

Cross-Flow Ultrafiltration with a Shear-Thinning Organic Based Slurry

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A document prepared for INTERNATIONAL CONFERENCE OF MULTIPHASE FLOW at New Orleans, LA, USA
from 5/27/2001 - 6/1/2001.

DOE Contract No. **DE-AC09-96SR18500**

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Cross-flow filtration with a shear-thinning organic-based slurry[†]

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Abstract

The Department of Energy is sponsoring the River Protection Project, which includes the design of a facility to stabilize liquid radioactive waste that is stored at the Hanford Site. Because of its experience with radioactive waste stabilization, the Savannah River Technology Center (SRTC) of the Westinghouse Savannah River Company was contracted to develop and test parts of the waste treatment process. One part of the process is the separation of highly radioactive solids from the liquid wastes by precipitation and cross-flow filtration. A cross-flow filter was tested with simulated wastes made to represent typical waste chemical and physical characteristics.

This paper discusses the results of cross-flow filter operation in a pilot-scale facility that was designed, built, and run by the Experimental Thermal Fluids Laboratory of SRTC. The waste simulant, which was used for the test, had an insoluble solids loading that was varied from 2 wt% to 22 wt%, with a bimodal distribution of particle sizes from 1 to 2 microns and 5 to 10 microns in diameter. The filter contained seven 316L stainless steel sintered-metal tubes in parallel. Each tube was identical, being 1.01 meter long, 9.5 mm inside diameter, and membrane thickness of 1.6 mm. The porous tubes were made to capture 95% of particles ≥ 0.1 micron.

The flow conditions for the test varied: Axial slurry velocities from 3 m/s to 5 m/s and transmembrane pressures (TMP) from 200 kPa to 500 kPa, at a temperature of 298 K. The results showed adequate permeability and good separation for the Newtonian slurry with solids loadings of 2 wt%. Under the flow conditions of a slurry velocity of 3.5 m/s and a TMP of 400 kPa, the observed filtrate flux was 17 cm/hour[‡]; meeting the plant design need of 16 cm/hour.

As the slurry was dewatered to increase the solids loading its rheology changed, becoming more non-Newtonian in character. At an insoluble solids loading of 22 wt% the slurry became a shear thinning, thixotropic fluid, with a yield stress of approximately 5.5 Pa and a consistency of 23 cP. Despite the changing rheology the filtrate flux continued, but dropped to 2.4 cm/hour.

Keywords: Filtration; Cross-flow; Radioactive; Hanford, Pre-treatment

[†] This work was carried out at the Savannah River Technology Center, managed by the Westinghouse Savannah River Company for the U.S. Department of Energy under contract DE-AC09-96SR18500.

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[‡] Volumetric flow rate per filter surface area (cm³/hour/cm²) was reduced to cm/hour for convenience.

1. Introduction

The United States of America has a large supply of radioactive waste left over from the cold-war years and much of it is in the form of slurries that are stored in federal repositories. To better stabilize this waste, a method of combining it with glass was developed. In the pretreatment for vitrification, the waste is separated into various constituents for more efficient handling. Separation begins by removing the highly radioactive insoluble solids from the liquid. However, combined with the radioactivity, the other slurry characteristics, like the ability to easily plug filters and becoming non-Newtonian at high solids concentrations, make such separation a challenge.

A form of filtration that has worked in the past (Gutman et al., 1989) for radioactive service is called cross-flow, where the turbulent flow (Tennekes and Lumley, 1983) of slurry (Fritz and Pahl, 1996) runs parallel to the permeable surface. This cross-flow action helps to keep the surface clean by continually shearing the cake of solids away from the permeable barrier (Murkes and Carlsson, 1988). If the main objective is to concentrate a slurry by the separation of some of its supernatant, then, cross-flow filtration is an appropriate technology that can be economical for certain industries (Roeleveld and Maaskant, 1999).

Cross-flow filtration is preferable to the more common dead-end filtration when the slurry to be filtered can easily plug, like those that contain gums (Carrère et al., 1998), colloidal solids (Sundaram and Santo, 1977; Howell, 1995), or other non-Newtonian flows (Carrère and René, 1998). Unfortunately, to date predicting the cross-flow filtration parameters for easily plugging slurries is still difficult and must be studied through experimentation. For simple slurries (e.g., sand and water) there exist today a certain level of sophisticated analyses that can be used to predict cross-flow filtration parameters (Song, 1998; Fritz and Pahl, 1996; Lu, Hwang, and Ju, 1993; Stamatakis and Tien, 1993; Murkes and Carlsson, 1988). Such analyses that make simplifying assumptions about particle types, cake compressibility, cake uniformity, etc. do not apply to slurries that may change in character with time or flow conditions. However, with better observational techniques (Li, et al., 1998) a better understanding of these challenging slurries will emerge.

BNFL, Inc. (BNFL) was contracted by the Department of Energy to design a facility to stabilize liquid radioactive waste that is stored at the Hanford Site. Because of its experience with radioactive waste stabilization, the Savannah River Technology Center (SRTC) of the Westinghouse Savannah River Company was contracted by BNFL to help design and test certain parts of the waste treatment facility. The Experimental Thermal Fluids Laboratory of SRTC developed a test to evaluate a selected cross-flow filter to show its filterability with a waste simulant.

The simulant was made to be physically and chemically similar to the real waste, except for its radioactivity. It, like the real waste, contained organic complexants and several compounds were added to precipitate strontium and the simulated transuranic constituents. The resulting Strontium-Carbonate/Manganese-Dioxide-based slurry is what will exist in the actual process. The resulting mixture behaved like a Newtonian fluid

when the insoluble solids concentration was 2 wt% or less, but as the solids concentration increased it became non-Newtonian. Specifically, the rheological character of the waste changed to a shear-thinning, thixotropic, and sticky slurry at higher solids concentrations.

The results from this filter test were useful to the overall project of building a plant to stabilize the radioactive waste and it is the hope of the authors that this information will be a useful addition to the growing body of data on hard-to-filter solutions.

2. Experimental

Details of the experimental setup and test procedure can be found in the 2001 ICMF paper by Duignan et al., 2001, however a brief summary is given below for convenience.

2.1. Test Rig

Figure 1 is a schematic of the entire test rig. The test rig was made of three flow loops:

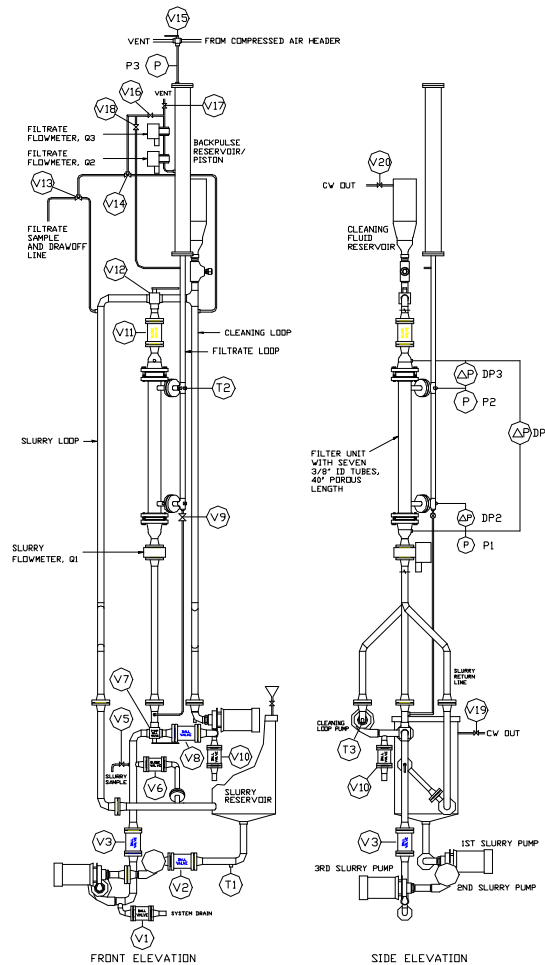


Figure 1. Pilot-scale cross flow filtration test facility

1. Slurry loop, which contained the cross-flow filter and its housing
2. Filtrate loop, which began at the filter housing and allowed the separated filtrate liquid to flow up through the backpulse piston before returning to the top of the slurry loop to close the circuit.
3. Cleaning loop, which enabled the cleaning of the filter in place.

2.2. Cross Flow Filter

The filter unit used in this test was manufactured by the Mott Metallurgical Corporation and had the following characteristics:

Material: 316L stainless steel (sintered metal)
Porosity: Nominal[†] rated 0.1 micron
Porous Length: 1.01 meter
Diameter: 9.5 mm inside and 12.7 mm outside diameters (filter area of 0.211 m²)
Number of tubes: 7

Figure 2 show the 7-tube bundle of filters before its installation in its housing. This assembly was sealed in an 83 mm inside diameter tube that allowed the filtrate to be directed outside the filter unit and collected.



Figure 2. Upstream view of the seven-tube bundle

As needed for plant service, the stainless steel sintered tubes have a fairly robust construction. Figure 3 shows an enlargement of two different pore-size filter elements, 0.5 and 100 microns. (Mott did not have a picture of a nominal rated 0.1 micron filter but stated that the appearance is identical to the larger sizes.) The sintering process leads to a labyrinth of pores which makes the structure strong but also increased the possibility of depth fouling for whatever solids manages to penetrate the metal substrate. For this filter backpulsing should be minimized so that the filter cake minimized the number of small particles that enter the metal pores.

[†] The word “nominal” for a filter is a vague term because its meaning is manufacturer dependent. Further, a “nominal” rating does not give an exact size to a filter medium; but rather an approximation to the expected performance of a filter. In the case of Mott, a nominal rated 0.1-micron filter means that approximately 95% of particles greater than 0.1 micron will not pass the filter. However, this measurement verified with a bubble-point test that is done to the ASTM Standard F316-80.

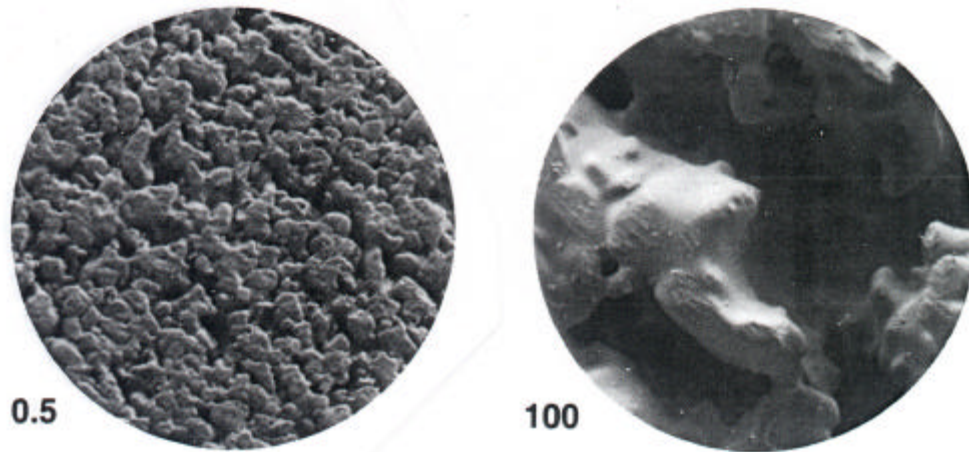


Figure 3. Magnified views (approximately 150X) of surfaces of two different pore-size rated Mott filters (the number to the left of each figure is the pore-size rating in microns)

2.3. Instrumentation and measurement uncertainty[†]

The measurement equipment used for this experiment included: five type E thermocouples (uncertainties from 1.2 to 1.3 K), six pressure transducers (uncertainties from 0.2 to 2.6 kPa), and three magnetic flow meters (uncertainties from 0.02 to 0.72 lpm).

The measurement uncertainties (95% confidence level) for the important calculated quantities were:

Slurry Velocity in a Filter Tube	=	V	± 8.1 %
Transmembrane Pressure	=	TMP	± 1.1 %
Filtrate Flux	=		± 11.7 %

2.4. Simulated Waste Slurry

The waste that needed to be simulated is a mixture of solids and organic and other complexants components. The simulant was made to represent the physical and chemical characteristics of the actual waste (Jo et al., 1996; Urie et al., 1999; Eibling and Nash, 2000) without being radioactive. The simulant development is complex and beyond the scope of this study, however it was made of supernatant, Fig. 4, and solids, Fig. 5, along with three additional compounds, NaOH, Sr(NO₃)₂, and NaMnO₄ to develop a target precipitant that is part of the waste plant pretreatment process. The resulting slurry was sticky, relatively thick, dark brown mixture at 2 wt% of insoluble solids and it had a ketchup-like consistency above 20 wt%.

[†] The measurement uncertainties were a function of the instrument and calibration. The uncertainty introduced through the use of the 16-bit data acquisition system was insignificant (<0.1% reading) and was not included in the values above. Details of the measurement uncertainty analysis can be found in Duignan, 2000.

Compounds	Formula	Conc., PPM	M
Calcium Nitrate	Ca(NO ₃) ₂ ·4H ₂ O	2083	1.18E-02
Cerium Nitrate	Ce(NO ₃) ₃ ·6H ₂ O	98	3.01E-04
Cesium Nitrate	CsNO ₃	14	9.58E-05
Copper Nitrate	Cu(NO ₃) ₂ ·2.5H ₂ O	66	3.78E-04
Ferric Nitrate	Fe(NO ₃) ₃ ·9H ₂ O	7315	2.42E-02
Lanthanum Nitrate	La(NO ₃) ₃ ·6H ₂ O	85	2.61E-04
Magnesium Nitrate	Mg(NO ₃) ₂ ·6H ₂ O	158	8.21E-04
Manganous Chloride	MnCl ₂ ·4H ₂ O	1213	8.18E-03
Neodymium Nitrate	Nd(NO ₃) ₃ ·6H ₂ O	174	5.31E-04
Nickel Nitrate	Ni(NO ₃) ₂ ·6H ₂ O	1571	7.21E-03
Potassium Nitrate	KNO ₃	2755	3.64E-02
Strontium Nitrate	Sr(NO ₃) ₂	8	5.16E-05
Zinc Nitrate	Zn(NO ₃) ₂ ·6H ₂ O	123	5.53E-04
Zirconyl Nitrate		114	6.13E-04
EDTA*	Na ₂ EDTA	4343	1.56E-02
HEDTA*	HEDTA	1294	6.21E-03
Sodium Gluconate		2349	1.44E-02
Glycolic Acid		16112	1.98E-01
Citric Acid		5648	3.59E-02
Nitrilotriacetic Acid		341	2.38E-03
Iminodiacetic Acid		3613	3.62E-02
Boric acid	H ₃ BO ₃	120	2.58E-03
Sodium Chloride	NaCl	1088	2.48E-02
Sodium Fluoride	NaF	176	5.59E-03
Sodium Sulfate	Na ₂ SO ₄	7299	6.86E-02
Potassium Molybdate	K ₂ MoO ₄	53	2.98E-04
Sodium Hydroxide	NaOH	15047	5.02E-01
Aluminum Nitrate	Al(NO ₃) ₃ ·9H ₂ O	3211	1.14E-02
Sodium Phosphate	Na ₃ PO ₄ ·12H ₂ O	2658	9.33E-03
Sodium Formate	NaHCOO	9401	1.84E-01
Sodium Acetate	NaCH ₃ COO·3H ₂ O	1418	1.39E-02
Sodium Oxalate	Na ₂ C ₂ O ₄	752	7.49E-03
Sodium Carbonate	Na ₂ CO ₃	88703	1.12E+00
Sodium Nitrate	NaNO ₃	178069	2.79E+00
Sodium Nitrite	NaNO ₂	54741	1.06E+00

*(EDTA=Ethylenediaminetetraacetic Acid Disodium Salt Dihydrate)
*(HEDTA=N-(2-Hydroxyethyl)ethylenediaminetriacetic Acid)

Solids

Compound Name	Compound Formula (particle size)	g/100g solids
Alumina	Al ₂ O ₃ (1-5 microns)	5.1%
Calcium Phosphate, tribasic	Ca ₃ (PO ₄) ₂ (5-10 microns)	0.1%
Chromium Oxide	Cr ₂ O ₃ (1-2 microns)	0.4%
Ferric Oxide	Fe ₂ O ₃ (1-2 microns)	2.4%
Ferric Oxide	Fe ₃ O ₂ (5-10 microns)	2.4%
Manganese Oxide	MnO ₂ (1-2 microns)	1.6%
Manganese Oxide	MnO ₂ (5-10 microns)	1.6%
Sodium Aluminosilicate	Na ₂ OAl ₂ O ₃ (SiO ₂)·2.5H ₂ O (3-6 microns)	1.6%
Sodium Oxalate	Na ₂ C ₂ O ₄ (*)	34.2%
Sodium Carbonate Monohydrate	Na ₂ CO ₃ ·H ₂ O (*)	32.3%
Sodium Fluoride	NaF (*)	5.0%
Sodium Sulfate Decahydrate	Na ₂ SO ₄ ·10H ₂ O (*)	4.1%
Sodium Phosphate Dodecahydrate	Na ₃ PO ₄ ·12H ₂ O (*)	9.3%
Total		100.0%

*These solids were not expected to hold their dry particle sizes

Figure 4. Simulant: Supernatant only[†]

Figure 5. Simulant: Solids Only[†]

The particle size distribution of the real waste was determined (Lumetta and Hoopes, 1999) to be bimodal, ranging from 1-2 microns and from 5-10 microns. Figure 5 includes the particle sizes of the solids which were used in the simulant and Fig. 6 shows the simulant particle distribution by volume, however a distribution by population had an average particle size of 1 micron.

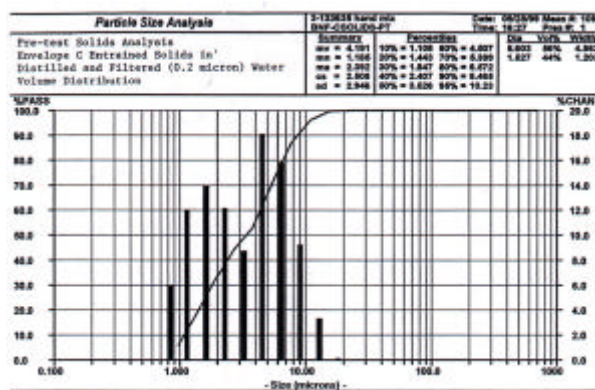


Figure 6. Insoluble solids distribution by volume

[†] This simulant represents the waste that is being stored in the Department of Energy Hanford Site tank number 241-AN-107 (Jo et al., 1996; Urie et al., 1999; Lumetta and Hoopes, 1999; Eibling and Nash, 2000).

Figure 7 shows several samples of the slurry in Nalgene containers that were drawn during the test with estimate of the insoluble solids concentration.



Figure 7. Settled solids in simulant

Suspended Solids, wt%	Total Solids, wt%	Density g/mL	Viscosity cP	Consistency* cP	Yield Stress* dynes/cm ²
0	34	1.27	3.2	-	-
2	36	1.29	4	-	-
9	41	1.36	-	7.4	3.4
14	44	1.39	-	11.6	9.2
22	49	1.47	-	23.4	55.4

*Based on a Bingham fluid model

Figure 8. Some of the slurry properties at 298 K

The data in Fig. 8 imply that for a high solids loadings the simulant rheologically behaved as a fluid that can be represented by the Bingham model. Using such a model is a simplifying assumption but this is adequate for engineering purposes, Fig. 9. However, the simulant at elevated insoluble solids loadings is actually a thixotropic fluid, or a pseudoplastic fluid where the properties are time dependent. A pseudoplastic fluid is known for its shear-thinning properties which means that there is a reduction in viscosity as the rate of shear increases in a steady shear flow.

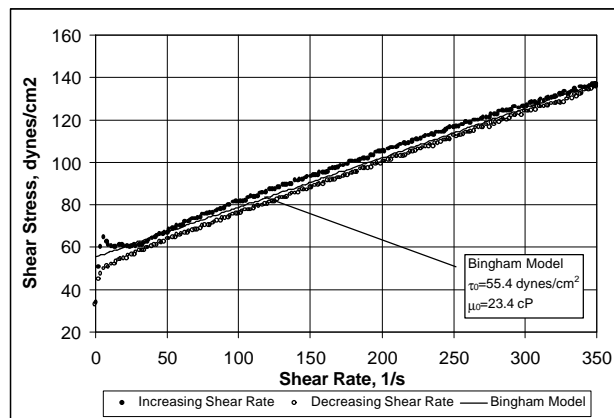


Figure 9. Bingham rheological model fit to the simulant at 22 wt% suspended solids

3. Results and discussion

3.1. Low insoluble solids concentration

Figure 10 compares all the low solids concentration test runs together and are displayed in chronological order with test run 1 being the earliest. The values for the filtrate flux given in the graph were averaged over the time of each test, which was approximately two hours; starting and ending with a backpulse. It would appear that the flow conditions of run 1 ($V=3.5$ m/s, $TMP=385$ kPa) gave the highest filtrate flux. A close second were for runs 5, 7, and 9, with an axial velocity of 4.6 m/s and TMP from 207 to 356 kPa. They all had a filtrate flux of 17 cm/hour, or better.

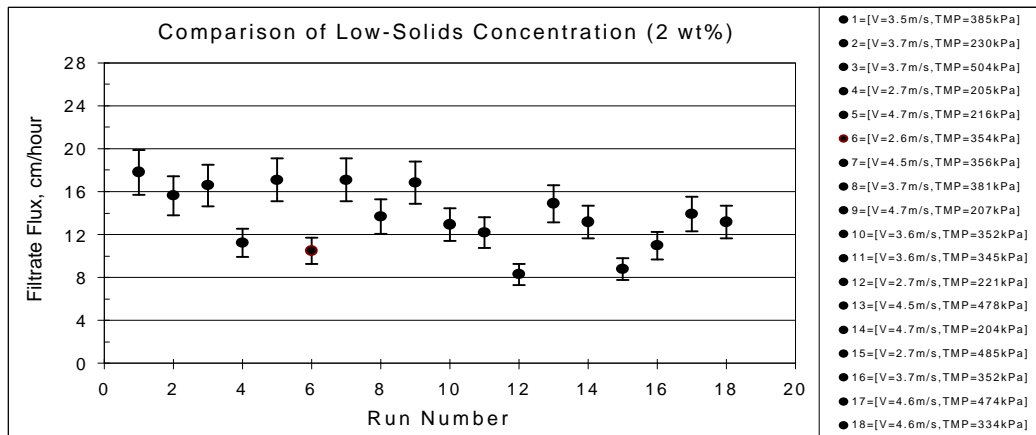


Figure 10. Composite of all low-solids concentration test runs.

Direct comparisons among the test runs are made difficult by the effect of filter depth fouling with time. To study this effect a comparison was made among the five runs (Nos. 1, 8, 10, 11, and 16) which were closely matched in slurry flow conditions, that is, 3.5 m/s $\leq V \leq 3.7$ m/s and 345 kPa $\leq TMP \leq 385$ kPa. Those data are shown in Fig. 11.

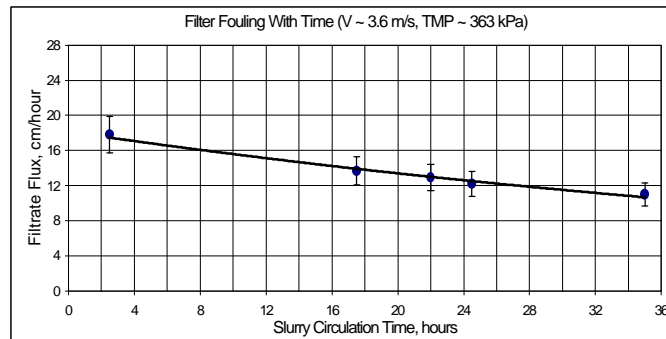


Figure 11. Effect of slurry circulation time on filter flux performance

Between the beginning of the first and end of the last of these five test runs the slurry had an accumulated circulation time of 35 hours through the filter where the filtrate flux decreased by approximately 60%. Therefore, during the period of each test shown in Fig.

10, which had a duration of approximately 2 hours, the filtrate flux degraded by approximately 3%. This degradation was a permanent loss of filter performance until it could be cleaned.

Considering the effect shown in Fig. 11, then, the general trend shown of the chronologically ordered data in Fig 10 makes sense. That is, independent of the flow condition, the overall trend of the filtrate flux data was to decrease with time due to depth fouling and therefore results can only be compared which are close to each other in time. Since the measurement uncertainty for the temperature corrected filtrate flux was 11.7%, which was previously mentioned, then a 3% filtrate flux degradation is insignificant between runs that are less than 8 hours apart.

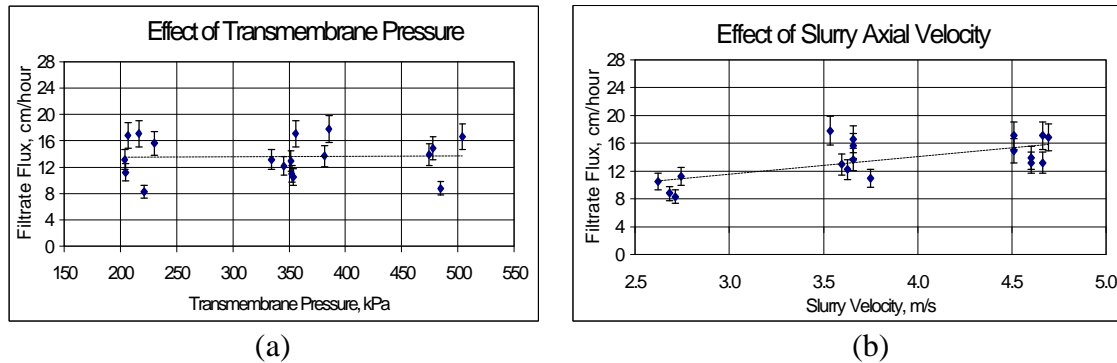


Figure 12. Filtrate Flux vs. TMP and slurry velocity: slurry had 2 wt% of insoluble solids

Even when taking into account the effect of fouling and the measurement uncertainty, two general results stand out when consider all the low insoluble solids data: The filtrate flux was independent of TMP, Fig. 12a, but was directly dependent on the slurry axial velocity, Fig. 12b. The lines drawn through the data on both figures were obtained from a least square fit to the eighteen points.

3.2. High insoluble solids concentration

Figure 13 is an overall comparison of the high-solids concentration test runs. Run 1 had an insoluble solids concentration of 22 wt%, but the remaining six runs had a concentration of 14 wt%. The intention was to do all the runs above 20 wt% but centrifugal pumps that were used could not handle the thick slurry. In fact, run 1 had to be stopped after 35 minutes of operation; therefore the filtrate flux in Fig. 13 is for that shorter time period. However, after the first 10 minutes run 1 stabilized at a constant filtrate flux of 2.4 cm/hour. Starting with run 2 the slurry was diluted to a concentration of 14 wt%, which allow the required two-hour period per test run to continue.

While the cross-flow filter had a continuous flux of filtrate at the higher solids loadings, the magnitude of the best sustainable flux was 25% (~ 4.5 cm/hour) of the best maintainable flux for the lower solids concentration. Further, the same conclusion made for the lower solids concentrations still held. That is, increasing the TMP had little affect on the filtrate flux, e.g., compare test runs 4 to 5, but increasing the slurry axial velocity had a significant affect on filtrate flux. e.g., compare test runs 3 to 5. It appears that the

only effect of the thicker, non-Newtonian, slurry had on filtration was to reduce the filtrate flux. Figure 14 shows one of the slurry runs at 14 wt% of solids. Besides the lower magnitude of filtrate flux, it behaved similar to when it behaved as a Newtonian fluid. The data in Fig. 14 do not smoothly transition to a constant value because the filtrate flow rate (0.16 lpm at a flux of 4.5 cm/hour) was near the bottom of the measurement range (0 – 4.5 lpm) of the magnetic flow meter.

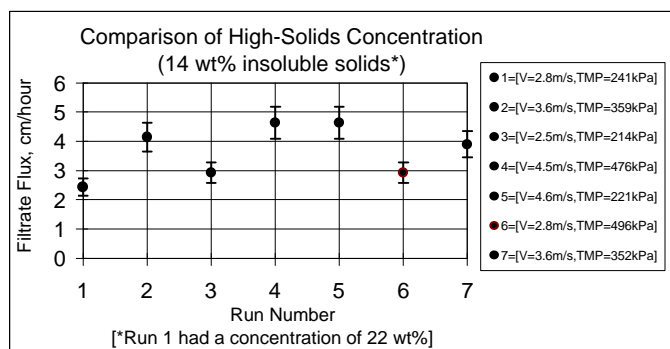


Figure 13. Composite of all 7 high solids concentration test runs

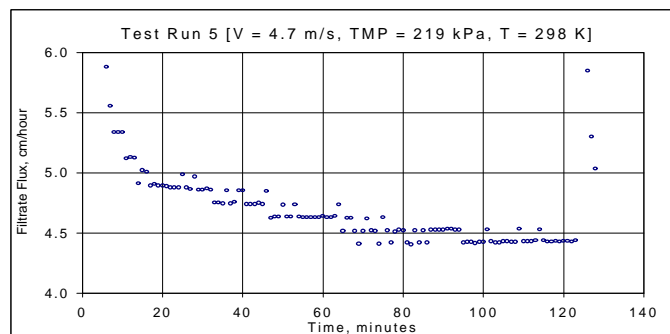


Figure 14. Slurry run at 14 wt% insoluble solids: Run 5

3.3. Comparisons to other experiments

The average filtrate flux obtained for all test runs with the low solids concentration simulant was > 8 cm/hour. This flux was 75% lower than that obtained by one cross-flow filtration investigation by Murkes and Carlsson, 1988; (p. 41), where a filtrate flux of approximately 40 cm/hour was measured after 2 hours of filtering for a much simpler slurry of distilled water and clay (kaolin). [The experimental conditions were: a nominal filter pore rating of $0.2 \mu\text{m}$, $\text{TMP} \sim 200$ kPa, $V \sim 2.5$ m/s, 0.9 wt% insoluble solids, particle sizes $< 2 \mu\text{m}$, a slurry viscosity of 1 cP, and a temperature of 297 K.] Conversely, a filtrate flux of 8 cm/hour was significantly higher (by almost an order of magnitude) than that of a shear-thinning slurry of guar gum, which was investigated by Carrère et al, 1998. [Their filtrate flux was approximately 1 cm/hour for the experimental conditions of: a nominal filter pore rating of $0.14 \mu\text{m}$, $\text{TMP} \sim 200$ kPa, $V \sim 3$ m/s, 0.4 w% concentration of guar gum, particle size of $0.24 \mu\text{m}$, a slurry apparent viscosity of ~ 400 cP at 1 s^{-1} and 62 at 10^3 s^{-1} , and a temperature of 293 K.]. However, when the solids concentration of the

slurry for this test was raised to 22 wt% the average filtrate flux (2.5 cm/hour) dropped to the same range as what was observed with the guar gum slurry (1 cm/hour).

3.4. Backpulsing

Most of the test runs discussed in this paper had a duration of two hours between backpulses. The cross-flow filter was backpulsed at the start of each run and after two hours, which ended the run. For the filter under study, the manufacturer recommends that the backpulse frequency be no greater than once an hour; but the longer the time between backpulses the better. Even though the filter elements used had a thick wall (1.6 mm as opposed to a thin membrane filter), it was made to function as a surface, and not a depth, filter. The solids that are removed from the slurry are to remain on the surface of the filter and not lodged within the filter wall. As the filter cake builds, it itself becomes a secondary filter (Murkes and Carlsson, 1988) and according to Fischer and Raasch, 1986 and Lu and Ju, 1989, it is the smallest particles in the slurry that form the cake. When a backpulse occurs, some (Mores et al., 2000), or all of the filter cake is knocked off the fixed filter surface, which allows a higher filtrate flux, but also exposes the filter substrate to more of the smaller solid particles. Continued backpulsing will cause depth fouling and a reduced performance, making further backpulsing less effective. Even with only a 2 hour backpulse interval Fig. 11 clearly shows that depth fouling did occur from the approximate two-dozen backpulses made during the 35 hours of those tests. Fortunately, once the filtrate flux reached an asymptotic value after approximately 80 minutes, see Fig. 14, it remained fairly constant. During an earlier test with a different slurry (Duignan, 2000), where the cross-flow filter ran for more than seven hours between backpulses, the filtrate flux was still within 10% of the value after 80 minutes. In fact, the indications were that the flux could have held for a considerably longer time period, which is not unrealistic since some cross-flow filters have run for 12 months without a chemical cleaning or backpulsing (Howell, 1994).

Even though there are reasons to minimize backpulsing, one of the high-solids concentration runs was done with a 20-minute backpulse interval to determine what kind of an improvement could have been realized. Figure 15 shows the result of that test.

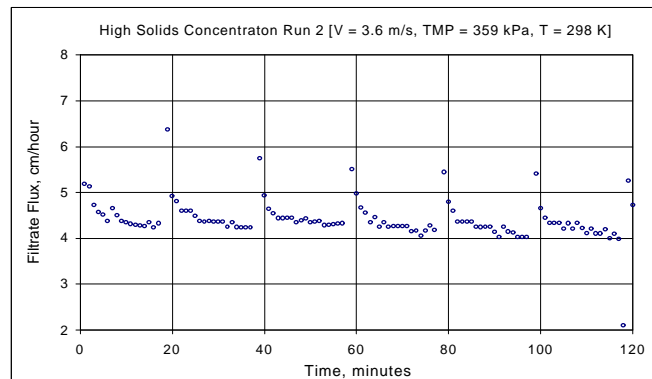


Figure 15. Slurry run at 14 wt% insoluble solids: Run 2

For this non-Newtonian fluid, at 14 wt% of insoluble solids, the increased backpulse frequency did not result in a significant increase in filtrate flux, which has been observed by others (Mores et al., 2000) for high solids concentrations. Compare the average result of Run 2 to Run 7 in Fig. 13. Both runs had the same slurry flow conditions and both had statistically the same filtrate flux, however Run 7 had no backpulse during its two-hour run, while Run 2 had five. It is believed that the shear-thinning nature of the slurry prevented any significant increase in filtrate flux. Moreover, since the filtrate flux generally returned to the same magnitude after each backpulse, it appeared that surface fouling was the predominate mode of fouling. Literature shows that the majority of cross-flow filters experience an improved filtrate flux with an increase of backpulse frequency (Mores et al., 2000; Gan, 1999; Levesley and Hoare, 1999; Ramirez and Davis, 1998). However, filters that work well at those frequencies are very thin membranes where depth fouling is generally not a factor, i.e., a particle that manages to enter a filter pore just goes right through because of the thin membrane. Further, most slurries are not the sticky non-Newtonian types, which may not readily dislodge after a backpulse.

4.0 Conclusions

The following conclusions are for the nominal rated 0.1 micron MOTT cross-flow filter that was used under the conditions stated herein at a slurry temperature of 298 K.

1. The increase in filtrate flux is strongly affected by the slurry velocity but only weakly by TMP.
2. For a low concentration of insoluble solids (2 wt%), the best overall filtrate flux obtained was 17 cm/hour at a slurry velocity of 3.5 m/s and a TMP of 385 kPa. However, most test runs at the higher velocity of 4.6 m/s gave similar results.
3. For a high concentration the insoluble solids (14 wt%), the best flux overall filtrate flux was 4.5 cm/hour at a slurry velocity of 4.6 m/s and a TMP of 221 kPa.
4. For the single test run (No. 1) with an insoluble solids concentration of 22 wt%, the filtrate flux was maintained at 2.4 cm/hour for approximately 35 minutes. (The run was stopped due to a pump seal failure and not from a filter pluggage.)
5. Surface fouling of the filter was dominant mechanism of fouling.
6. For the slurry at the higher concentrations of insoluble solids backpulsing the filter did not significantly increase the average filtrate flux.

Acknowledgments

The author would like to thank all that were involved in this task including members of the Savannah River Technology Center of the Westinghouse Savannah River Company and BNFL, Inc. The work was funded by the U.S. Department of Energy under Contract DE-AC09-96SR18500.

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