Development of residence time distribution measurement techniques to improve reliability and accuracy

Développement de techniques de mesure de la distribution des temps de séjour afin d'améliorer la fiabilité et la précision

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RESUME

La distribution de temps de séjour hydraulique (Hydraulic Residence Time Distribution) est une manière efficace d'évaluer le régime de flux à n'importe quelle échelle, que ce soit en laboratoire ou en industrie.

Les études effectuées précédemment ont nécessité d'innombrables variables d'entrées avec l'injection manuelle du colorant et la surveillance du flux, ainsi que des analyses ultérieures détaillées des variables sortantes du SCUFA® fluorometer. Dans cette communication, une application informatique construite en LabView® est décrite, dans le but d'automatiser le procédé et ainsi réduire le contact avec les opérateurs. L'automatisation permet aussi de diminuer les erreurs dues à l'opérateur par le contrôle des entrées et la surveillance des données RTD acquises. Les applications réalisées sur un DynaSand® sont par ailleurs exposées, en évoquant les applications industrielles qui peuvent en découler.

ABSTRACT

Hydraulic residence time distribution (RTD) is an effective way of gauging the flow regime of a given vessel at any scale from a laboratory based model through to a full industrial plant. Previous work carried out has required considerable operator input with manual dye injection and monitoring of flow and subsequent detailed analysis of the data output from the SCUFA® fluorometer. In this paper, a description of how a LabVIEW® program was built to automate the process to minimize operator contact in the process and reduce operator error through the control of the input and subsequent monitoring for the acquisition of RTD data. The programs application on a DynaSand® laboratory based demonstrator is subsequently discussed with further applications at industrial scale considered.

KEYWORDS

DynaSand, DynaOxy, up-flow filters, residence time distribution (RTD), Lab-View, control methods

1. INTRODUCTION

Previous work carried out into residence time distribution (RTD) data focussed on the manual injection of a pulse of Rhodamine WT Dye as a tracer into an influent stream and monitoring the fluorescence in the effluent at a given time (T) using a SCUFA® fluorimetric detector (Higgins 2000). It was found that unless great care was taken experimental limitations made manual pulse injection difficult to control, increasing the uncertainty in the output data. It was therefore decided to introduce a control system into both the input and measurement of the residence time distribution data to allow better correlation between runs and a higher resolution of the data and improved consistency of experimentation.

On this occasion the RTD work was carried out on a DynaSand® demonstrator unit loaned to the University by Hydro International Plc as part of a parallel project. DynaSand® devices are a type of continuously operated up-flow filter (CoUFs) are primarily designed to capture suspended solids and which have been utilised in both wastewater and potable water treatment works for a number of years . In wastewater treatment they are primarily used as a final suspended solids capture device in a tertiary treatment capacity. A key feature of this device is the constant, but slow movement of the bed, to provide continuous regeneration of a cleaned surface on the support particles.

However, with the addition of an aeration ring at the base of the filter bed they can become a CoBUAF (continuously operated biological uplow filter (the DynaOxy® device) and be applied to nitrify an incoming influent stream and convert ammonium ion (NH_4^+) to nitrite (NO_2^-) by means of a biofilm on the substrate media. One of the key variables in the conversion process is contact time between the water to be treated and the biofilm. In order to construct an effective model, detailed residence time distribution calculations are required, hence their investigation here. Measurements on this system which involves a 3 phase flow regime will be more demanding, so it was decided to first use the DynaSand demonstrator as a test bed for the updated dye input control and subsequent monitoring methodology when examining the hydraulic regime.

2. RESIDENCE TIME DISTRIBUTION BACKGROUND

The RTD measured by pulse injection involves introducing a concentrated spike of fluorescent dye as a tracer into the influent stream and subsequent monitoring of the concentration of the tracer over time at the outfall of the device. In theory this injection should satisfy the requirements of the Dirac delta function so that ideally this pulse would be infinitely high and infinitely narrow. Fluorescence is then measured at the outfall of the device with results from the outfall obtained as fluorescence-time curves. As fluorescence is linearly related to concentration over the range used, fluorescence measurements are used directly thus negating the need for dye mass balance analysis. For subsequent comparison and analysis data was normalised, where *E(t)* is shown in equation 1 and where and F(t) is the fluorescence (in arbitrary units (v)) at time t.

Equation 1

$$E(t) = \frac{F(t)}{\int_0^\infty F(t)dt}$$

The mean residence time (t_m) is then calculated as:

Equation 2

$$t_m = \int_0^\infty tE(t)dt$$

With the mean residence time being the time (t) at which 50% of the total integral value recorded has passed (Levenspiel 1999).

3. COMPARISON OF METHODOLOGIES

Previously, the method used to determine the RTD of a hydraulic system required a rapid manual injection of a small volume of tracer dye (typically 10-50ml of diluted dye solution) using a syringe at a point approximately 20 pipe diameters upstream of the inlet (Phipps et al. 2008). Due to the problems encountered during manual injection it was decided to try and automate the process. Both to improve accuracy and to allow capture experiments on full scale plant where access to an inlet could potentially be even more problematic. After discussion the following requirements were decided upon:

- A control device was required that could take out the human error that could occur with manual dye injection and monitoring..
- Ideally no input should be required from the operator after the test had been started.
- The system should be able to create the correct E(t) normalised values without any additional operator input.
- The system should be adaptable so if required additional inputs could be incorporated into its command and control system for example, flow monitoring and control and repeated automated RTD monitoring of a system.
- The system should allow more accurate results to be taken and a larger dataset established with higher accuracy.

Components of new control system.

The new RTD methodology consisted of the writing of a LabVIEW program with control mechanism supplied by a National Instruments control interface (USB DAQ) with numerous digital input/output and analogue control points. The LabVIEW program was designed as a full control mechanism. A peristaltic pump was linked up with an actuator on/off control valve controlled through the LabVIEW interface and controlled the initial dye injection which could be set at however long the operator required. In this case injection time was carried out at 1,2,3,5, and 10 seconds. This injection time was absolute and allowed very accurate input over several rounds to be undertaken. Additionally 0-2.5 V output was monitored from the SCUFA which was monitoring the outfall fluorescence to give a fluorescence- time curve. This was then programmed to be outputted as an Excel file with the E(t) normalisation equation values given.

4. PHYSICAL TESTING OF THE CONTROL DEVICE ON A DYNASAND® DEMONSTRATOR UNIT

It was decided to test the new LabVIEW control program on a DynaSand® demonstrator on loan from Hydro International Plc. Experiments were conducted on a transparent Perspex® constructed small-scale CoUF (overall diameter 300mm, operating water volume approximately 60 litres excluding any connecting pipe work and filter media) shown schematically in Figure 1. The device reproduced the primary features of a DynaSand® (but with a substantially shallower sand bed depth) with dimensions as outlined and illustrated in Figure 1 (all lengths in mm). Flow rates were measured by an in-line flowmeter in the inlet. The DynaSand® demonstrator's operation is described in Section 5. The main purpose of the device is to capture suspended solids from a given effluent stream without the need for periodic backwashing. It achieves this by constant movement and cleaning of the sand bed with a high pressure air line forcing dirty sand up from the base of the filter and washing the filter media through an attrition process and a countercurrent stream in the washwater labyrinth at the top of the filter. This leads to a washwater flow of approximately 5-10% of influent entering into the filter. It was hoped through analysis of the hydraulic characteristics of the filter the command MRT program could be proved and the characteristics of the filter established to test the premise that plug flow would be dominant.

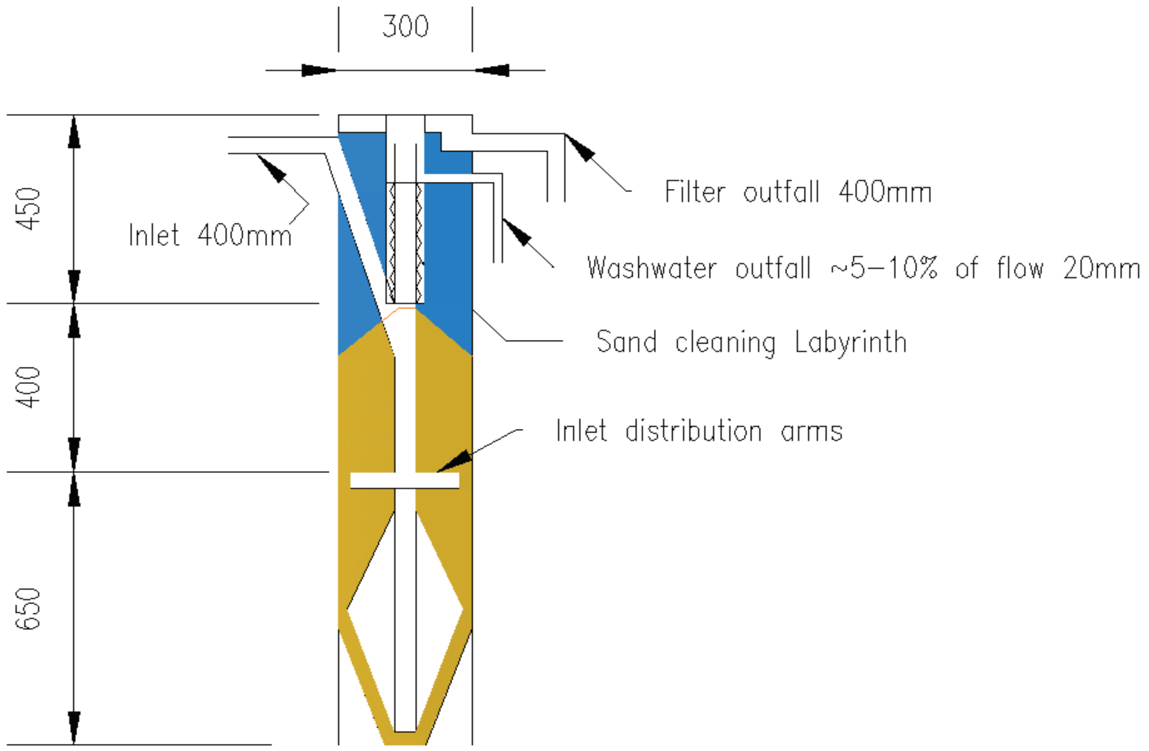

Figure 1. Schematic of the experimental CoUF (not to scale) with additional photo for comparison.

DYNASAND® OPERATION

Figure 2, provides a schematic sectional view through a DynaSand® filter. Its method of operation is described below and adapted from (Barter et al. 2007).

1. Wastewater is introduced at the bottom of the filter and spread across the available surface by a number of distribution arms (1).
2. The water flows up through the sand bed (2) where solid particles are captured.
3. Most of the cleaned water (filtrate) passes over the fixed final filtrate weir (3).
4. A small percentage travels up through the sand washing labyrinth (4), where entrained solid particles are released from the sand grains as they fall down through the washer.
5. The sand bed moves down the filter and over the sand distribution cone (5) as a result of the action of an air-lift pump.
6. Sand, trapped solid particles and water are pulled through the air-lift pump to the washing section (6).
7. The sand particles, because of their greater size and density fall through the sand washer, against a counter current of process filtrate, which carries the lighter effluent particles over the washwater weir and out of the system (7).
8. The clean sand is returned to the top of the bed. By adjusting the washwater weir height (and therefore its relationship with the filtrate weir), the amount of washwater generated can be increased or decreased (8).

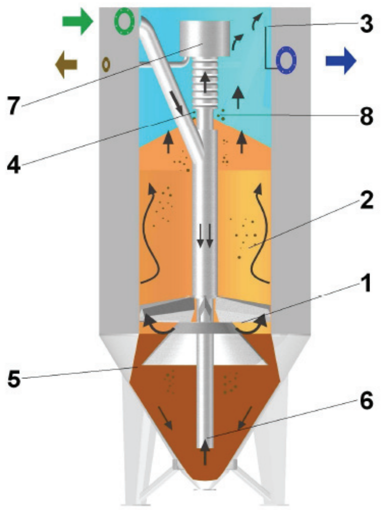

Figure 2. DynaSand Operation.

5. RTD RESULTS

The results of a typical RTD dye tracer experiment taken from the study are shown in Figure 3 with the data taken as an output from the LabVIEW program. This shows that after injection it takes approximately 1min 20s for the first detectable dye to pass through the sand bed and out of the filter, with the mean residence time (equivalent to the time taken for half the volume of injected dye to reach the exit) calculated from the equation 2 above being approximately 2 minutes 50 seconds (it should be borne in mind that the filter bed depth on the demonstrator was substantially less than would be typical on a full scale unit; as such full-scale residence times would be correspondingly longer). The long tail gives an indication of the length of time some influent may remain within the system before being lost through the effluent pipe. The amount that the MRT differs from the predicted plug flow residence time gives an indication of the hydraulic performance of a device. This taken in conjunction with the profile generated by the E(t) calculation gives a snapshot picture of the hydraulic regime operating in a given device.

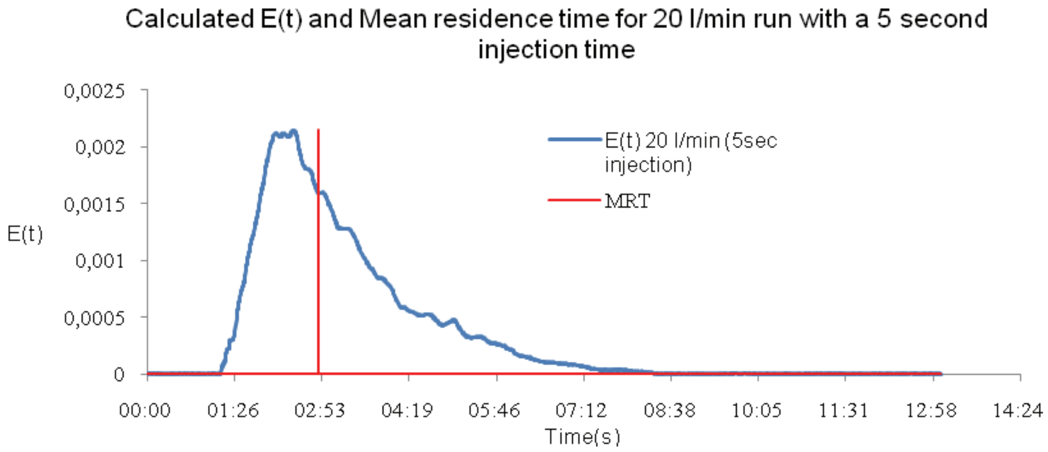

Figure 3. Typical RTD curve.

The experimental program consisted of the injection into the system of 5 different dye concentrations over 5 different injections times over 3 different loading rates. The calculated mean residence time for the experiments are shown below in figure 6.

Previous work had assumed that in the DynaSand Devices that a plug flow regime would be predominant (Sanz et al. 1996) along with research suggesting treatment rates vary with flow rate (Peledan et al. 1996) hence the reason behind testing whether this premise was well founded.

Figure 4 represents the entire calculated integral value of each experimental run plotted against injection times. This variation in injection time and concentration when plotted as an integral of fluorescence values should give a wide range of answers as the integral represents the total fluorescence injected into the system. Therefore if a given concentration is injected for twice as long the total integral value should double. These values are plotted in the graph below in figure 5 and are used to test the accuracy of the capture software. From the lines generated by the different concentrations of dye used the accuracy of the system appears to be confirmed.

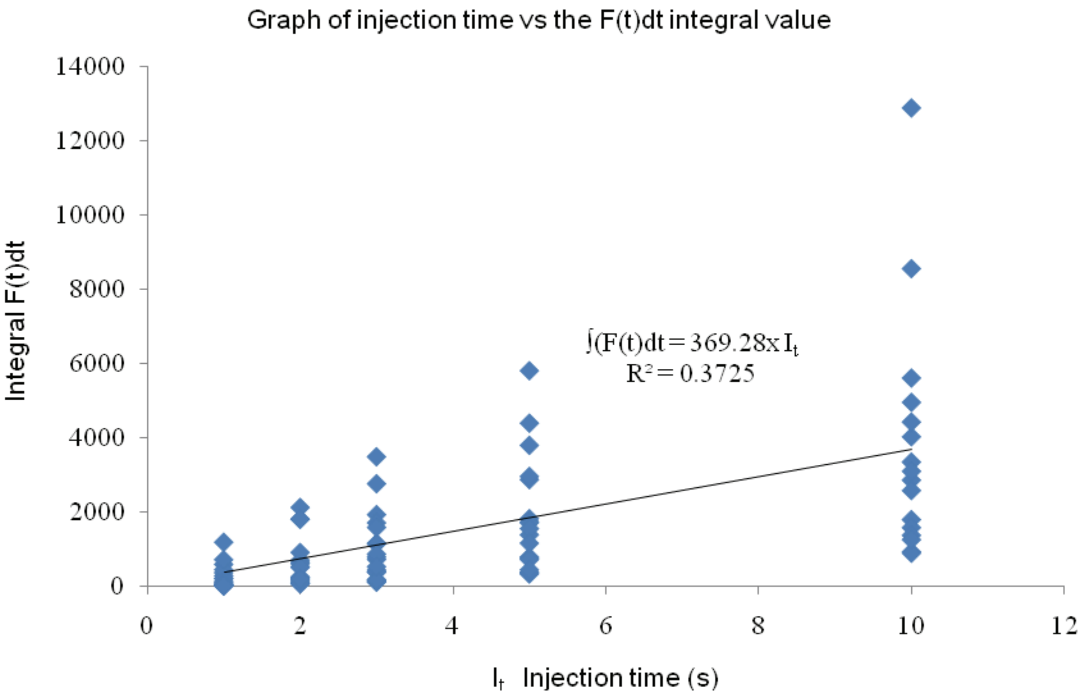

Figure 4 Calculated mean residence times for every experimental run.

The stratification of mean residence times in figure 4 are due to differences in injection times and dye concentration. As you can see from the linear relationship between them The accuracy of the capturing software is very high resulting in an accurate extrapolation of the integral dye value and subsequent calculation of the MRT of the devices. The flow rates used in the experiments were varied to give different hydraulic loading rates. The mean horizontal cross-sectional area of the demonstrator bed was 0.07 m^2. Loading rates for the DynaSand® and DynaOxy filters are typically in the region of 12 m/hr, equating to a flow rate in the demonstrator of around 14 l/min, though RTD curves were generated for three flows 10, 15 and 20 l/min.

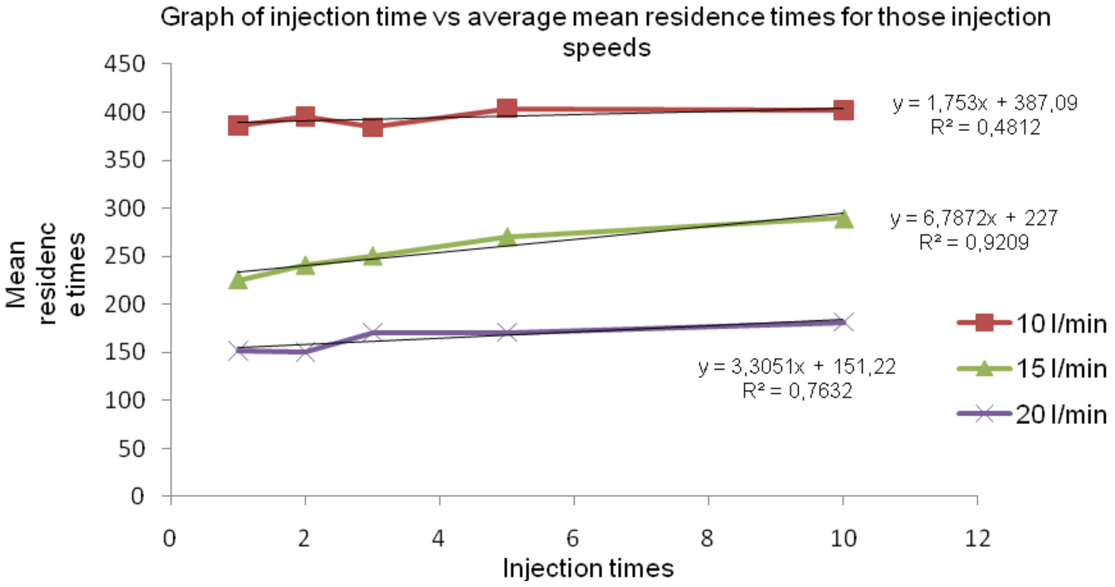

Figure 5. Dye injection time vs average mean residence times for those injection times.

Figure 5 has MRT values plotted against injection times to try to establish if injection times affect the MRT. Ideally the injection should be as small as possible. Theoretically being infinitely tall and infinitely small. These graphs tend to show that at lower flow rates it becomes harder to monitor the system as the ratio between loading rate and injection time becomes larger. However generally the system appears to have performed well in the monitoring role particularly at the typical loading rates the filters would be operated at which is typically 12 m/hr. This can be seen from the fact that the MRT's are generally near vertical.

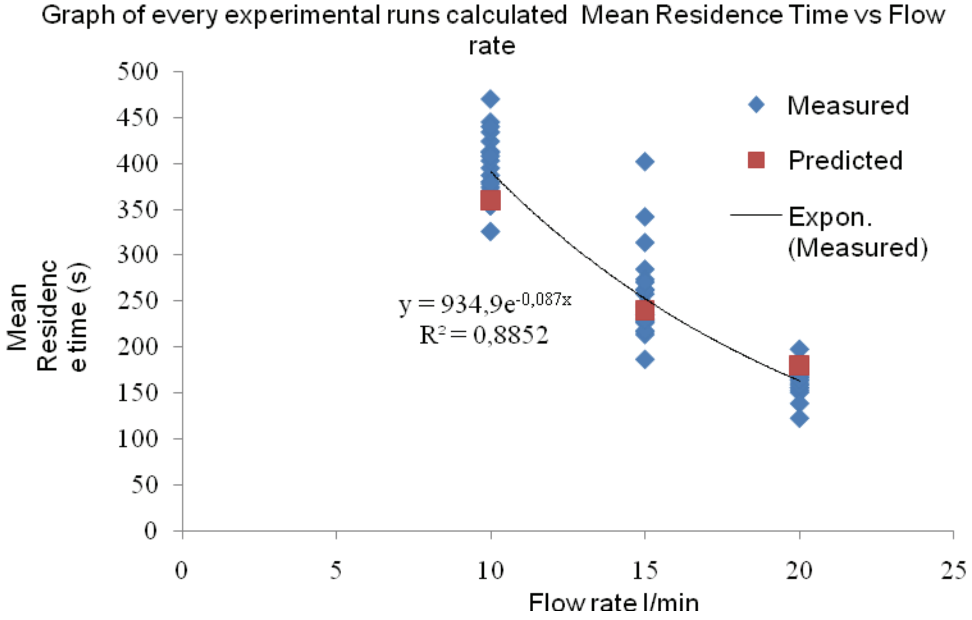

Figure 6. Calculated mean residence times for every experimental run. The stratification of mean residence times being due to differences in injection.

Figure 6 shows the calculated MRT from all the test runs conducted as calculated above and plotted against flow rate. What it shows is that the measured values recorded are generally in line with those values predicted from plug flow.

As seen from figure 6 the relationship between the data set and the predicted mean residence times for the unit are very similar indicating that the regime at these flow rates seems to indicate plug flow being the dominant hydraulic regime.

6.DISCUSSION

Previous work on the HDVS (Hydrodynamic Vortex Separator (Phipps et al. 2008) has shown that residence time is an important aspect of plant design, having significant implications for overall plant efficiency. This is especially relevant in biological systems due to the influences of the kinetics in 3 phase plant. In both types of system it is normally desirable to achieve plug-flow, minimising both the degree of short-circuiting, in which flow elements transfer from inlet to outlet with a short residence time and the degree of back-mixing. What this work carried out has shown is that accurate RTD data can be setup and controlled with a computer program to gain an accurate understanding of the RTD characteristics and hydraulic retention time of any given system. This degree of accuracy is highly desirable and with additional work could be further improved with shorter dye injection times and potentially be linked into a system as a safeguard for a given biological process. If for example in the case of these continuous upflow filters there was a blockage in the movement of the sand bed, this through regular monitoring with a controlled automated system would be able to potentially be detected and flagged to an operator as both the MRT and the E(t) profile would change of the measured fluorescence values would change.

In this investigation work on residence times has shown that at higher flow rates (incorporating flow rate ranges corresponding to typical full-scale plant loading ranges) short-circuiting within this CoUF device is minimal, with mean residence times roughly in line with what would be expected from the space-time or plug-flow predicted mean residence times . However at lower flow rates (below typical design loadings) this relationship is less applicable.

7.CONCLUSION

The more advanced control methodology developed and implement within this study reflects the need for injection and monitoring methodology to be more effective and hence allow for the accuracy and resolution of the data to be increased. With 3 phase systems the need for accurate MRT and HRT studies becomes more pronounced particularly if flow is being diverted off in a washwater stream. This development of an existing methodology clearly shows the benefits of automating the process to better investigate the hydraulic characteristics of a given hydraulic application with additional scope for automating the investigative process to potentially spot potential problems in a system to better optimize and control the operation.

In this example test MRT and E(t) profiling have clearly shown that the CoUF investigated in this study demonstrates an orderly hydraulic regime in line with what would be expected from plug flow. With development the system could be developed further to a point whereby residence time and hence efficiency and performance of a given hydraulic system could potentially be monitored remotely with warning thresholds for MRT set to be activated if and when problems with the system were encountered.

This study has shown that remote profiling of a system can be carried out and implemented to achieve a high level of accuracy and monitoring of MRT with potential for the aiding of the efficiency of a system by regularly monitoring the hydraulic profile characteristics of a given process.

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