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AN INVESTIGATION ON PERMEABILITY OF CERAMIC FOAM FILTERS (CFF)

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Abstract

CFFs are used to filter liquid metal in the aluminum industry. CFFs are classified in grades or pores per inch (PPI), ranging from10-100 PPI. Their properties vary in everything from pore and strut size to window size. CFFs of 80-100 PPI are generally not practical for use by industry, as priming of the filters by gravitational forces requires an excessive metal head. Recently, co-authors have invented a method to prime such filters using electromagnetic Lorentz forces, thus allowing filters to be primed with a low metal head.

In the continuation of this research work, an improved experimental setup was developed in the present study to validate previous results and to measure the permeability of different filters, as well as a stack of filters. The study of permeability facilitates estimation of the required pressure drop to prime the filters and the head required to generate a given casting rate.

Introduction

CFFs have been widely used in aluminum industry to filter inclusions/particles from molten metal since the 1990's [1-4]. These nonmetallic inclusions can be refractory particles, aluminum oxides, magnesium oxides, spinels, nitrides, borides and carbides [5-6]. Such impurities have negative effects on process-ability, mechanical properties and the surface quality of the products produced from the aluminum [2], [6-7].

A CFF has a porous structure of voids created by a web or 'mesh' of ceramic material [2]. CFFs are made in different grades or PPIs. Therefore the physical properties of the filters: porosity, tortuosity, pore, window and strut size vary with PPI [4], [8]. Such differences have an influence on the priming and permeability of the filters [4], [6].

In general, molten metal poured on the top of a filter has to reach to a certain height to achieve a certain level of pressure (gravity head) to prime the filter media. Priming is defined as filling the filter with metal and removing the entrapped air. Consequently, in larger PPI or small pore size filters a higher metal head is required to achieve priming, due to the lower permeability of the filters [4], [6]. Thus, filters like 80-100 PPI are typically not practical in industry due to the excessive metal head required for priming and high pressure drop during casting operations. Therefore, achieving more efficient filtration by using CFFs with more than 50 PPI is an industrial challenge and establishing new techniques for priming high PPI filters would be a significant enabling technology.

Recently co-authors [4], [6], [9] have proven that electromagnetic Lorentz forces will prime up to 80 PPI filters using metal heads equal to or less than those typically used for 30 PPI in the laboratory. The Lorentz force creates a driving force in addition to gravity and considerably reduces the required metal head. This has created an opportunity for the possible application of higher PPI filters industrially.

To predict the pressure drop of CFFs analytically or numerically the permeability of the filters must be known. Permeability is the ability of a media (such as a CFF) to let a fluid (such as liquid metal) to pass through its pores and openings. Permeability enables the prediction of the required metal head or pressure necessary to push metal through the filter media at a given flow rate [4], [10]. The Forchheimer equation shown as Equation (1), can be used to predict the pressure drop at both low and high velocity if the Darcy and Non-Darcy permeability coefficients are both known [4], [10]–[12].

$$\frac{\Delta P}{L} = \frac{\mu V_S}{k_1} + \frac{\rho V_S^2}{k_2} \qquad (1)$$

Where ΔP is pressure drop in [Pa], L is filter thickness [m], V_s is superficial velocity [m/s], μ is the dynamic viscosity [Pa·s], ρ is the fluid density [kg/m^3], k_1 [m^2] and k_2 [m] are the Darcy and Non-Darcy permeability coefficients respectively.

The Darcy and non-Darcy coefficients can be estimated by measuring the pressure drop of a fluid such as water flowing through a known filter thickness at a known velocity and temperature. Recent studies on 30-80 PPI filters by Kennedy *et al.* [4] show that to perform a correct measurement it is essential to avoid fluid bypassing at the wall by proper sealing. A low permeability method of wall sealing led to high level of agreement between experimental, analytical and FEM methods [4]. In a continuation of the previous research, an improved experimental setup has been developed to validate previous results by proving that the measured pressure drop increases linearly with thickness (i.e. that there is zero bypassing at the wall) and to measure the permeability of additional filter types.

Experimental Details

Liquid permeability of 30, 50 and 80 PPI commercial ceramic foam filters, have been determined using water in the temperature range of 282 K to 284 K (9℃ to 11℃). Water was circulated through a 47 mm diameter smooth pipe with mass flow rates from 0.62 to 1.74 kg/s. There was a straight inlet pipe length of 1.2 m or about 25 *L/D*'s in front of the pressure measuring apparatus to allow the flow profile to develop and similar length of straight pipe after the apparatus. Previous studies revealed no significant influence by using a longer inlet length on the measured pressure drop [4]. Two Plexiglas® filter holders; one for single and the other for triple filter measurements were fabricated and used, as shown in Figure 1. Pressure differential measurements were obtained using a DF-2 (AEP, Transducer, Italy) pressure transducer; with a measuring range from 0 to 1 bar, an output range of 4 to 20 mA DC, and a certified error of ‹±0.04% of reading based on the factory calibration. The current produced by the pressure transducer was measured using a FLUKE 289/FVF true-RMS digital multi-meter with a data logging feature and a resolution of 0.01 µA DC.

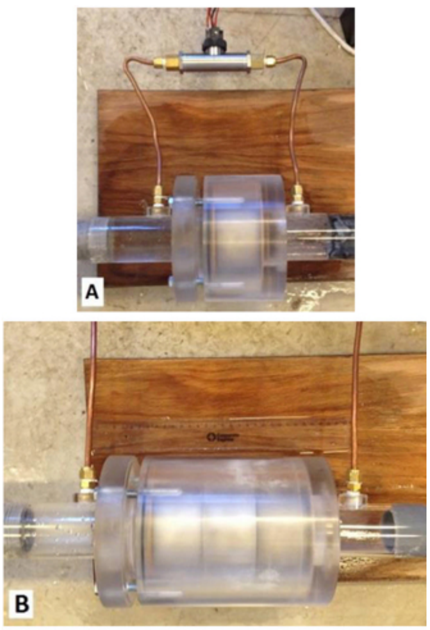

Figure 1: A) the transducer and apparatus used for pressure drop measurements of single filters and B) the apparatus used for pressure drop measurements for stacks of 3 filters.

Water velocity was calculated based on the mass flow measured using the weight gain in a container with a maximum capacity of 53 kg of water during a specified time period. In order to measure and log the gain-in-weight, an OHUAS T31P scale (3000 series indicator) equipped with OHAUS Data Acquisition Software (D.A.S.) was used. The temperature has been measured using a FLUKE 80PT-25 T-Type probe with the accuracy of ±1°C in the temperature range of 0°C to 350°C. Temperature data has been logged by a National Instruments NI USB-TC01 logger. Data were collected at one second intervals for all three logging devices.

The water flow was produced by a 1000 W, 0.8 bar submersible pump that was placed at the bottom of a 53 kilograms capacity container. The flow rate was regulated by a DN 25 ball valve located between the outlet of the pump and the inlet of the experimental setup pipeline.

A series of nine 51 mm diameter samples: (3) 30, (3) 50, and (3) 80 PPI were cut by a CNC controlled water jet cutting machine from standard 9" commercial CFFs. The samples were later manually resized to about 49 mm diameter to fit into the filter holder. This was done to avoid any bias in size that might happen during cutting and to fabricate an equal gap between the outside of the samples and the inner diameter of the filter holder for later sealing. The sealing procedure includes; blocking the side walls of the samples, resizing, and wrapping in grease impregnated cellulose fiber to tightening the samples while fitting in filter holder. All the samples were taken from the corner of a 9" filter, as shown in Figure 2. Exactly the same preparation procedure has been applied to all nine samples.

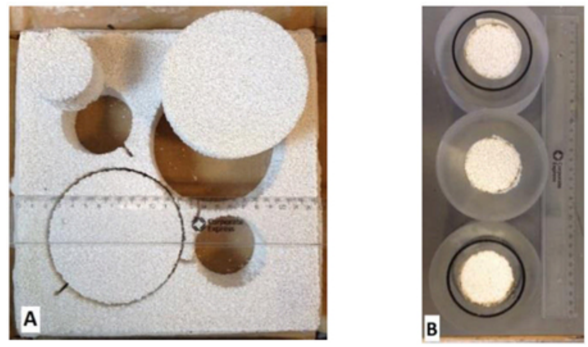

Figure 2: A) a 9" 50 PPI filter with the samples taken from the filter B) samples sealed into sample holders and prepared for the experiments.

Samples were divided into three groups, N1-N3, and N3 was used as a benchmark sample where no sealing procedure was applied, allowing for unhindered bypassing of fluid along the wall of the holder apparatus. After performing experiments with the single filter apparatus, a stack of three filters were measured. In this series of experiments three filters and filter holders were used, as shown in Figure 2 B. Samples from group 1 (N1) were always kept as the ones facing the inlet of the apparatus. Group 2 Samples (N2) were in the middle and Group 3 (N3) were always placed at the end or faced to the outlet of the apparatus.

In order to determine the porosity of the filters, the samples were first dried in oven at 150°C for 15 hours and then resized to fit in the filter holders. Then the dimensions of the samples were measured using a digital caliper with accuracy of 0.03 mm and a resolution of 0.01 mm. The samples were weighed using a digital laboratory scale with resolution of 0.01 g. Then the volume was measured using a series of graduated cylinders. The total and open porosities of the filters were calculated based on both weight (Equation 2) and volume (Equation 3). The open pore porosity is the total porosity excluding the trapped porosity, i.e. inside of struts and the micro-porosity of the filter media [4], [13]. The difference in the porosity values are expected to be less than 5 pct. [14]. The results of the measurements can be found in Table I. The recorded diameter and thickness in Table I are the average values of ten readings.

$$Porosity\ 1 = \frac{(Mt - Ma)}{Mt} \times 100 \quad (2)$$

$$Porosity\ 2 = \frac{(Vt - Va)}{Vt} \times 100 \quad (3)$$

Where M_t is the theoretical weight [kg] estimated from the measured volume using a recommended density of 3.48 g/cm^3 from reference [4], M_a the measured weight [kg], V_t the total volume [m^3] and V_a the open pore volume [m^3].

Table I: Dimension and Porosity Measurements

Filter No.	Type	*Diameter [mm]*	*Thickness [mm]*	*Porosity 1 [%]*	*Porosity 2 [%]*
N1	30	49.33	50.42	90	88.8
N2	30	49.00	50.83	91	90
N3	30	49.38	50.76	90	91.5
N1	50	49.58	50.88	86	83.5
N2	50	49.30	49.98	86	84.6
N3	50	49.68	50.63	85.9	82.6
N1	80	49.63	49,79	85.6	81.5
N2	80	49.38	50.28	86.4	85.8
N3	80	49.30	50.96	87	85.1

Porosity 1 is based on weight (Equation 2) and *Porosity 2* is based on volume (Equation 3).The porosity difference are in the range of 1-3 pct.

Results

Permeability measurements on individual filters of different PPI, and stack of three filters of the same PPI were performed by using the apparatus shown in Figure 1 A and 1 B as indicated previously. Results of pressure drop per unit length as a function of superficial velocity for both single and stacks of 3 filters of 30, 50 and 80 PPI are plotted in Figure 3. This figure also includes results from the previous studies, which are labeled as P (previous) [4]. The results from stacks of three different PPI filters (one 30, one 50 and one 80), are shown in Figure 4.

Darcy k_1 [m2] and Non-Darcy k_2 [m] permeability coefficients (calculated using the Forchheimer Equation 1) were calculated using second order least square regression equations derived automatically using Excel 2010 of the same form as Equation 4.

$$A = bV_s + cV_s^2 \qquad (4)$$

Where A is measured differential pressure over the length of a sample [Pa/m], b is the fluid dynamic viscosity divided by the Darcy coefficient [(Pa.s)/m^2], and c is the fluid density divided by the Non-Darcy coefficient [(kg/m^3)/m].

Water density and viscosity has been calculated based on the measured temperature during experimental trials using precise correlations available in the literature [15], [16]. The calculated values of the viscosity and density were used with the correlation coefficients found using Excel to estimate the Darcy and Non-Darcy coefficients of Equation 1, as summarized in Table II.

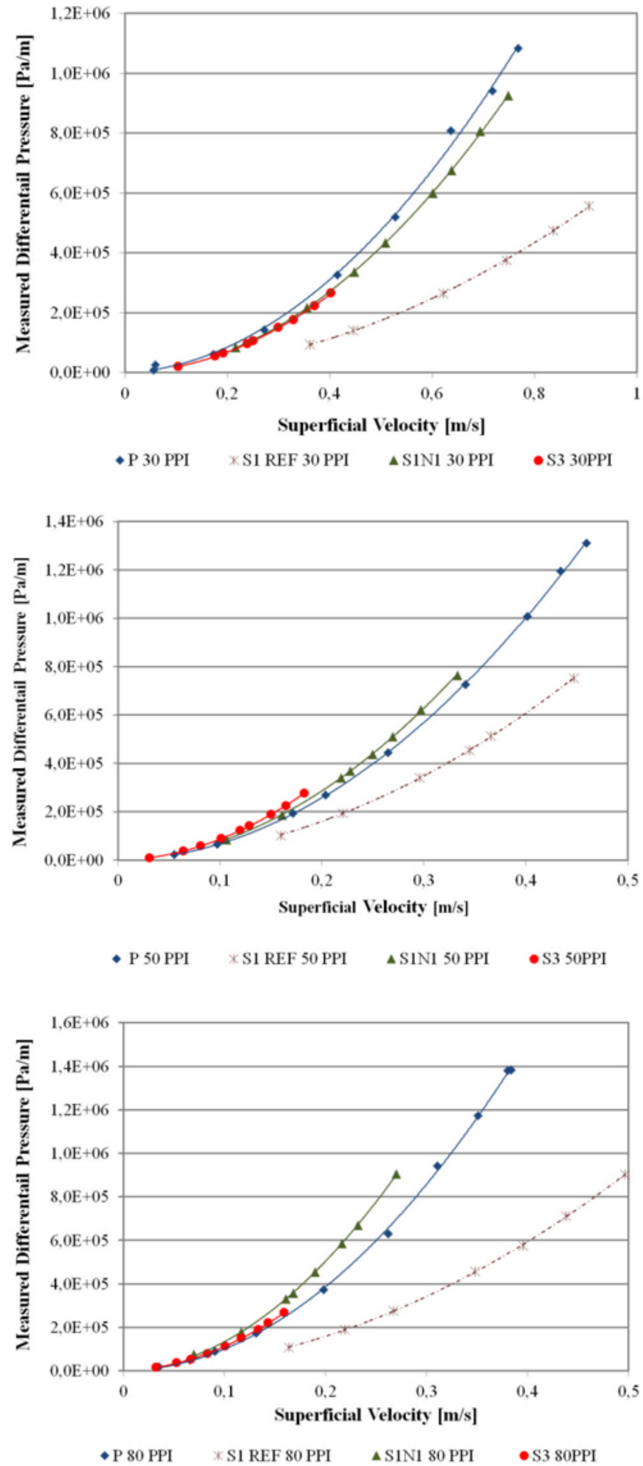

Figure 3: Pressure drop per unit length measurements [Pa/m] of single 30, 50 and 80 PPI filters (S1N1), triple filters (S3) and comparison with unsealed (REF) samples and previously published results (P) [4] as a function of superficial velocity [m/s].

Table II: Permeability Measurement Results

Sample No	*Water Temperature [K]*	*Water Viscosity [Pa·s]*	*Water Density [kg/m³]*	*Forchheimer k_1* [m²]*	*Forchheimer k_2 [m]*
S1N1 30	283,6	1,29E-03	999,7	3,93E-08	5,00E-04
S1N1 50	282,5	1,33E-03	999,8	1,22E-08	1,43E-04
S1N1 80	283,8	1,28E-03	999,7	7,94E-09	1,00E-04
S3 30	283,7	1,28E-03	999,7	3,77E-08	5,00E-04
S3 50	283,6	1,29E-03	999,7	1,51E-08	1,25E-04
S3 80	284,2	1,27E-03	999,6	7,39E-09	1,11E-04

*The k_1 term has been estimated 'automatically' using Excel, from high velocity measurements. This method concentrates experimental 'noise' into the k_1 term, making only the k_2 values statistically reliable. k_1 values will be directly measured by additional experiments using a low pressure range transducer at velocities closer to those traditionally used during metal casting. These k_1 values can therefore not be directly compared to previously published values [4].

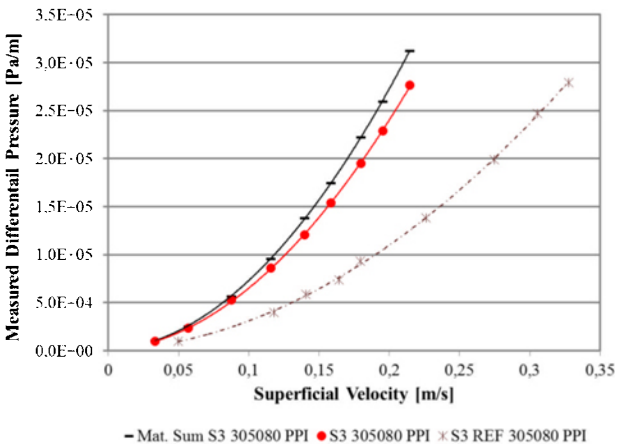

Figure 4: Pressure Drop measurements [Pa/m] of stack of 3 different PPI filters as a function of superficial velocity [m/s]. The dotted line represents unsealed trial. Results are compared to the mathematical sum of the individual filter pressure drops evaluated using Equation 1 and the permeability constants given in Table II.

Discussion

Sealing Procedure

As can be seen from Figures 3 and 4 there is a factor of 1.5 to 2 times difference in pressure drop at any given flow rate when comparing a well-sealed to an un-sealed filter sample. The maximum fluid flow rate is higher for un-sealed samples due to the same peak pressure pump pressure being available. The figures show an increasing difference at higher flows as the increasing filter pressure drop causes more bypassing along the wall for un-sealed samples at higher flows rates, i.e. the gap between sample and wall represents the path of least resistance. Hence inadequate sealing or no sealing would result in extremely poor estimates of the Forchheimer coefficients and a consistent underestimation of the pressure drop at any given flow rate under 'well-sealed' conditions.

Single Filter Experiment

The permeability results for samples extracted from different commercial filters indicate that there is a measureable variation in filter-to-filter permeability, as shown in Table II. This emphasizes the need to sample many filters in order to get a statistically reliable estimate of k_1 and k_2 for a given grade of filter from any given manufacturer.

Comparing with the Previous Single Filter Experiments:
The pressure gradients shown in Figure 3 and the calculated second order Forchheimer coefficients in Tables II and III show nearly identical results to those obtained previously [4], with a typical difference of only 8-14% in the obtained k_2 values. The new experiments on 30, 50 and 80 PPI filters are therefore considered to validate the previous study. The slightly lower k_2 values from the current study are most likely due to better wall sealing, which resulted in a higher measured pressure drop at each flow rate.

Table III: Comparison between New and Previously Measured [4] Non-Darcy (k_2) Coefficients

Filter [PPI]	New Study k_2 [m]	Previous Study k_2 [m]	Deviation [%]
30	5,00E-04	5,46E-04	-8.42
50	1,43E-04	1,66E-04	-13.86
80	1,00E-04	1,15E-04	-13.04

Comparing Single Filter Results to Stacks of Three Filters of the Same Type: The red curves in Figure 3 indicate the measured pressure gradient as a function of superficial velocity for stacks of three filters of the same type: 30, 50 and 80 PPI. As expected [11] it can be seen that the measured pressure gradient is not changed by changes in filter thickness (between 1 and 3 filters), i.e. Equation 1 is valid and wall bypassing did not occur. A three times higher pressure must be applied to achieve the same fluid velocity in a stack of three identical filters when compare to a single filter of the same type. Hence, nearly identical Forchheimer coefficients were obtained for individual and stacks of three filters as shown in Table II.

Stack of Three Filters

Figure 5 summarizes the results for stacks of 3 filters. Results are shown for stacks of 30, 50 and 80 PPI as well as one stack consisting of one each of 30, 50 and 80 PPI. As can be seen a stack of three 80 PPI filters requires the highest pressure achieve a given flow due to the lower porosity (see Table 1), greater tortuosity and smaller window and cell sizes as found previously [4]. As a result lower permeability is determined for filters of higher PPI, i.e. a higher pressure gradient is required to achieve any given fluid velocity. The measured differential pressure gradient decreases and permeability increases for lower PPI filters due to the decrease in tortuosity, and increase in the porosity, window and cell sizes.

A stack of one 30, one 50 and one 80 PPI filter has an 'average' permeability and hence intermediate pressure gradient. The total pressure drop is dominated by the 50 and 80 PPI filters as indicated by the relative position of the red line in Figure 5.

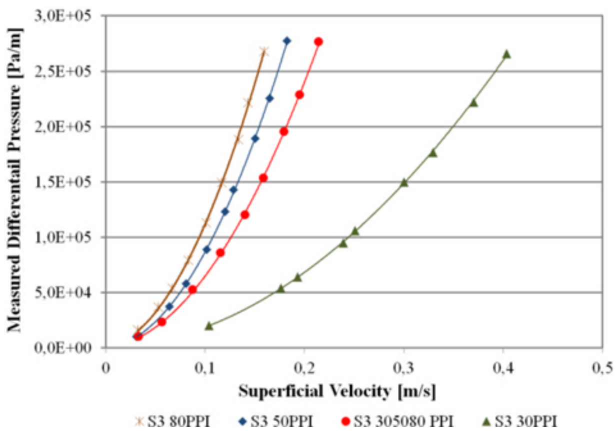

Figure 5: Comparison between the measured pressure drop per unit length [Pa/m] for stacks of 3 filters (30, 50 and 80 PPI) with one stack consisting of one 30, one 50 and one 80 PPI.

Conclusion

An improved experimental setup was developed to validate previous results and to measure the permeability of different filters, as well as stacks of filters. Darcy and Non-Darcy coefficients for the Forchheimer equation were calculated using Equation 1.

The Non-Darcy coefficients of the current trials have been compared to previous results for single filters and found to reproduce the previous results with a typical difference of only 8-14%.

Stacks of three identical filters gave substantially the same results in terms of the measured pressure gradient as for single filters, i.e. pressure drop was shown to increase linearly with filter thickness in accordance with Equation 1, indicating that the samples were 'well-sealed'. These results also confirm that both the previous experimental results were also 'well-sealed'.

The pressure drop for a stack of three different filter types (30, 50, and 80 PPI) were shown to have the mathematical sum of the individual pressure drops further confirming the accuracy of the individual estimated Forchheimer coefficients and the lack of bypassing along the wall.

It has been shown that pressure drop data obtained from samples without wall sealing have more than a factor of 2 error and cannot be used to derive accurate permeability constants, due to bypassing along the walls. In order to avoid wall bypassing it is necessary to completely seal the walls of the specimens.

Future Work

Additional experiments will be conducted using a lower range (~0.1 bar) pressure transducer in order to directly measure the Darcy k_1 term of the Forchheimer equation using velocities closer to typical casting velocity and where the second order non-Darcy term is not significant. CFD modelling of the recent and future work will be conducted using COMSOL® to compare with the experimental data. Evaluations of cell, window and strut size will be made to correlate with the obtained k_1 and k_2 values.

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