Filter Clogging Data Collection for Prognostics

O. F. Eker[1], F. Camci[1], and I. K. Jennions[1]

[1] *IVHM Centre, Cranfield University, UK*

o.eker@cranfield.ac.uk
f.camci@cranfield.ac.uk
i.jennions@cranfield.ac.uk

ABSTRACT

Filtration is a critical process in many industrial systems to obtain the desired level of purification for liquids or gas. Air, fuel, and oil filters are the most common examples in industrial systems. Filter clogging is the main failure mode leading to filter replacement or undesired outcomes such as reduced performance and efficiency or cascading failures. For example, contaminants in fuel (e.g. rust particles, paint chips, dirt involved into fuel while tank is filling, tank moisture rust) may lead to performance reduction in the engine and rapid wear in the pump. Prognostics has potential to avoid cost and increase safety when applied to filters. One of the main challenges of prognostics is the lack of failure degradation data obtained from industrial systems. This paper presents the process of design and building of an experimental rig to obtain prognostics data for filter clogging mechanism and data obtained from the rig. Two types of filters have been used during the accelerated filter clogging and 23 run-to-failure data have been collected. Flow rate and pressure sensors are used for condition monitoring purposes. The filter clogging has been recorded through a camera to evaluate the findings with pressure and flow sensors. The data collected is very promising for development of prognostics methodologies.

1. INTRODUCTION

Filtration is basically described as a unit operation that is separation of suspended particles and fluid utilizing a medium where only the liquid can pass (Cheremisinoff, 1998). Filtration phenomenon is interest of several engineering processes including automotive, chemical, reactor, and process engineering applications. Besides, several industrial applications such as food, pharmaceuticals, metal production, and minerals embrace filtration process (Sparks, 2011).

Sharing an important role with pumps, fuel filters filtrate dirt, contaminants in the fuel system such as rust & dust particulate which has been released by holding tank, pipe work, paint chips, tank moisture, or other numerous type of dirt has been delivered via the supply tanker (Wilfong et al., 2010). Consequences like engine & pump performance reduction due to increased abrasion and inefficient burning in the engine are the main motivation for necessity of fuel filtration. System flow rate and engine performance decreases once a fuel filter is clogged where it doesn’t function well in its desired operation ranges. A picture of clogged and clean filter is shown in Figure 1. The difference in between clogged and clean mesh is visible. Fuel filters replaced & cleaned on a regular basis. Monitoring and implementation of prognostics have the potential to avoid costs and increase safety.

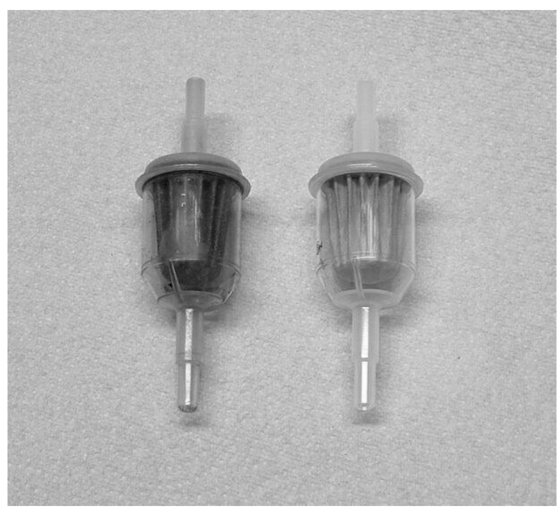

Figure 1. Clogged vs. clean filter (WikiHow, 2013)

The rest of the paper is organized as follows. Section two gives a brief literature review of prognostics in condition-based maintenance (CBM), and literature of physics-based modeling on filter clogging. Section three discusses in detail the filter clogging experimental scenario under accelerated aging conditions. The paper concludes with discussion of the results and future work.

2. LITERATURE REVIEW

Condition-based maintenance (CBM) is a predictive maintenance strategy, where the maintenance tasks are performed when the need arises. The necessity concept is determined by assessing and trending the health condition of the equipment (Camci and Chinnam, 2010; Eker et al., 2011). Although CBM minimizes the spare part costs, time spent on maintenance and system downtime; it has difficulties such as modeling failures or installing and using of monitoring equipment.

Diagnostics and prognostics are the two major disciplines of CBM. Diagnostics involves identifying degradation and current health status of asset as well as revealing their causes and locations which is relatively mature area compared to prognostics. It aims to stop and schedule a maintenance task for the system once an abnormality has been detected or let the system continue otherwise. In general, incipient failures follow a slow degradation path (Kwan et al., 2003). Detection of failure progression is more valuable compared to the detection of failure once it has reached to severe point. Furthermore, it is a prerequisite for prognostics (Xiong et al., 2008).

Prognostics is forecasting the systems or components future health level by trending the current health level up to failure status and predicting the remaining useful life (RUL). It is considered to be one of the most challenging and key enabling technology among the other phases of CBM (Zhang et al., 2006; Peng et al., 2010; Daigle and Goebel, 2010).

Several studies on modeling of filtration process and fuel system investigations have found in the literature. (Roussel et al., 2007) has experimentally explained the general clogging process as a function of; ratio of particle to mesh hole size (D), solid fraction (Ø), and the number of grains arriving at each mesh hole during one test (N_e). They conducted several clogging experiments and optimized the clogging parameters in their model. (Park, 2002) has investigated F-5F aircraft engine failure caused by erosion-corrosion of a fuel manifold. They claimed that engine failures are caused by sudden pressure drop due to particles (mostly steel and iron) from the welding beads of fuel manifold. Internal welding beads are corroded and metal particles spread out which makes the fuel pump failed. Results are obtained by using EDX analysis of related surfaces. A comprehensive investigation of UAV fuel systems has been conducted in IVHM Centre, Cranfield University, UK (Niculita et al., 2012; Niculita et al., 2013). Several failure scenarios including clogged filter and faulty gear pump has been investigated and mostly diagnostics based studies have been conducted. Direct Proportional Valves (DPV) that have the ability to mimic fuel filter blockage have been utilized to imitate the clogging filter scenario. Darcy's Law and Kozeny-Carman Equations are two commonly used formulations applied in in the field of fluid dynamics to model the pressure drop of a fluid flowing through a porous medium (Carman, 1997). (Sappok et al., 2010) worked on the effects of ash accumulation in diesel particulate filters (DPV). They presented the results of their detailed measurements with formulated lubricants, correlating ash properties to individual lubricant additives and their effects on filter pressure differentiation. (Pontikakis et al., 2001) developed a mathematical model for dynamic behavior of filtering process in ceramic foam filter. The model is able to estimate the filtration efficiency, accumulation of particle mass in the filter, and pressure drop throughout a filter.

3. FILTER CLOGGING EXPERIMENTAL RIG

This section discusses in detail the filter clogging experimental scenario under accelerated aging conditions. We study the effects of different pump speed and solid ratio. Accelerated degradation data collecting mechanism for prognostic purposes is discussed in this section.

3.1. Design & Installation

Filter clogging system was designed as cyclical in order to have continuous flow so that system flow continues till the filter has fully clogged. It's not necessary to add particles or water as shown in Figure **3** and Figure **4**. Figure **3** is the top down perspective view of the real test rig with the components tags.

A peristaltic pump was installed in the system to maintain the flow of the suspension prepared. The pump sucks the suspension with a desired flow rate and pumps it through the filter and letting the suspension pour into the tank back. Pressure sensors across the filter and a flow meter was installed in the system to measure the pressure difference and flow rate during the clogging.

A colorful (necessary for image processing), solid type of particles with a desired size range, having the features of; low water absorption level, closer to water density level, and water-insoluble, was determined to be the optimal way for the particle selection process. Polyetheretherketone (PEEK) particles have been selected among several other types of solids. The 450PF PEEK particle size distribution is shown in Figure 2. A stirrer was installed in order to sustain constant amount of particles flowing through the system. Stirrer was necessary since the PEEK particles sink after a while leaving the water clean due to the density difference.

Pressure and flow rate values are considered to be health indicators of filter degradation. Pressure difference across the filter is expected to increase and flow rate is expected to be decreased during a clogging process. A high quality macro lens camera was installed in the system and macro pictures of the filter were taken in every two seconds. A macro picture and zoomed view of a filter mesh is shown in Figure **5**.

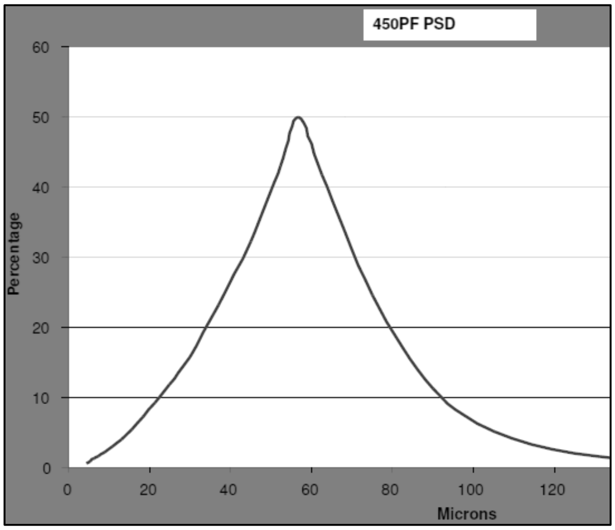

Figure 2. PEEK particle size distribution

The mesh inside the filter can clearly be captured and it can be utilized in image processing applications for clogging rate calculations which gives the ground truth information of clogging. Other sensory information can be compared with the clogging rate obtained from the macro pictures dataset.

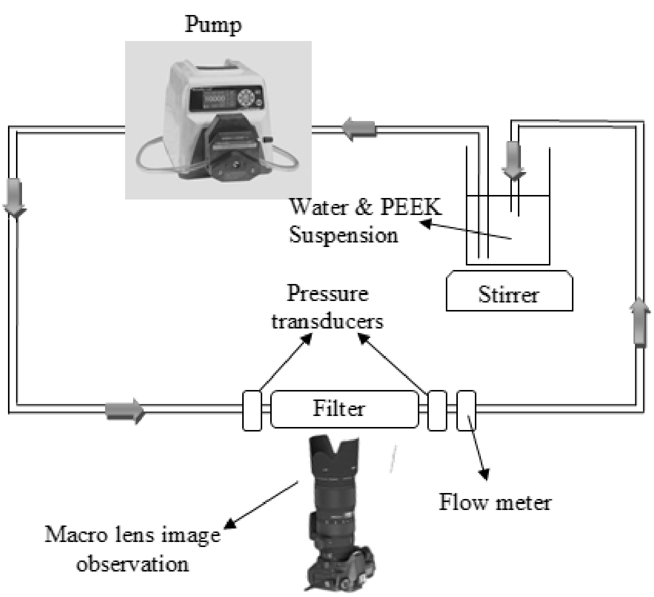

Figure 3. Filter clogging rig system design

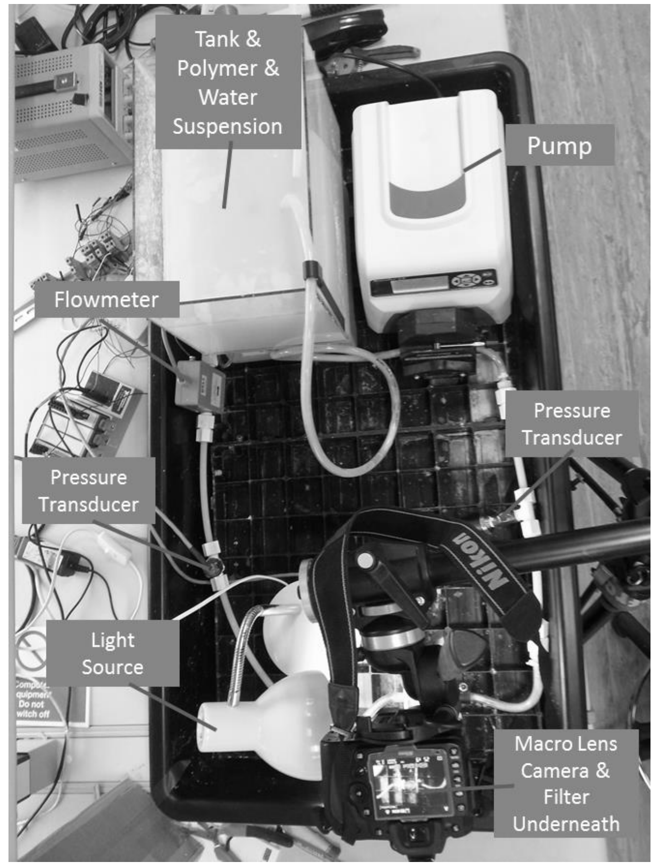

Figure 4. Filter clogging test rig & components

Components of the system were selected so that no other component will degrade other than the filter due to the solid particles inside the liquid. A peristaltic pump and magnetic flow meter were selected since they don’t get affected by the debris inside the liquid. Peristaltic pump compresses the flexible tube connected to the rotor in which the pump does not interconnect with the suspension. Similarly, magnetic flow meters don’t have moving parts inside where existences of particles are not harmful to the sensor at all. The system design shown in Figure 3 was selected among several other types of designs since it promises better solution for degradation process and requires less human labor.

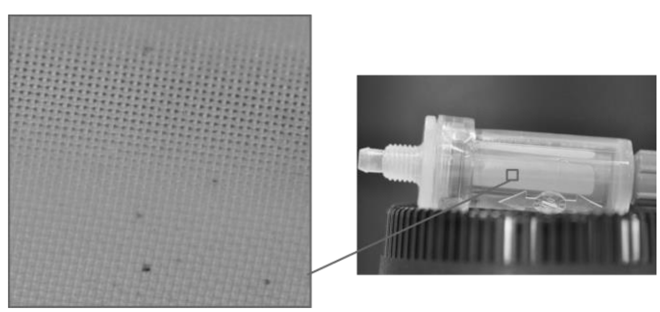

Figure 5. Zoomed capture of a filter mesh

125 micron pore sized car fuel filters have been selected to be used in the system as shown in Figure **6**. The ratio of filter pore size to the mean size of particles is higher than 1 which means the clogging process is stochastic since the majority of particles can flow through the mesh without being captured. Bridges are being formed and clogging is occurred when the considerable amount of particles approaches to each hole (Roussel et al., 2007).

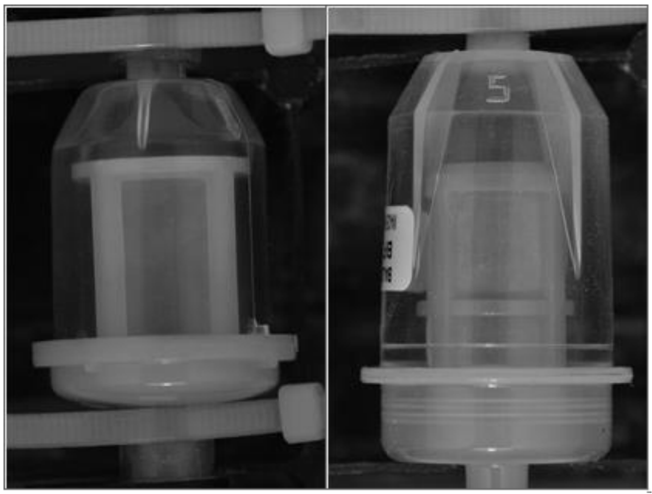

Figure 6. Filters type 1 and type 2

A box was designed to cover the filter area. The interior side of box was covered with a white colored material and a light source was directed inside the box to provide a constant uniform light so that the filter is isolated from varying environmental light.

3.2. Data Collection

This section provides the details of accelerated clogging experiments of two types of fuel filters.

125 micron pore sized two type of fuel filters have been utilized for clogging experiments in the lab environment and pressure and flow rate measurements have been collected. Details of the operating conditions are shown in Table 1. Maximum amount of particle capturing levels for the filters have been measured and the suspension solid ratio have been prepared considering these values. 10 and 12 run-to-failure experiments have been conducted for filters type 1 and type 2 respectively. Each clogging experiment has run and monitored till the pressure drop (e.g. Differential Pressure, ΔP) has reached to peak value and remains stable for a while as shown in Figure **7**.

Basically ΔP values calculated as subtracting the pressure values obtained from pressure sensor 1 (i.e. upstream pressure) from the pressure sensor 2 (i.e. downstream pressure) values. Upstream pressure and ΔP values show similar degradation profile since pressure values collected from pressure sensor 2 are quite low range compared to upstream pressure. Figure 7 plots show the raw measurements obtained from these three sensors. Upstream and downstream pressure values show linear degradation for the majority of lifetime and exponential degradation behaviors are seen after that as shown in plot 1 and plot 2, Figure **7**. Exponential degradation behavior of downstream pressure measurements can only be seen in the zoomed version (i.e. plot 2, Figure **7**). On the other hand, flow rate values remain same for a long period of time and show a dramatic drop at the end of experiments due to clogging.

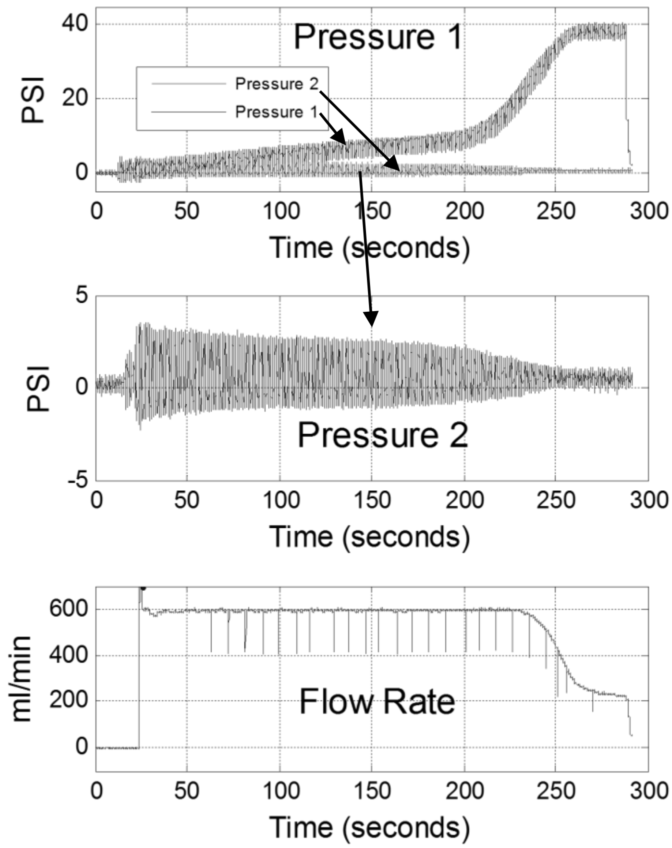

Figure 7. Raw sensor measurements

Macro lens camera was set to take pictures once in two seconds during each clogging test. Experiments were stopped due to prevent potential failures in the other components of the system. Examples of the pictures during the filter clogging are shown in Figure 10. Clogging of the filter can be seen clearly by examining the pictures. Image processing techniques will be implemented on these pictures to obtain the ground truth information regarding the filter clogging level. Accelerated aging experiments took around four minutes with the operating conditions mentioned in Table 1. At the end of experiments, flow rate values are dropped 57% and 48% in average for filters type1 and type2 respectively.

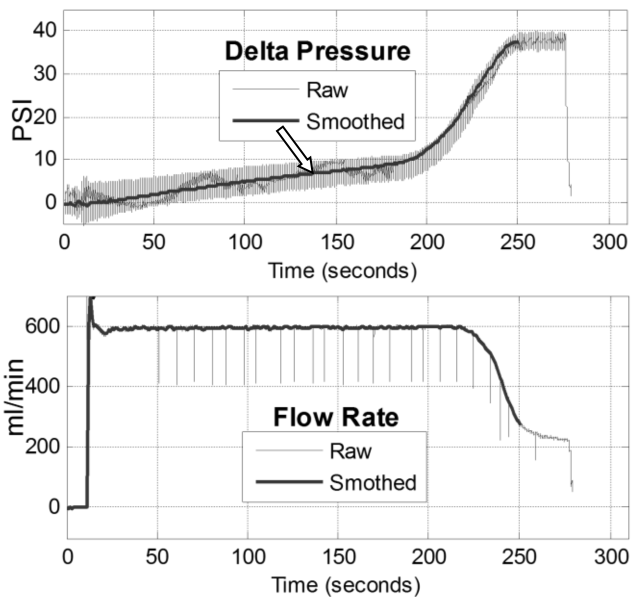

Figure 8. Filter type1 experiment 6 smoothed vs. raw data

Table 1. Operating conditions

Filter Type	Type 1	Type 2
Pore Size (micron)	125	125
Mean Particle Size (micron)	60	60
Max. amount of particles captured by the filter (g)	5.2	7.0
Total weight of particles in the tank (g)	26.0	21.0
Water Weight in the tank (g)	7507.9	7500
Solid Ratio (beginning)	0.35%	0.28%
Solid Ratio (end of clogging)	0.28%	0.19%
Solid Ratio change (max)	20%	33%
Flow Rate (RPM)	211	211

Smoothing has been performed on the raw dataset obtained from experiments. It has been done by taking the median values of each 100 data points since the raw data was collected with 100 Hz sample rate. Smoothed vs. raw data plot is shown in Figure 8 and Figure 9. Figure 9 depicts the zoomed two seconds (200 data points) of an experiment and corresponding two smoothed points. In addition, it shows the pressure peak reflections of the pump pulses.

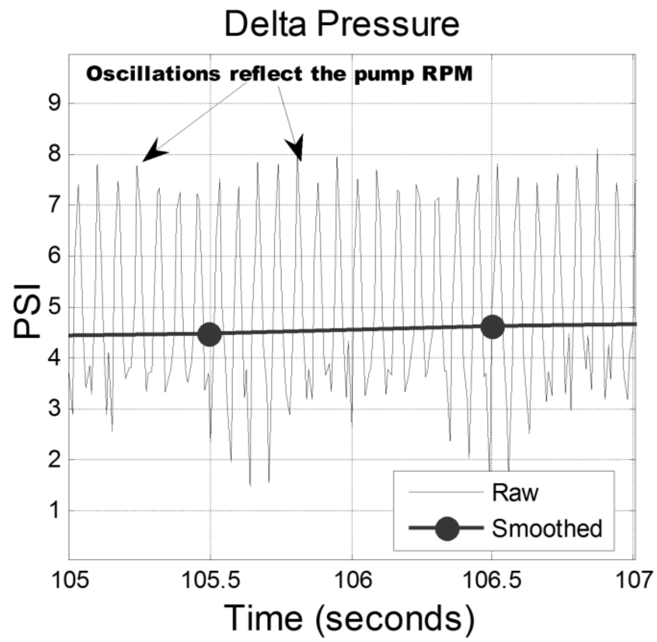

Figure 9. Zoomed pressure plot of a sample

Figure 11 and Figure 12 depict ΔP and flow rate measurements obtained from filter type one and two respectively.

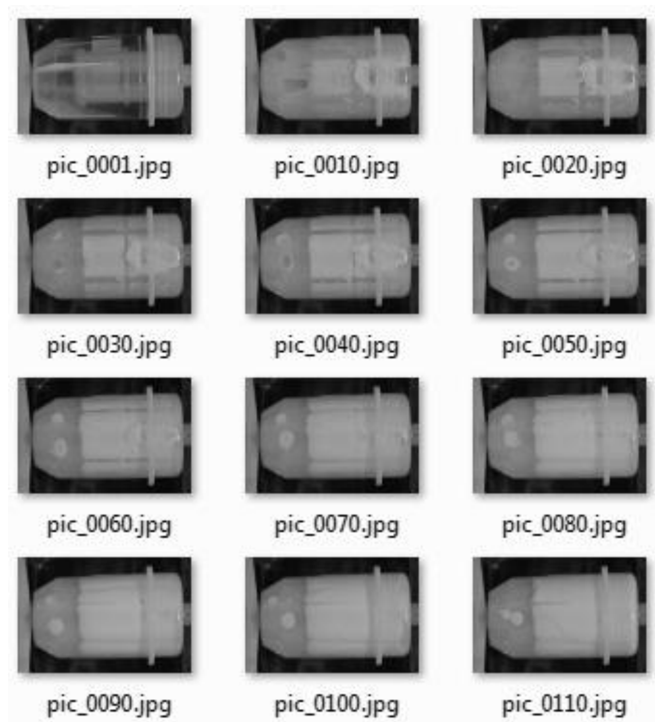

Figure 10. Filter pictures during an experiment

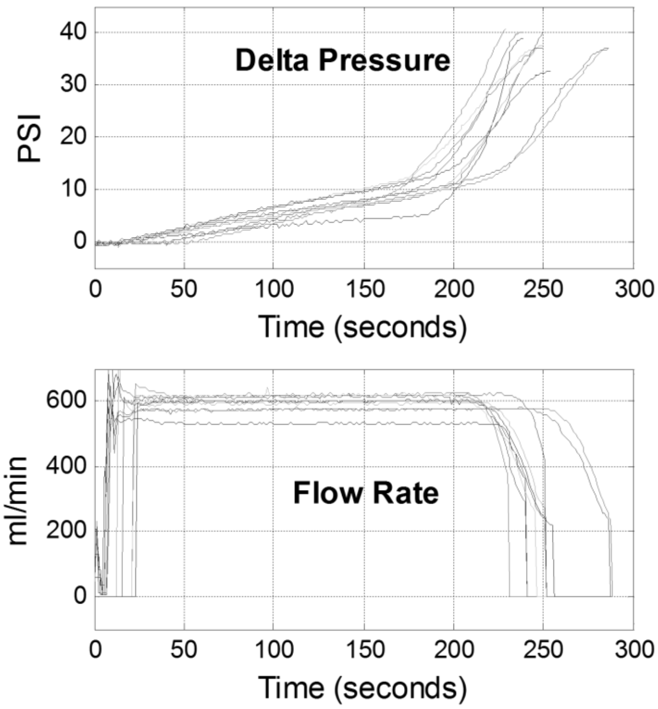

Figure 11. Filter type1 smoothed data

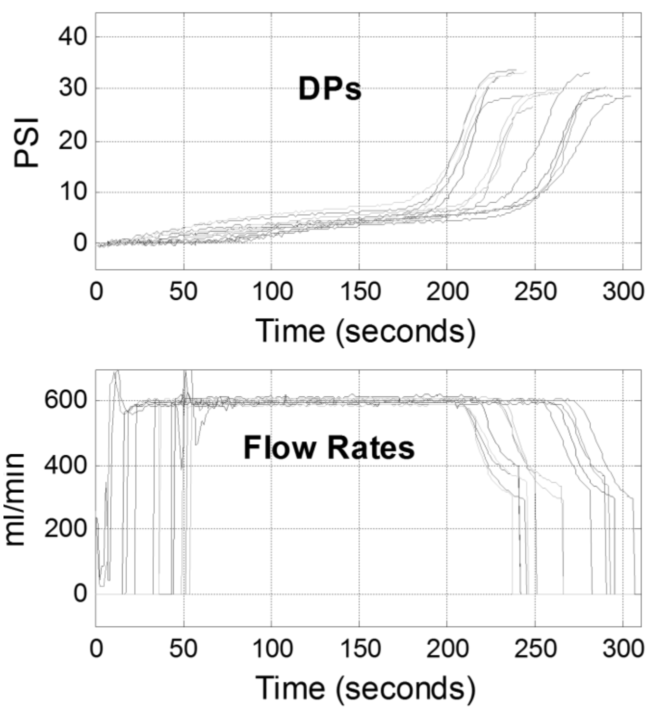

Figure 12. Filter type 2 smoothed data

3.3. Discussions Regarding the Data Collection & New Rig Design and Experiments

After analyzing the dataset we collected, it has been realized that the data collection can be improved more. Discussions about the dataset are summarized in Table 2.

Table 2. Dataset discussions & action table

Challenge	Action	Goal
Picture quality & light reflection problem	Covering the filter area with a chamber	Image processing improvements
Keeping the operating condition same	Several enhancements done listed below	Reproducibility
Change in solid ratio	Putting another tank in the system	Physics-based modelling enhancement
High variety in filter lifetimes (22% - 30%)	Some enhancements done listed below	• Reproducibility • Improvements in prognostic modelling
High oscillation amplitudes in pressure measurements	Putting dummy filters or chambers in the line before upstream pressure sensor	• Lowering oscillation amplitude
Vague clogging pictures	Testing of lower solid ratios	To see the degradation clearly on the macro pictures
Bubbles emerge in the filter	Filling all the system with a clean water prior to tests	• Avoiding the bubble effect on clogging of filter mesh • Reproducibility
Invisible flow movements	Using colourful liquid	To track the flow inside the filter during the clogging

Several other experiments have been conducted by taking into account of these concepts. First we have started changing the design of the test rig by putting another tank in the system. In the main tank we prepared the suspension with a lower solid ratio (i.e. 0.14%) in order to see the clogging process more clearly in the pictures and have longer lifetime for filters. Another tank was initially empty in the beginning of each test. End of tubing has been connected to other tank so that the solid ratio did not change during the experiment. Test rig design was cyclical for the previous experiments. End of tubing was connected to the same tank so solid ratio used to change during the experiment due to considerable amount of particles was being captured by the filter. In the new experiments, suspension was prepared with a specific solid ratio so that the main tank became almost empty at the end of each experiment ended up with a clogged filter. We utilized only filter type 2 since the mesh material quality and robustness is quite higher than the type 1 filter.

It has been seen that the length of soft tubing was affecting the life variety of experiments, particle capture rate, and also the pressure measurement oscillation amplitude. We didn't have chance to avoid using soft tubing since the peristaltic pump mechanism requires soft material in order to pump it by squeezing it. Hereupon we have made the length of soft tubing as short as possible and constant for each experiment and results got better and have become reproducible as shown in Figure 13. In that figure smoothed pressure and flow rate measurements of six different run-to-failure experiments are shown. And the lifetime variation in these experiments are reduced to 12% (variation was 25% in average before).

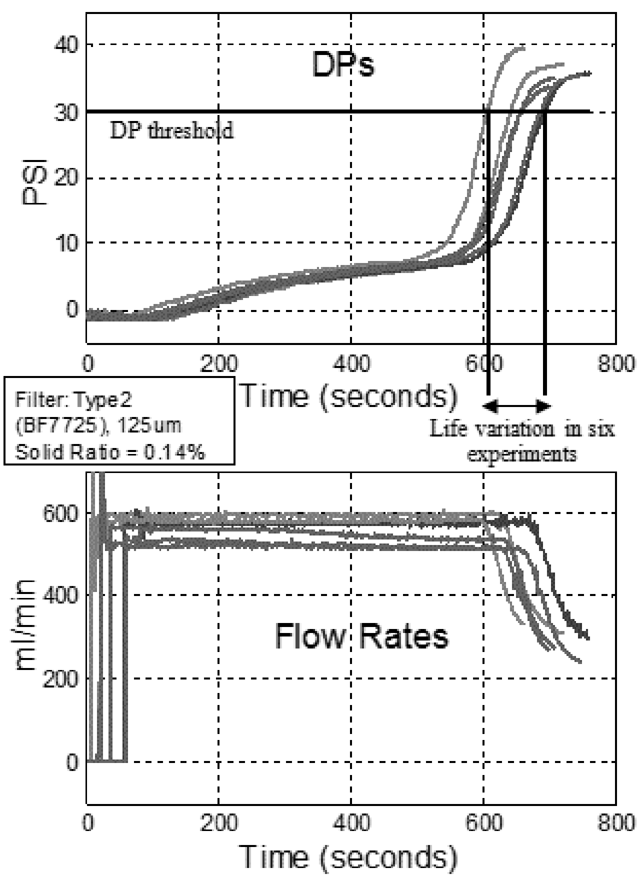

Figure 13. New experiments with constant solid ratio

After these experiments we have tried to reduce the fluctuation amplitude which would make problems in physics-based modeling and reproducibility concerns. In order to do that we installed dummy filters in the system just before the upstream pressure sensor. Basically a dummy filter is an empty chamber which helps to reduce the pump pulse effects. Addition of dummy filter in the line helped to decrease the fluctuation amplitudes in pressure measurements. Comparison of pressure values with or without dummy filter is shown in Figure 14. Pressure fluctuation due to the pump reduces dramatically with a dummy filter. Adding a second dummy doesn't change as the way the first one did. That amplitude (~2PSI) of fluctuation in pressure is similar to the flow created by the atmospheric pressure. We did an experiment with the atmospheric pressure, where the pump wasn't used. It gave the similar amplitude to the experiments done with one or two dummy filters.

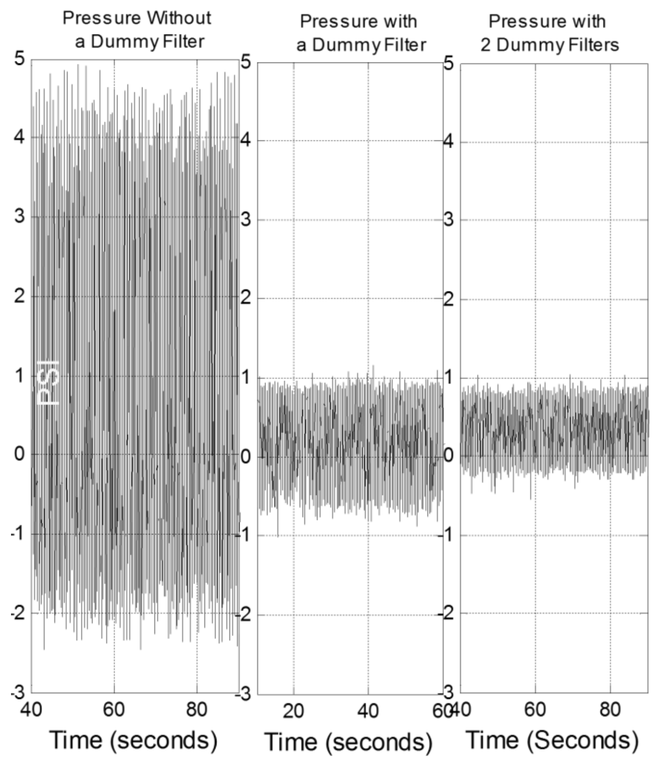

Figure 14. Dummy filter effect comparison

Finally we have tried to get rid of bubbles occur inside the filter. In order to do that, we filled all the system with clean water prior to the tests. We made sure that no air left in the system. Then we managed to get rid of bubbles. However fluctuations got back to the same level similar to the system without a dummy filter which means the dummy filter with full of water started reflecting the pressure pulses generated by the pump.

4. CONCLUSION & FUTURE WORK

This paper presents design & data collection process for filter clogging phenomenon to be used in prognostic application. Accelerated filter clogging experiments have been conducted. Pressure and flow rate signals have been collected during the experiments and macro pictures of filters have been taken too. The experiments were continued till each filter got clogged and considerable amount of reduction in the flow rate was monitored at the end of each clogging. Operating and environmental conditions are kept same. Two different types of fuel filters have been clogged using PEEK polymer particles & water suspension. Several enhancements have been done on data collection & design to improve the reproducibility and to help the physics-based modeling. Results show that the enhancement actions taken provide better reproducibility and an improved dataset. Accelerated filter clogging experiments are planned to be conducted with the latest operating conditions and test rig design. Data-driven, physics-based and hybrid modeling studies will be done on the final dataset to be collected.

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BIOGRAPHIES

Omer Faruk Eker is a PhD student in School of Applied Sciences and works as researcher at IVHM Centre, Cranfield University, UK. He received his B.Sc. degree in Mathematics from Marmara University and M.Sc. in Computer Engineering from Fatih University, Istanbul, Turkey. He got involved in a project funded by TUBITAK, and Turkish State Railways. His research interests include failure diagnostics and prognostics, condition based maintenance, pattern recognition and data mining.

Dr. Fatih Camci works as a faculty at IVHM Centre at Cranfield University since 2010. He has worked on many research projects related to Prognostics Health Management (PHM) in USA, Turkey, and UK. His PhD work was supported by National Science Foundation in USA and Ford Motor Company on development of novelty detection, diagnostics, and prognostics methods. He worked as senior researcher at Impact Technologies, world-leading SME on PHM, for two years. He has involved in many projects funded by US Navy and US Air Force Research Lab. These projects involve development of maintenance planning and logistics with PHM. He then worked as Asst. Prof. in Turkey. He has led a research project, funded by TUBITAK (The Scientific and Technological Research Council of Turkey) and Turkish State Railways, on development of prognostics and maintenance planning systems on railway switches. In addition to PHM, his research interest involves decision support systems and energy.

Ian Jennions Ian's career spans over 30 years, working mostly for a variety of gas turbine companies. He has a Mechanical Engineering degree and a PhD in CFD both from Imperial College, London. He has worked for Rolls-Royce (twice), General Electric and Alstom in a number of technical roles, gaining experience in aerodynamics, heat transfer, fluid systems, mechanical design, combustion, services and IVHM. He moved to Cranfield in July 2008 as Professor and Director of the newly formed IVHM Centre. The Centre is funded by a number of industrial companies, including Boeing, BAe Systems, Rolls-Royce, Thales, Meggitt, MOD and Alstom Transport. He has led the development and growth of the Centre, in research and education, over the last three years. The Centre offers a short course in IVHM and the world's first IVHM MSc, begun in 2011.

Ian is on the editorial Board for the International Journal of Condition Monitoring, a Director of the PHM Society, contributing member of the SAE IVHM Steering Group and HM-1 IVHM committee, a Fellow of IMechE, RAeS and ASME. He is the editor of the recent SAE book: IVHM – Perspectives on an Emerging Field.

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