<br>High severity | 🟥↓ | 🟥↑ | 🟥↓ | 🟥↓ | 🟥↓ | 🟥↓ |
| FM2 | Faulty pump<br>Low severity | 🟧↓ | 🟧↓ | 🟧↓ | 🟧↓ | 🟧↓ | 🟧↓ |
| | Faulty pump<br>High severity | 🟥↓ | 🟥↓ | 🟥↓ | 🟥↓ | 🟥↓ | 🟥↓ |
| FM3 | Faulty valve<br>Low severity | 🟧↓ | 🟧↑ | 🟧↑ | 🟧↑ | 🟧↓ | 🟧↓ |
| | Faulty valve<br>High severity | 🟥↓ | 🟥↑ | 🟥↑ | 🟥↑ | 🟥↓ | 🟥↓ |
| FM4 | Leaking pipe<br>Low severity | 🟧↓ | 🟧↓ | 🟧↓ | 🟧↓ | 🟧↓ | 🟧↓ |
| | Leaking pipe<br>High severity | 🟥↓ | 🟥↓ | 🟥↓ | 🟥↓ | 🟥↓ | 🟥↓ |
| FM5 | Clogged nozzle<br>Low severity | 🟧↓ | 🟧↑ | 🟧↑ | 🟧↑ | 🟧↑ | 🟧↓ |
| | Clogged nozzle<br>High severity | 🟥↓ | 🟥↑ | 🟥↑ | 🟥↑ | 🟥↑ | 🟥↓ |

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🟧 Small variation
🟥 Large variation

*Table 7: Failure Mode Effects and Criticality Analysis Table*

The failure mode effects, and criticality analysis (FMECA) table above will serve as a guideline for the diagnostic tree. FMECA is a technique that identifies potential failures in systems and equipment, the effects of each failure modes on the system are noted and the critical nature of the failure (*What Is FMECA_ Definition & Examples _ Fiix.* ).

If pressure 1 is high, check the filter, valve, and nozzle, if pressure 2 is up, check the valve and nozzle, however, if P2 is down, the fault is at the filter. If pressure 3 is down, the fault is at the valve and if pressure 4 is down, the fault is at the nozzle.

If pressure 1 is down, check the pump and pipe, if pressure 3 is less than 1.2 bar, the fault is at the pump.

If pressure 3 is up, check the valve and nozzle. If pressure 4 is down, the fault is at the valve, otherwise, the fault is at the nozzle. If pressure 3 is down, check the filter, pump, and pipe. If pressure 3 is less than 1.2 bar and greater than 1.15 bar, the fault is at the filter. However, if the pressure is less than 1.15 bar and greater than 1.1 bar, the fault is at the pump.

With FMECA and diagnostic trees, we can accurately and quickly pinpoint where the fault is located in the system.

# Chapter 5

## 5.0 Contextualization of Pump Test Data and Surface Model Construction

The Oberdorfer N999R external gear pump is the brain of the testbed, it drives it, a model is to be created, with the contextualization of the test data and construction of a surface model. The pump's performance under healthy conditions is key to achieving this. Two datasets are collected, one from initial campaign and another from the final campaign. A model was created using MATLAB/Simulink, with data generated from the last campaign. This model was used to predict the flow rate of the pump and compared with the measured flow rate values. This is key to determining how the model can be improved to build a digital of the pump.

### 5.1 The Pump Dataset

Oberdorfer presented a performance curve of the pump in the datasheet, however, it was tested at only 1140rpm and 1750rpm, making it insufficient to model the pump for a digital twin, as the pump will be used at different pump speeds.

A better understanding of the pump under different loads is needed, to establish the relationship between the speed and the load it carries, with the flow rate as the result. Two test campaigns were carried out at different speeds, between 400rpm-1140rpm. The initial campaign was carried out under healthy conditions, same as the last campaign, which was carried out at 400rpm-1140rpm and 700rpm-950rpm respectively.

### 5.1.1 Initial Campaign

The initial campaign was conducted at pump speeds of 400rpm to 1140rpm under healthy conditions, in a bid to understand the relationship between the flow rate in l/min and the differential pressure. This data was visualized using Matlab.

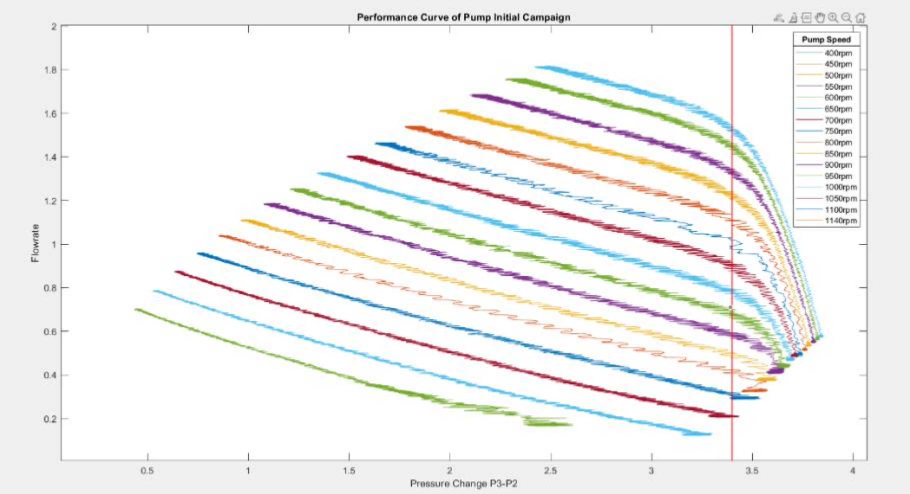


*Figure 11: Performance Curve of Pump Test Initial Campaign*

The graph shows the degradation of the pump at different pump speeds, with the flow rate serving as an indicator. The deterioration indicator starts at just before a differential pressure of 3.5, which indicates that the pump is working harder than normal to transport its load. It should be noted that the pump is equipped with a relief valve, that is calibrated at 3.4 bar, the valve gradually opens when the pump pressure exceeds 3.4 bar, to release more liquid from the outlet to the inlet. This is due to a blockage at the upstream of the pump, this will lead to a systematic failure of other components in the testbed, such as a leak in the pipes, sticking of the valve, and clogging of the nozzle. It is of absolute importance to ensure there are no blockages upstream, to avoid a breakdown downstream.

### 5.1.2 Final Campaign

The final campaign involves a chart of the pump flow rate against the differential pressure for pump speeds ranging from 700rpm to 950rpm. The aim is to compare any change in the pump performance when compared to the initial campaign.

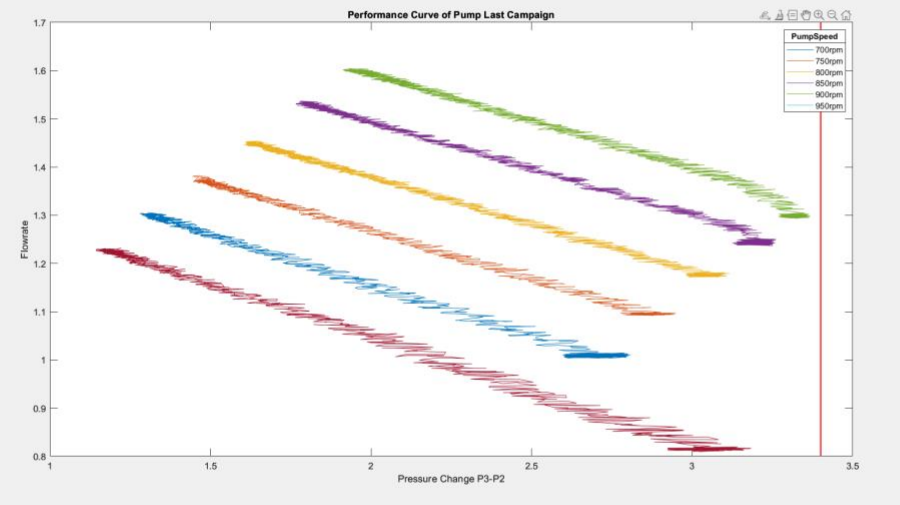


*Figure 12: Final Campaign of the Pump Performance Curve*

The flow rate and differential pressure are inversely proportional, as the flow rate rises, the differential pressure drops. However, the flow rate and pump speed are directly proportional. To avoid a possible breakdown of the pump, operating at the range mapped in the final campaign, appears to be ideal.

## 5.2 Development of the Pump Model

The data collected from the final campaign is used to construct the pump model on MATLAB/Simulink. The behaviour and performance of the pump is adequately represented at different severity by the model.

The foundation of the model is in a 3-D surface map  created using the curve fitter application in MATLAB. The map comprises of a residual plot and a fit plot. Error patterns that point out poor model fitting are shown on the residual plot, while the fit plot does as the name suggest, how the model will perform in visually fitting the data. Subsequently the map is exported to Simulink, which creates a model with the ability to print the flow rate in the signal block, after the two constants, pump speed and differential pressure are varied in the input block.

### 5.2.1 Surface Map

#### i. Initial Campaign:

The map below gives an in-depth view of the 2-D graph created under 5.1.1, there is a steepness noticed as the pump speed goes over 750rpm and the differential pressure is at 3.4 bar. As earlier stated, the relief valve starts operating at this pressure, as more liquid flows from the outlet to the inlet of the pump.

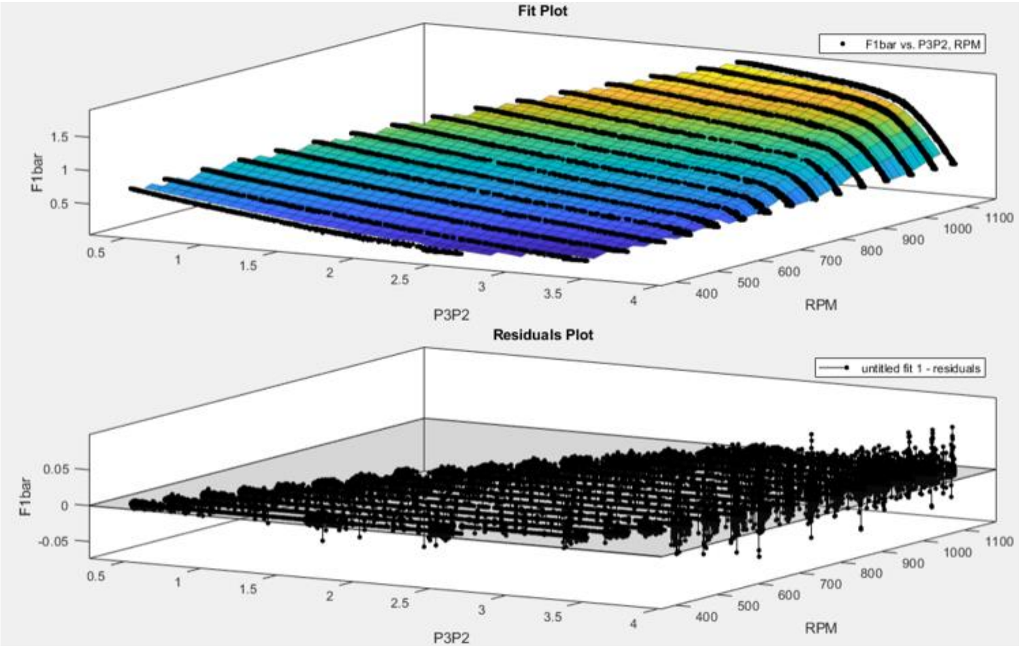


*Figure 13: The Initial Campaign Surface Map*

#### ii. Final Campaign:

Just like the initial campaign, this is a clearer picture of figure 12, a dip is noticed at 950rpm, just as the differential pressure slightly surpasses 3bar. This is well within the optimal operating conditions of the pump, as can be noticed in the flow rate of 1.6 l/min.

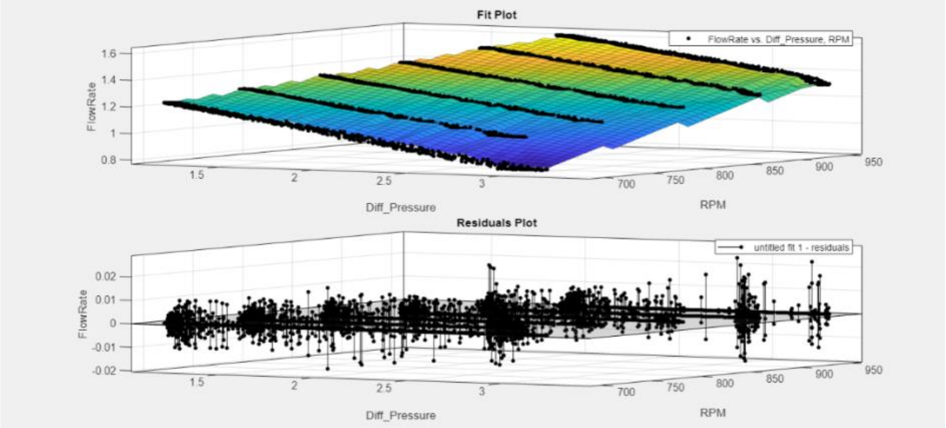


*Figure 14: Surface Map of the Final Campaign*

### 5.2.2 Pump Model Verification

The surface map created with the curve fitter application, was used to build the model by importing into Simulink. However, before it can be used, we must ensure the model works, the accuracy of the model is checked against real-world events and the discrepancy percentage is checked.

The decision to use the final campaign is down to several reasons, one of the main reasons is the low sum of square errors when compared to the initial campaign. The initial campaign has a value of 0.79% which is considerably high when compared to the final campaign of 0.05%. A low sum of square error means the final campaign can accurately predict the flow rate based on the input values of the pump speed and the differential pressure. This makes it more reliable to deploy as a model than the initial campaign.

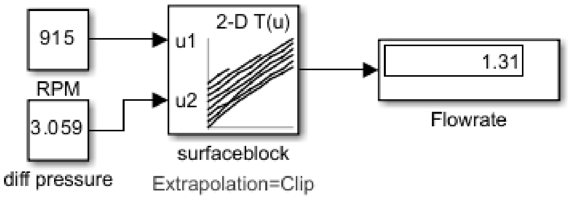


*Figure 15: The Simulink Model*

The table below shows the lookup table automatically generated by the model, BP1 represents the pump speed and BP2 represents the differential pressure. The corresponding predicted flow rate is shown in the table.

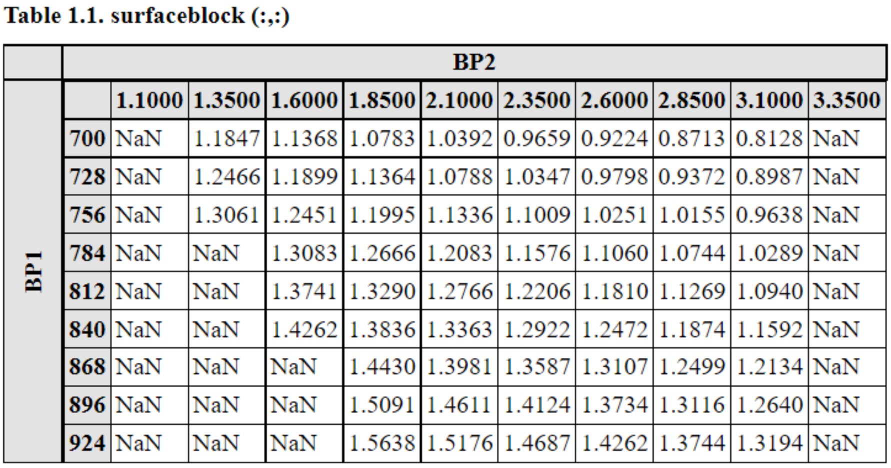


**Table 1.1. surfaceblock (:,:)**

| | BP2 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **BP1** | **1.1000** | **1.3500** | **1.6000** | **1.8500** | **2.1000** | **2.3500** | **2.6000** | **2.8500** | **3.1000** | **3.3500** |
| **700** | NaN | 1.1847 | 1.1368 | 1.0783 | 1.0392 | 0.9659 | 0.9224 | 0.8713 | 0.8128 | NaN |
| **728** | NaN | 1.2466 | 1.1899 | 1.1364 | 1.0788 | 1.0347 | 0.9798 | 0.9372 | 0.8987 | NaN |
| **756** | NaN | 1.3061 | 1.2451 | 1.1995 | 1.1336 | 1.1009 | 1.0251 | 1.0155 | 0.9638 | NaN |
| **784** | NaN | NaN | 1.3083 | 1.2666 | 1.2083 | 1.1576 | 1.1060 | 1.0744 | 1.0289 | NaN |
| **812** | NaN | NaN | 1.3741 | 1.3290 | 1.2766 | 1.2206 | 1.1810 | 1.1269 | 1.0940 | NaN |
| **840** | NaN | NaN | 1.4262 | 1.3836 | 1.3363 | 1.2922 | 1.2472 | 1.1874 | 1.1592 | NaN |
| **868** | NaN | NaN | NaN | 1.4430 | 1.3981 | 1.3587 | 1.3107 | 1.2499 | 1.2134 | NaN |
| **896** | NaN | NaN | NaN | 1.5091 | 1.4611 | 1.4124 | 1.3734 | 1.3116 | 1.2640 | NaN |
| **924** | NaN | NaN | NaN | 1.5638 | 1.5176 | 1.4687 | 1.4262 | 1.3744 | 1.3194 | NaN |

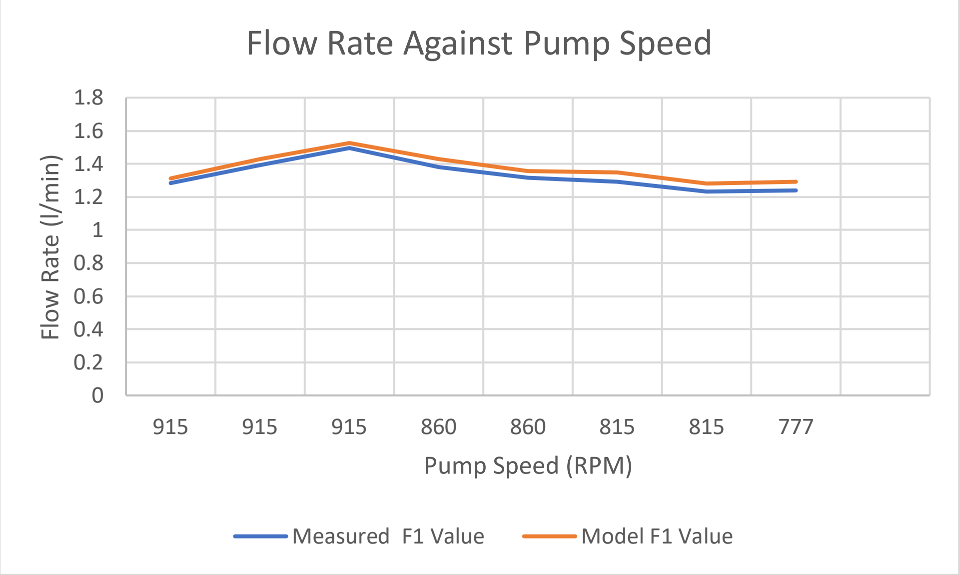
*Table 8: Pump Model Lookup Table*

The table below is the result of the validation test conducted, by manually inputting different pump speeds and differential pressures. The resulting model flow rate value is compared to the measured flow rate value.

| DPV3 Opening% | DPV4 Opening % | Pump Speed (RPM) | Diff Pressure | Measured F1 Value | Model F1 Value | Discrepancy (%) |
|---|---|---|---|---|---|---|
| 40% | 40% | 915 | 3.059 | 1.2824 | 1.31 | 2.152214598 |
| 55% | 55% | 915 | 2.481 | 1.394 | 1.429 | 2.510760402 |
| 80% | 80% | 915 | 1.959 | 1.4956 | 1.526 | 2.032629045 |
| 60% | 100% | 860 | 1.837 | 1.3824 | 1.428 | 3.298611111 |
| 40% | 100% | 860 | 2.236 | 1.314 | 1.358 | 3.348554033 |
| 100% | 55% | 815 | 1.775 | 1.2932 | 1.348 | 4.237550263 |
| 100% | 40% | 815 | 2.108 | 1.2324 | 1.281 | 3.94352483 |
| 55% | 100% | 777 | 1.605 | 1.2384 | 1.292 | 4.328165375 |

*Table 9: Pump Data Verification Table*

A comparison of the measured and model flow rate value is shown in the chart below. The percentage discrepancy ranges from 2.03% to 4.32% and an average percentage discrepancy of 3.23%. The accuracy of the model can be analysed with the chart, and areas needing improvement is visible. The discrepancy falls within an acceptable range.



# Chapter 6

# Development of A Digital Twin

## 5.0 Knowledge Gained from The Module

**Collection of Data:** To build a digital twin, the important thing is to first gather the data that will form an integral part of the virtual asset. Data telling the story about the healthy and faulty conditions of the fuel supply testbed was gathered at different operating conditions. The parameters captured in this initial phase are the pump speed, the flow rate, and pressure at the different components in the system. To ensure the virtual asset is reliable and accurately depicts the physical system, the data was collected and collated at different operating conditions, with the different DPVs, DPV1 to DPV5, modified to mimic different faulty conditions of the key components.

The data was logged and separated based on the different levels of severity and conducted at specific timeframes.

**Data Analysis and Visualization:** The data collated was very large and had to undergo different data preprocessing tactics for better visualization. The statistical approach undertaken was taking an average of the healthy conditions and the faulty conditions at the different levels of severity, which made for easier visualization of the conditions.

The healthy and faulty conditions were visualized using R. The trends and patterns were easily visible, and the data was not too crowded, giving a clearer picture of the different conditions. The change in the pressure and flow rate over the different severity was retained during the aggregation of the data and the visualization was clear to read.

## 5.1 What Is Required to Create a Digital Twin?

General Electric defines digital twin as a software representation of components, assets, systems, and processes that are used to understand, predict, and optimize performance to achieve improved performance.

1. An Accurate Virtual Representation: The fuel supply testbed should be accurately represented virtually. The healthy and faulty conditions should be accurately represented and implemented in the construction of the virtual system. The pressure change, flow rate and pump speed at different conditions within the system, should be accurately captured.
2. Data Collection and Analysis in real-time: Data from the fuel supply testbed should be gathered and analyzed in real-time, for an accurate examination and prediction of failure in the fuel supply testbed. The crucial aspects like pressure and flow rate must be adequately analyzed, based on the accurate implementation of the virtual system, which is a representation of the physical system. The healthy and faulty conditions must be recognized and differentiated from each other.
3. Fault Prediction and Simulation: Based on the data analyzed of the system, both the healthy and faulty conditions, the digital twin must be able to recognize different failure modes from the other. It must be able to simulate the different possible faults and accurately predict where the fault is coming from, to enhance the maintenance of the system.

4. Communication With the Physical System: A digital twin lives in the virtual world and for it to work optimally, it must be in constant communication with the physical system it represents. The use of different communication hardware and software, like cloud computing and edge gateway, using either LAN based, cellular or satellite communication protocols ensure the accuracy of the data received from the physical asset in real-time.
5. Able To Expand and Scale Up: the physical system is bound to be modified and updated during its lifespan, a digital twin should be capable of adapting and expanding as the physical system evolves with time. It should be able to handle increased data levels and integrate any new components added to the physical asset.

## 5.2 Developing the Digital Twin from the Digital Shadow

The purpose of this article is about to come to fruition. The fuel testbed was analysed with the aim of creating a digital twin from the digital shadow that has been designed so far in this article.

A digital shadow is one of the building blocks of a digital twin. The two models are closely related, however, the digital shadow collects data just like the digital twin, but feedback to the physical model is not produced, unlike the digital twin model. To produce a digital twin from the digital shadow, the evolution of the fuel supply testbed can be predicted by a hybrid data-driven and mechanistic approach (Bogdán, Tamás and Matyi, 2023).

The data garnered from the fuel testbed and the model subsequently created, sets the basis of a digital shadow which can be used to create the digital twin. The pump which is the engine that drives the testbed should be the focus of the digital twin, as a failure in the pump will lead to a total deterioration of the entire testbed. The previous chapter is focused on the characterization of the pump dataset, and the flow rate was predicted from the model created. A digital twin predicts how a physical system will act based on the data collected (Lopez *et al.,* 2020).

The knowledge gained on the fuel testbed, from the flow rate, pump speed, and differential pressure that culminated in the development of the model, can be used to develop a digital twin that accurately predicts the performance of the system and its behaviour under different operating conditions.

The historic data, real time operational data, maintenance history, and the FMECA along with the model created form the backbone of the digital twin of the fuel supply testbed. All the details are available in this report, except the maintenance history and real time operational data, and will help in creating the digital twin.

# References

Guo, R. *et al.* (2020) ‘Research on identification method of wear degradation of external gear pump based on flow field analysis’, *Sensors (Switzerland)*, 20(14), pp. 1–21. Available at: https://doi.org/10.3390/s20144058.

Hiltz, J. *et al.* (2002) *DIESEL ENGINE VALVE FAILURES*. Available at: https://www.researchgate.net/publication/275641222.

Komariah, L.N. *et al.* (2018) ‘Biodiesel effects on fuel filter; Assessment of clogging characteristics’, in *Journal of Physics: Conference Series*. Institute of Physics Publishing. Available at: https://doi.org/10.1088/1742-6596/1095/1/012017.

Korlapati, N.V.S. *et al.* (2022) ‘Review and analysis of pipeline leak detection methods’, *Journal of Pipeline Science and Engineering*. KeAi Communications Co. Available at: https://doi.org/10.1016/j.jpse.2022.100074.

Lambert, Martin Francis *et al.* (2001) *Leak detection in pipeline systems and networks: a review Acoustic methods for leak detection in water networks View project Water Distribution Networks Optimization View project LEAK DETECTION IN PIPELINE SYSTEMS AND NETWORKS: A REVIEW*. Available at: https://www.researchgate.net/publication/256103533.

Lamoureux, B., Massé, J.-R. and Mechbal, N. (no date) *An Approach to the Health Monitoring of a Pumping Unit in an Aircraft Engine Fuel System*.

Liu Haochen *et al.* (2021) ‘Machine Learning based clustering approach to diagnose multicomponent degradation of aircraft fuel systems’, *Neural Computing and Applications* , 35, pp. 2973–2989.

Skaf Zakwan, Eker Omer and Jennions Ian (2015) ‘Filter Clogging of a UAV Fuel System’, *Annual Conference of the Prognostics and Health Management*, pp. 334–342.

*What Is FMECA_ Definition & Examples _ Fiix.* Available at: https://www.fiixsoftware.com/glossary/fmeca/ (Accessed: 13/05/2023).

Bardakis, I., Niculita, O. and Wallace, P. (2020) 'Requirements and Data Integrity Considerations for Diagnostics Testbeds', *International journal of prognostics and health management*, 11(2). doi: 10.36001/ijphm.2020.v11i2.2927.

Bogdán, Z.R., Tamás, P.P. and Matyi, H.H. (2023) *Possibilities of using digital shadows in the procurement process of technological equipment* Advanced Logistic Systems, Theory and Practice.

Lopez, P.C., Udugama, I.A., Thomsen, S.T., Roslander, C., Junicke, H., Mauricio-Iglesias, M. and Gernaey, K.V. (2020) 'Towards a digital twin: a hybrid data-driven and mechanistic digital shadow to forecast the evolution of lignocellulosic fermentation', *Biofuels, bioproducts and biorefining,* 14(5), pp. 1046-1060. doi: 10.1002/bbb.2108.

Young, O.R. (2019) 'Constructing diagnostic trees: A stepwise approach to institutional design', *Earth System Governance,* 1, pp. 100002. doi: 10.1016/j.esg.2019.02.001.