Physics-Based Degradation Modelling for Filter Clogging

O. F. Eker[1], F. Camci[2], and I. K. Jennions[1]

[1] *IVHM Centre, Cranfield University, UK*
o.eker@cranfield.ac.uk
i.jennions@cranfield.ac.uk
[2] *Industrial Engineering, Antalya International University, Turkey*
fatih.camci@antalya.edu.tr

ABSTRACT

Separation of solids from fluid is a vital process to achieve the desired level of purification in industry. Contaminant filtration is a common process in a variety of applications in industry. Clogging of filter phenomena is the primary failure mode leading to replacement or cleansing of filter. Reduced performance and efficiency or cascading failures are the unfortunate outcomes of a clogged filter. For instance, solid contaminants in fuel may lead to performance reduction in the engine and rapid wear in the fuel pump. This paper presents the development of an experimental rig to collect accelerated filter clogging data and a physics-based degradation model to represent the filter clogging. In the experimental rig, pressure drop across the filter, flow rate, and filter mesh images are acquired during the accelerated clogging experiments. The pressure drop across the filter due to deposition of suspended solids in the liquid is modelled and employed in the degradation modelling. Then, the physics based degradation model simulated using MatLab is compared with the real clogging data and the effectiveness of the degradation model is evaluated.

1. INTRODUCTION

Filtration is basically described as a unit operation that is separation of suspended particles from fluid utilizing a filtering medium where only the fluid can pass (Cheremisinoff, 1998). Driving force for filtration is the pressure gradient generated across the filter. Solid-liquid filtration processes can be classified into three categories. These are: 1. deep-bed filtration, 2. cross-flow filtration, and 3. cake filtration. Deep-bed filtration can be done using depth-filters. Depth filters retain the particulate through the porous packed bed. Sand filters are the common examples of depth filtration. In cross-flow filtration mechanism, slurry flows parallel to the filter medium where only clean liquid can pass to the other side leaving the particulate inside the filter. In cake filtration, the solid particles in suspension flowing through the filter media are retained building up an increasing thicker cake as shown in Figure 1. From now onward in this paper, we discuss in detail the cake filtration.

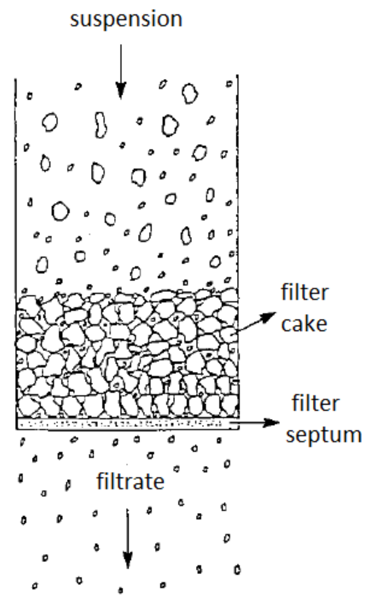

Figure 1. Schematic representation of cake build up on filter medium (Abboud and Corapcioglu, 1993)

Two types of cake filtration processes are common in the literature and industry. These are: 1. constant rate filtration, 2. constant pressure filtration. Figure 2 depicts the flow rate and pressure behaviors in each operating condition. Regime A represents constant rate filtration where fluid flow rate of the system remains constant. Pressure drop across the filter increases as the cake builds up. In most cases cake becomes compressed and more compact as the pressure increases, leading to higher cake resistance. Regime B represents constant pressure cake filtration where flow rate of the system declines as the cake builds up.

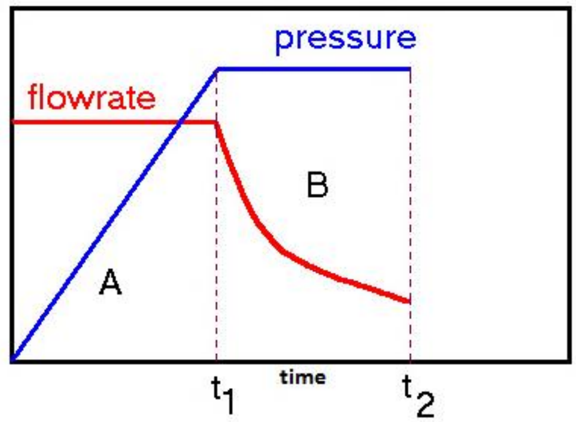

Figure 2. Constant rate vs. constant pressure filtration

Filtration phenomenon is interest of several engineering processes including automotive, chemical, reactor, and process engineering applications. Besides, several industrial applications such as food, petroleum, pharmaceuticals, metal production, and minerals embrace filtration process (Sparks, 2011).

The goal of the filtration systems is to keep the rest of the system running smoothly. Filtration systems play a vital role in maintaining the process operating. Filtration and separation equipment plays a big portion in production of transport equipment manufacturing with 15.5 percentage. Modern commercial vehicles and automobiles have numerous types of filters including fuel, lubricant, and intake air (Sutherland, 2010).

Sharing an important role with pumps, fuel filters filtrate dirt, contaminants in the fuel system such as paint chips, dust, or rust particulate which have been released from a fuel tank due to moisture, or other numerous type of dirt, have been delivered via supply tanker (Wilfong et al., 2010). Consequences like engine and pump performance degradation due to increased abrasion and inefficient burning in the engine are the main motivators for 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. In today's conditions, fuel filters are replaced or cleansed on a regular basis. Monitoring and implementation of prognostics have the potential to avoid costs and increase safety.

The rest of the paper is organized as follows. Section two provides a brief literature review of physics-based degradation modeling studies done on cake filtration processes. Section three discusses in detail the filter clogging experimental scenario under accelerated aging conditions. The methodology of clogging modelling is given in section four. Comparison of the simulation results with experimental data is discussed in section 5. The paper concludes with discussion of the results and future work.

2. LITERATURE REVIEW

Researches have been attracted to model the pressure drop and cake formation in cake filtration processes since early 1930s. Darcy's Law has been used for calculating the permeability of a filter septum (Wakeman, 2007). Darcy described the volumetric flow rate (Q) of a system as a function of pressure drop (Δp), permeability (K), cross sectional area to flow (A), viscosity (μ) of the fluid, and the thickness (L) as shown in Eq. 1.

$$Q = \frac{KA}{\mu L}\Delta p \quad (1)$$

Kozeny-Carman (Carman, 1997) and Ergun (Ergun, 1952) equations are two commonly used formulations applied in the field of fluid dynamics to model the pressure drop of a fluid flowing through a porous medium. Detailed examination of the formulations is discussed in section four. (Tien and Ramarao, 2013) brought an issue that Kozeny-Carman equations are questionable when it comes to porosity calculation of compressible and randomly packed filter cakes in gas-solid separation processes. They claimed that Kozeny-Carman is appropriate when it's used only for pressure drop – flow rate correlations. (Tien and Bai, 2003) discussed a more accurate procedure of applying the conventional cake filtration theory. Conventional cake filtration theory has the capability of estimating the cake thickness, cake resistance, porosity, and pressure drop of the system.

Cake thickness and compressibility of the cake have the highest influence on pressure drop across the filter. Several methods have been implemented in order to measure the cake thickness depending on the filter geometry including ultrasonic, electrical conductivity techniques, nuclear magnetic resonance micro-imaging, optical observation, or cathetometer measuring (Hamachi and Mietton-Peuchot, 2001). (Ni et al., 2006) have modelled cake formation & pressure drop of a filtration mechanism in particle level (micro) where majority of the studies in literature are done in macro level. They simulated the cake filtration process using FORTRAN in both constant pressure and constant rate stages.

3. EXPERIMENTAL SETUP & DATA COLLECTION

This section discusses in detail the filter clogging experimental scenario & data collection for prognostic purposes under accelerated aging conditions.

3.1. Design & Installation

A peristaltic pump was installed in the system to maintain the flow of the prepared suspension as shown in Figure 3. The pump is a positive displacement pump providing constant flow rate where it takes the suspension with a desired flow rate and pumps it through the filter, letting the suspension pour into the reservoir. A stirrer was installed in the system to ensure that particles were fully mixed. This is necessary as the particles, even though they are meant to be naturally buoyant, sink after a while leaving the water clean. Upstream and downstream pressure transducers are installed in the system to measure the pressure drop across the filter; this is considered as the main indicator of clogging. A magnetic flow-meter is installed in the system in order to measure the flow rate of liquid.

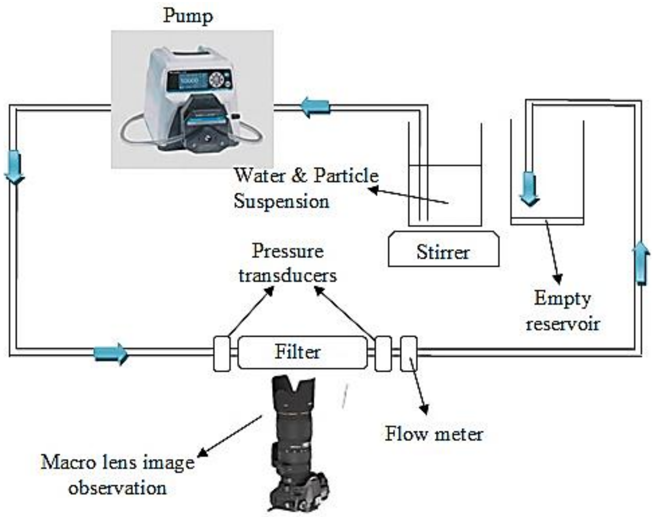

Figure 3. Filter clogging rig system design

A high quality macro lens camera is installed in the system and macro pictures of the filter were taken every two seconds. 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 where other sensory information can be compared with the clogging rate obtained from the macro picture dataset. Polyether ether ketone (PEEK) particles have been selected to be used in accelerated aging experiments for clogging the filter. Distribution of the particles is shown in Figure 4.

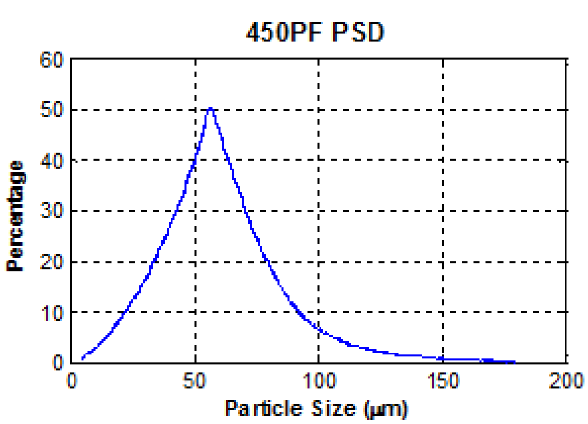

Figure 4. PEEK particle size distribution

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. Components of the system were selected so that no other component will deteriorate other than the filter. Details of the system design and the data collected under different operation profiles can be found in (Eker et al., 2013).

3.2. Data Collection

This section provides the data collection details of accelerated clogging experiments.

Operation profiles were kept the same for the six run-to-failure accelerated aging experiments. 125 micron pore sized fuel filters have been utilized for clogging experiments in the lab environment. Suspension solid fraction rate was kept 0.14% for each experiment. Pressure and flow rate measurements have been collected. Each clogging experiment has been run and monitored until the filter has clogged where the pressure drop (e.g. Differential Pressure, $\Delta P = Upstream\ Pressure - Downstream\ Pressure$) value has reached its peak value and remains stable where flow rate value has reduced to half as shown in Figure 5.

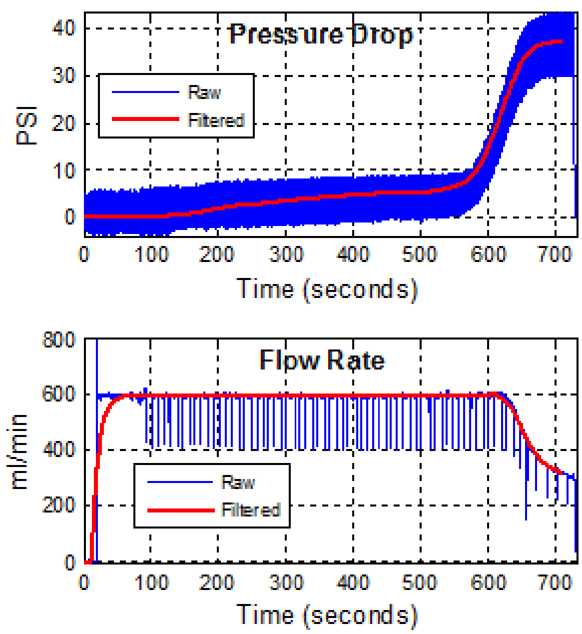

Figure 5. Pressure drop and flow rate measurements

Fluctuations in pressure measurements are generated from the peristaltic pump reflecting the pump RPM shown in Figure 6. Final shape of the data is given by implementing low-pass filtering and sampling. One out of hundred data points has been selected in the sampling phase since data collection sampling rate defined was as 100Hz. Filtered and sampled version of all samples are shown in Figure 7 used in degradation modelling in section four. Each curve in the figure represents a run-to-failure experiment measurement.

A macro lens camera was set to take pictures once every two seconds during each clogging test. Filter mesh pictures will be employed in image processing phase and clogging rates will be calculated and correlated with pressure drop and flow rate measurements.

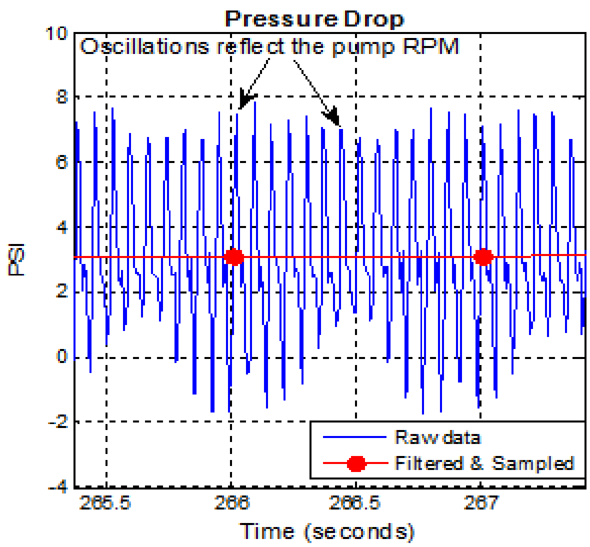

Figure 6. Zoomed pressure plot of a sample

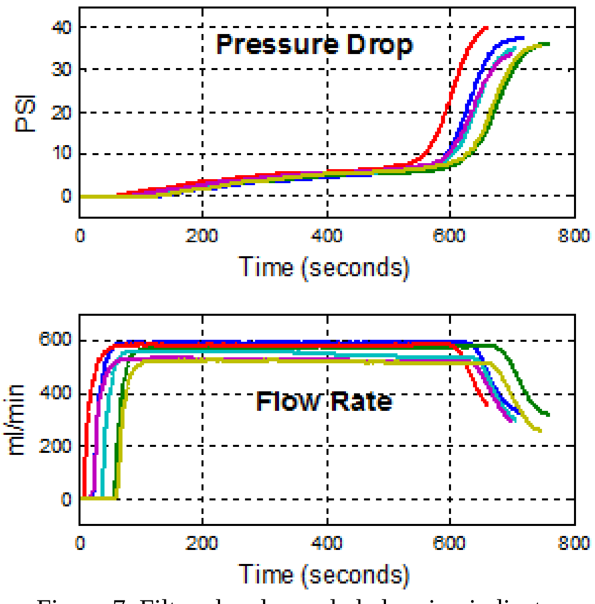

Figure 7. Filtered and sampled clogging indicators

4. METHODOLOGY

This section gives the governing formulations developed in pressure drop modelling of an accelerated clogging of filter.

In this study, the experimental rig is designed so that no other component is failed but the filter itself. Pressure drop across the filter, volumetric flow rate, cake thickness and porosity parameters are the main dynamic indicators showing the clogging level of a filter. These parameters need to be measured or derived from other parameters. In this study, correlations in between these parameters are modelled.

As mentioned in the introduction, Kozeny-Carman and Ergun equations are the most used models to calculate the pressure drop of a fluid through a packed bed of solids. Solid particles deposited on the filter mesh stands for the packed bed phenomena in cake filtration.

$$\Delta P = \frac{kV_s\mu}{\Phi_s^2 D_p^2}\frac{(1-\epsilon)^2 L}{\epsilon^3} \tag{2}$$

$$\Delta P = \frac{150V_s\mu(1-\epsilon)^2 L}{D_p^2\epsilon^3} + \frac{1.75(1-\epsilon)\rho {V_s}^2 L}{\epsilon^3 D_p} \tag{3}$$

Where:

Δp : *Pressure drop*
L : *Total height of the bed*
V_s : *Superficial (empty-tower) velocity*
μ : *Viscosity of the fluid*
ϵ : *Porosity of the bed (or cake)*
Φ_s : *Sphericity of the particles in the packed bed*
D_p : *Diameter of the spherical particle*
ρ : *Density of liquid*

Eq. (2) represents the well-known Kozeny-Carman model whereas Eq. (3) stands for the Ergun equation. Viscosity & velocity of fluid, cake thickness, and porosity of cake are directly proportional to the pressure drop across the filter in contrast with particle diameter and sphericity. The Ergun equation is a detailed version of the Kozeny-Carman equation. The first term in the Ergun equation represents viscous effect whereas the second term associates with the inertial effect. Inertial effect is not considered in Kozeny-Carman model.

Cake thickness and porosity are the dynamic cake structure parameters required to be modelled separately. Cake structure is assumed uniform which means cake thickness is uniform along the cake. Cake thickness growth show similar profile with the pressure drop values across the filter as confirmed by several studies in the literature. Therefore we modelled the cake thickness growth as logarithmic as shown in Eq. (4). '$\sum Qx$' term stands for cumulative particle volume retained in the filter chamber where 'Q' is flow rate, 'x' is solid fraction of the suspension. 'A_f' stands for filtration area.

$$L = \frac{\ln(l_1 \frac{\sum Qx}{A_f})}{l_2} \tag{4}$$

Porosity 'ϵ' defined as the void fraction of a filtration mechanism. We derived a porosity model of the filter as shown in Eq. (5). '$\frac{\sum Qx}{V_f}$' term gives the solid fraction of the cake where 'V_f' is the maximum filtration volume can be filled in the filter chamber.

$$\epsilon = 1 - \frac{e^{(p_1 \frac{\sum Qx}{V_f})}}{p_2} \qquad (5)$$

'p_1', 'p_2', 'l_1', and 'l_2' are the parameters to be optimized by fitting the model to the dataset. Pressure drop across the filter can be determined once the cake thickness and porosity values are calculated respectively. Comparison of the simulation results with the clogging data is given in the next section.

5. RESULTS

Simulation results of filter clogging employing Eqs. (2-5) in comparison with the collected data are discussed in this section. Tests have been conducted by setting the pump at 211 RPM to obtain 600 ml/min flow rate. Pump shows constant flow rate behavior until it reaches the critical clogging regime. The critical regime is reached in 500-600 seconds as shown in Figure 7. Then the pump reaches to the maximum pressure level it can provide where it remains constant at the top pressure level. Approximately 90% of the filter lifetime can be considered under constant rate filtration regime. Then the system passes to the constant pressure filtration regime for the rest of its life time. Operational profile, the parameters chosen for the simulation, and the optimized parameters are summarized in Table 1.

Table 1. Operation profile and fitted parameters

Constant parameters	Value
PEEK particle density (kg/m^3)	1290
Tap water density (kg/m^3)	998.23
Solid fraction of the suspension (%)	0.14
Mean particle diameter (m)	5.8e-5
Fluid viscosity ($kg/m.s$)	8.9e-4
Filtration mesh area (m^2)	0.001344
Filtration volume (m^3)	6.7e-06

Optimized parameters	Value
l_1	4e+4
l_2	899
p_1	1.2346
p_2	9.1464

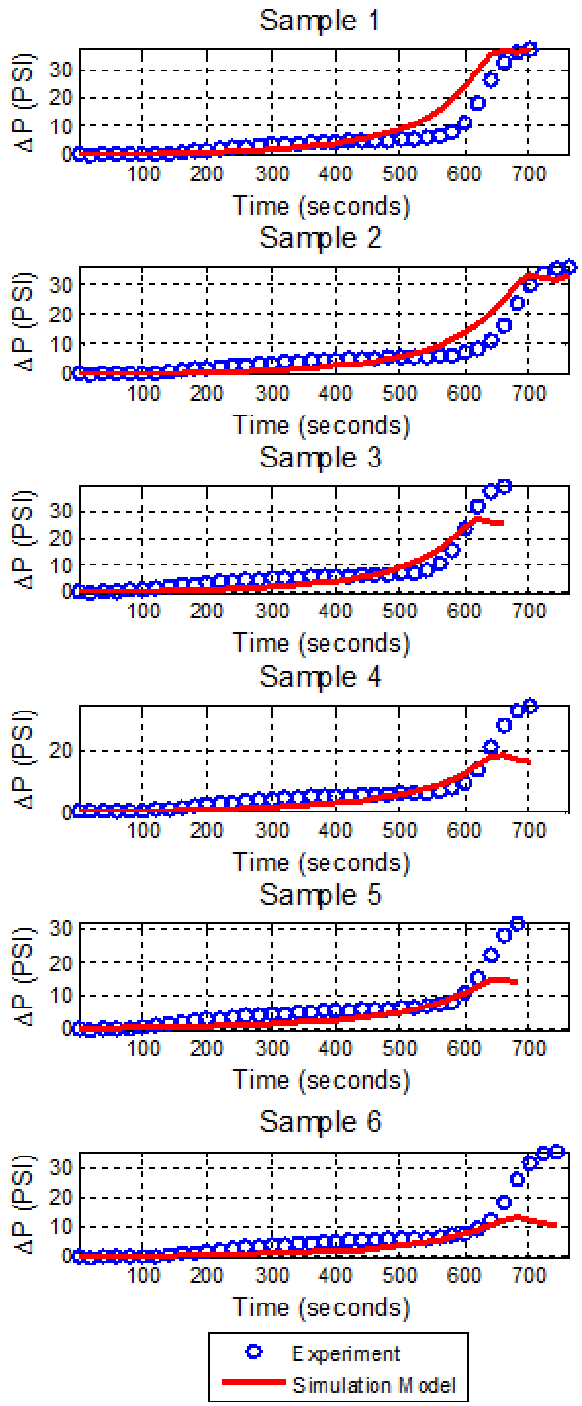

Figure 8. Experimental data vs. simulation

Figure 8 plots show that the proposed simulation model of clogging fits to the data collected from the experimental test rig where the lines represents the simulation model and the circles are the pressure drop data points for each clogging experiment. Normalized root mean squared error (nRMSE) values are calculated for each simulation in order to evaluate the performance. The mean normalized RMSE value of six experiments is 13.91%. Figure 9 depicts the porosity and cake thickness modelling plots for six samples. Porosity of the filtration starts with values close to 100% in the beginning of each experiment and decreases by time showing different degradation profile inversely proportional to the cake thickness simulation values. On the other hand, thickness of cake shows a logarithmic growth similar to the growth in pressure drop until the clogging regimes. Logarithmic growth in cake thickness during a cake filtration experiment is an expected type of degradation behavior which can be confirmed with the several studies conducted in the literature (Hamachi and Mietton-Peuchot, 2001; Ni et al., 2006).

Aim of the proposed methodology in this paper is to calculate the pressure drop across the filter given the varying flow rate. Flow rate of the filtration system varies during the experiments due to porosity change in the filter cake. Tracking and predictions of the future pressure drop levels can be achieved when the flow rate is constant since cake thickness and porosity is effected by the flow rate of the system.

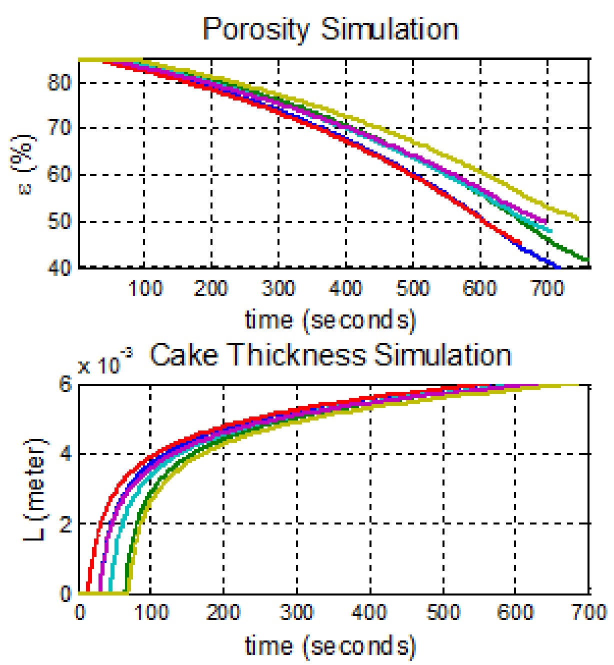

Figure 9. Cake thickness and porosity simulation

6. CONCLUSION & FUTURE WORK

This paper presents a data collection and physics-based degradation modelling of an accelerated filter clogging experimental rig. Data acquisition, especially for the pressure drop across the filter and the flow rate of the pumping system, has been conducted. Degradation modelling of the pressure drop due to retaining particles on the filter mesh has been modelled and efficiency of simulation results has been evaluated by comparing with the actual dataset. Results show that the effectiveness of the proposed degradation model is satisfactory in terms of identifying the current pressure drop level in the system. Future studies will be based on physics-based prognostic modelling of the cake filtration mechanism. Cake thickness, porosity, and the pressure drop will be modelled dynamically and utilized in prognostic modelling.

ACKNOWLEDGEMENT

This research was supported by the IVHM Centre, Cranfield University, UK and its industrial partners.

REFERENCES

Abboud, N. M. and Corapcioglu, M. Y. (1993), "Modeling of Compressible Cake Filtration", *Journal of colloid and interface science*, vol. 160, no. 2, pp. 304-316.

Carman, P. G. (1997), "Fluid flow through granular beds", *Chemical Engineering Research and Design*, vol. 75, no. 1 SUPPL., pp. S32-S46.

Cheremisinoff, N. P. (1998), *Liquid Filtration* , Second Edition ed, Elsevier Inc.

Eker, O. F., Camci, F. and Jennions, I. K. (2013), "Filter Clogging Data Collection for Prognostics", *Proceedings of the Annual Conference of the Prognostics and Health Management Society*, 14-17 Oct 2013, New Orleans LA, USA, pp. 624-632.

Ergun, S. (1952), "Fluid Flow through Packed Columns", *Chemical Engineering and Processing*, vol. 48, pp. 89-94.

Hamachi, M. and Mietton-Peuchot, M. (2001), "Cake thickness measurement with an optical laser sensor", *Chemical Engineering Research and Design*, vol. 79, no. 2, pp. 151-155.

Ni, L. A., Yu, A. B., Lu, G. Q. and Howes, T. (2006), "Simulation of the cake formation and growth in cake filtration", *Minerals Engineering*, vol. 19, no. 10, pp. 1084-1097.

Sparks, T. (2011), *Solid-Liquid Filtration: A User's Guide to Minimizing Cost & Environmental Impact, Maximizing Quality & Productivity*, First Edition ed, Elsevier Science & Technology Books.

Sutherland, K. (2010), "Mechanical engineering: The role of filtration in the machinery manufacturing industry", *Filtration and Separation*, vol. 47, no. 3, pp. 24-27.

Tien, C. and Ramarao, B. V. (2013), "Can filter cake porosity be estimated based on the Kozeny-Carman equation?", *Powder Technology*, vol. 237, pp. 233-240.

Tien, C. and Bai, R. (2003), "An assessment of the conventional cake filtration theory", *Chemical Engineering Science*, vol. 58, no. 7, pp. 1323-1336.

Wakeman, R. (2007), "Filter media: Testing for liquid filtration", *Filtration and Separation*, vol. 44, no. 3, pp. 32-34.

Wilfong, D., Dallas, A., Yang, C., Johnson, P., Viswanathan, K., Madsen, M., Tucker, B. and Hacker, J. (2010), "Emerging challenges of fuel filtration", *Filtration,* vol. 10, no. 2, pp. 107-117.

BIOGRAPHIES

Omer Faruk Eker is a PhD candidate in School of Applied Sciences and works as a 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 has got involved in a project funded by TUBITAK, and Turkish State Railways from 2009-2011. His research interests include failure diagnostics and prognostics, condition based maintenance, pattern recognition and data mining.

Dr. Fatih Camci works as a faculty member Industrial Engineering Department at Antalya International University in Turkey. He has worked on many research projects related to Prognostics Health Management (PHM) in USA, Turkey, and UK. After completion of his PhD at Wayne State University in 2005, he worked as senior researcher at Impact Technologies for two years. He has involved in many projects funded by US Navy and US Air Force Research Lab. 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. He has worked as faculty member at Cranfield University in the UK for three years and led several research projects at IVHM Centre.

Prof. 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.