Low Resistance, High Flow PrimaFlow® Filters

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Abstract

Extended surface filter bags (ESB), also known as StarBags™, have been used for over fifteen years in primary aluminium smelter gas treatment centers (GTC). They were initially validated as a cost-effective way to increase the capacity of an existing GTC when potlines increase production with line amperage increase, thereby debottlenecking production increases without the need for capital upgrade in the GTC. Since inception and lapse of the initial product patent, there have been several design modifications to the commercially available ESB filters. Most of these modifications have been focused single facedly on increasing the available filtration area in order to further leverage the initial application benefits.

With the trend towards the continued incremental increase in amperage, ESB filter product application and design modifications have now been shown to have benefit limitations. Failing to recognize these limitations, some more recent ESB projects have now failed to achieve all of the project target outcomes in several aluminium smelters.

Recognising this application limitation, a new systematic approach to the StarBag™ design and implementation has been developed. This paper will discuss the limitations of current ESB filter designs, present a new systematic approach to this problem and outlines some successful application case studies. In one particular application case study presented, it will be shown that the latest ESB design development has achieved all of the project target outcomes while at the same time has achieved a much higher gas flow through the GTC than has been achieved with any other technology previously used.

Keywords: Gas treatment centre, Alumina dry scrubber, Extended surface filter bags, StarBag™, PrimaFlow®.

1. Introduction

In the 1970s, pleated cartridge filters were introduced [1] as an alternative to fabric filter bags in an effort to reduce the footprint of new capital equipment. This was achieved by a reduction in air-to-cloth (ATC) ratio by drastically increasing the cloth area. However, limitations were encountered where high dust loading bridged the tight pleats in the cartridge filters [2], and it was soon discovered that cartridge filters were not appropriate in high dust load environments [3].

In the mid-1990s the ongoing need to lower ATC ratios in existing equipment seeking better baghouse performance without pleat bridging, inspired the invention of the StarBag™ [4]. The process of commercializing this invention was initially slow, until after assignment of the original patent, Albany International (currently known as Solaft Filtration Solutions) undertook the first pilot trial of StarBags™ and subsequent full GTC retrofit at Boyne Smelters in 2005-2006 [5].

As is common with many new developments, there were many design changes between the original patented concept and the fully commercialized product. These design modifications focused mainly on maximising the available filter cloth area within the geometry outlined in the patent, enabling a product capable of mass production in a cost-effective manner and providing sufficient structural integrity to the filter support cage.

Subsequent aluminium smelter GTC StarBag™ retrofit projects [6] proved StarBags™ to be a genuine and repeatable viable alternative to GTC capital equipment upgrade when the smelter increased metal production though amperage increase. In such amperage increase installations where the conversion to StarBags™ were conducted with either no additional gas flow to the GTC or with a small percentage of increase in gas flow, the efficiency and productivity gains when compared to the results from the standard cylindrical filter bags are typically expressed as:

- 30-35 % reduction in filter differential pressure (DP)
- 50-70 % reduction in pulse frequency
- 40-45 % reduction in particulate and gaseous HF emissions from the GTCs
- Reduced electrical load on the ID fans.

However, in other later installations where total gas flow through the GTC was increased more significantly, application limitations of the current design ESB filters meant that some of the abovementioned process improvements were no longer achievable.

2. Design and Limitations of Current ESB filters

The original filter cages of the ESB concept [4, 7, and 8] incorporated pleated filter bag on a twin wire cage to support an eight pleat ESB filter. The wire cage was supported by wire horizontal support members, which were manually constructed using jigs and spot welders. These support members were variable in quality and created difficulties in welding to the longitudinal components, Figure 1 left. Such manufacturing difficulties could not prevent large protruding knuckles of wire on the horizontal support members that exposed the ESB filters to significant abrasion on the back of the filter media during pulse cleaning. Some manufacturers continue to use the wire design originally developed regardless of quality issues in manufacture.

Figure 1. ESB filter cage support, Left: original wire design, Right: subsequent pressed metal component.

Subsequent filter cages of the concept [9] incorporated a pleated filter bag on a single wire cage to support 10 or 12 pleat ESB filters. The increase in number of pleats was to enable a further increase in available filtration surface area over prior art. Pressed metal horizontal support members were cut and pressed automatically with consistent quality, with a more robust cross-sectional shape to support the wire cage and this significantly reduced the difficulties in welding to the longitudinal components. These subsequent cages thus focused the design on maximizing filtration area and increasing the structural integrity and quality of the filter support cage, Figure 1 right.

Full conversion of GTCs to the subsequent cage design of the ESB technology in aluminium smelters in Canada and Iceland successfully repeated the typical benefits outlined above. However, in some other full GTC conversions using the pressed component cage design where more significant increases in gas flow to the GTC were implemented (Middle East, Russia and Iceland), they were unable to provide the same reduction in DP, emissions and pulse frequency and in some cases, actually added total gas flow resistance (increased DP).

Whilst some of these more problematic applications were typified by a more significant increase in gas flow to the GTC when compared to the more successful applications, the problematic applications also incorporated subsequent embodiments of ESB greater than 5 m in length. One unpublished study in Canada, conducted by a modern aluminium smelter with extensive testing capabilities, directly compared, concurrently in adjacent filter cells, the operating results between ESB filters that were greater than 5 m in length incorporating the original wire design cage and the subsequent pressed component cage design. The unpublished study concluded, “the design of the 12-ply cage has been identified as a root cause vs the limitation of flow rate or max filtration rate (sic)”.

The author of this paper has reviewed unpublished operating results of ESB filters across a number of smelters from which it was hypothesized that the more recent design direction to maximize cloth area as well as cage structural integrity may have been at the expense of clean side pressure drop and pulse cleaning efficiency in some applications. It was also hypothesized that this performance limitation was more evident in higher gas flow situations and notably with the longer length ESB installations where the cage design limitations appeared to have translated into newly discovered ESB filter application limitations. Furthermore, in the opinion of the author, any increased gas flow restriction by the pressed component cage design on the clean side of the filter is also likely to be restricting the flow and effectiveness of the reverse pulse air, making cleaning at the bottom of the bag in particular, less effective. This opinion has been reinforced by the fact that this problem has not been encountered in off-line cleaning systems.

3. Filter Bag Pressure Drop Literature Review

There have been several publications discussing the theory of each component of pressure drop across fabric filters. One study on ESB filters [8] stated that the pressure loss across the filter bag is attributable to just two causes: namely gas flow through the dust cake and filter media, and pressure loss caused by gas flow on the clean side of the filter. The study outlined equations governing these two causes as follows.

$$\Delta P_{total} = \Delta P_{cake\,+\,fabric} + \Delta P_{internal} \tag{1}$$

$$\Delta P_{total} = K_c \mu w v_s + K_f \mu w v_s + \lambda \frac{L}{D} \frac{\rho {v^2}_s}{2} + k_s \frac{\rho {v^2}_s}{2} \tag{2}$$

where:

$\Delta P_{cake} = K_c \mu w v_s$	Pressure loss through filter cake (Pa)
$\Delta P_{fabric} = K_f \mu w v_s$	Pressure loss through the fabric filter (Pa)
$\Delta P_{internal,\,filter} = \lambda \frac{L}{D} \frac{\rho {v^2}_s}{2}$	Pressure loss from friction inside the filter (Pa)

$\Delta P_{internal, ring} = k_s \frac{L}{D} \frac{\rho v^2_s}{2}$	Pressure loss through the cage support rings (Pa)
K_c	Specific resistance of cake (-)
K_f	Specific resistance of fabric (-)
μ	Gas viscosity (Pas)
w	Specific weight of cake on filter bags (kg/m^2)
v_s	Superficial gas velocity (m/s)
ρ	Gas density (kg/m^3)
λ	Friction factor (-)
k_s	Cage ring friction factor
L	Length of filter bags (m)
D	Diameter of filter bags (m)

This study goes on to hypothesize a "sweet spot" of maximum filter length for one filter design in this one application, and an "intuitive" maximum gas flow per filter module. The study does not specifically observe that the pressure drop due to the internal filter is a function of the square of the gas flow velocity (v^2). However, it does observe that above "intuitive" maximum gas flow the pressure drop due to the internal filter is nearly half the total filter pressure drop, indicating the increasing significance of internal pressure loss at high gas flow rates.

Another study [10] more critically analysed with CFD modelling the non-uniform flow along the length of long filter bags. The results indicated that gas flow does not readily enter the filter at the bottom of long filters, and that it is possible that 70 % of the flow is filtered in just the top 30 % of a long bag filter.

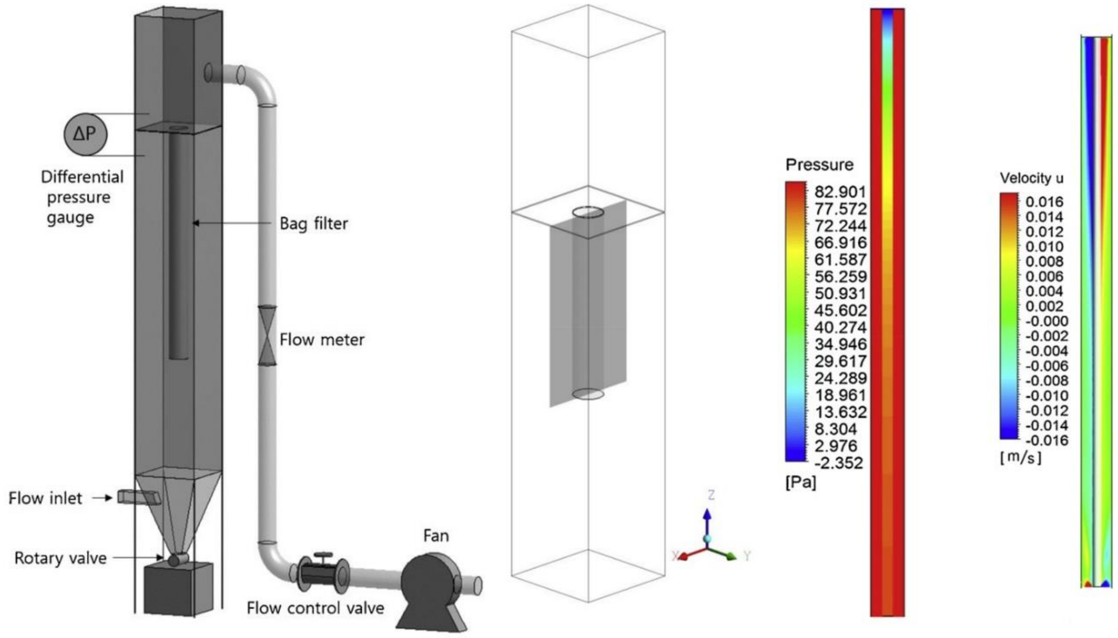


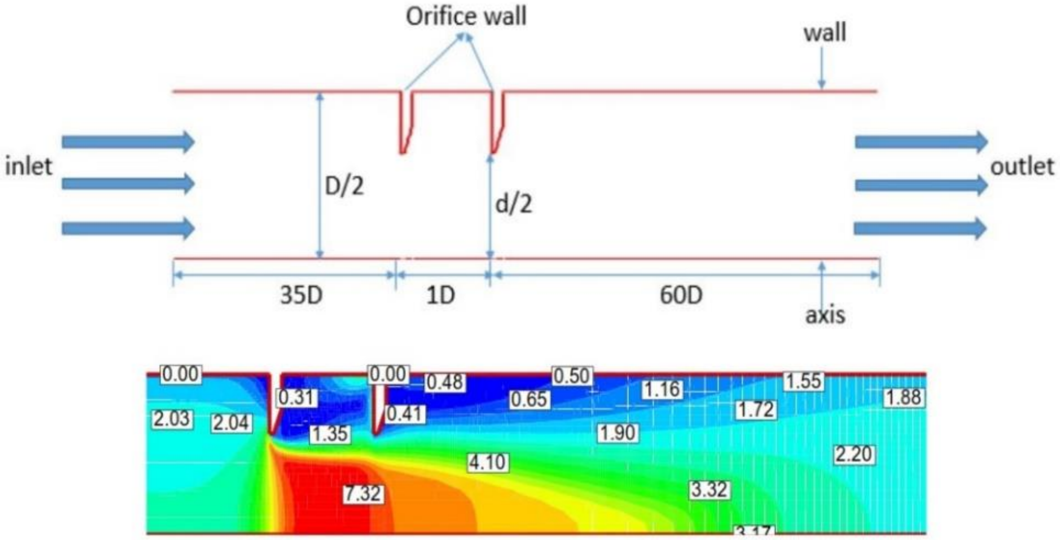
Figure 2. CFD flow through long filter bags, extract from [10].

This study concluded that when designing a system to extend the operating life of a filter bag, an important design consideration that is often overlooked is the uniformity of gas flow when long filter bags are installed.

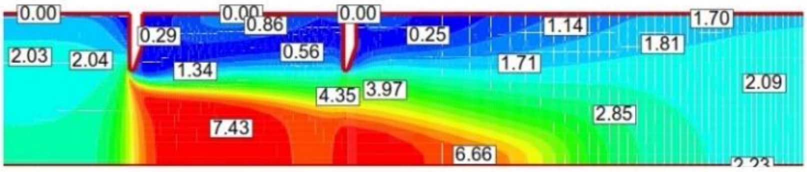
A further study [11] used CFD modelling to demonstrate the flow and subsequent pressure drop induced by multiple restriction orifices in a cylinder.

This study concluded that double orifices produced a pressure drop largely from the abrupt change in the flow passage cross-sectional area causing high level of turbulence and thus creating a double peak in velocity and pressure co-efficient, and that these peaks were higher than the case of a single orifice. When the spacing of these orifices was at a distance of two times the pipe diameter, the peak velocity was higher than when the orifices were closer together.

The filter cage within the pressed component ESB filter contains multiple flow restricting orifices and the spacing between these orifices is approximately two times the nominal external filter diameter. Logically, this study implies that in the clean side of the ESB filter, the flow through the multiple pressed components would impart turbulence, increased gas velocity and pressure drop that increase with filter length.



a) Double orifice-1D-spacing



b) Double orifice-2D-spacing

Figure 3. CFD flow through multiple orifices, extract from [11].

Lastly, it is important to consider the effect of turbulent flow, not just on the cleaned gas flow through the filter, but also the reverse pulse jet airflow down the length of the filter. Just as it was shown [10] that the internal cleaned gas flow is uneven along the length of long filter bags, it is likely that the reverse gas flow is also uneven along the length of long filter bags. Furthermore, the increased turbulence and pressure drop with every consecutive cage horizontal support is likely to create turbulent flow further exacerbating these effects. It is important to recognize that some models [8] use formulas based on laminar flow with a linear relationship between pressure drop and filter length. Whereas, if at velocity through multiple orifices the gas flow is actually turbulent, then these linear relationships become non-linear and the effects described above become exacerbated further [12].

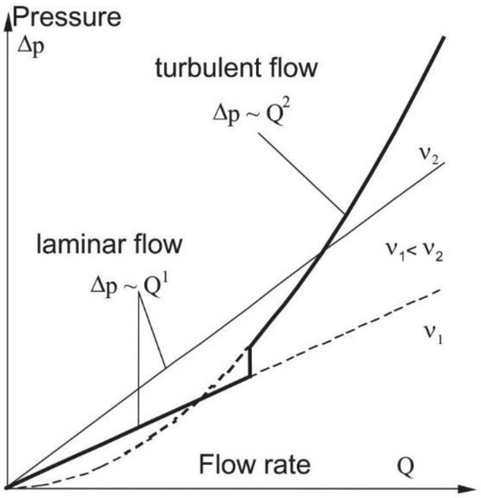


Figure 4. Relationship between pressure loss and flow rate, showing increased pressure drop with turbulent flow, extract from [12].

4. A New Pilot Test Unit

Recognizing the importance of internal pressure loss and the need to redesign the ESB filter bag, the ESB filter cage and the filter media, a new pilot test unit was constructed to verify the abovementioned theory and cross test the established designs against newer designs.

The pilot filter previously used in one of original on-site validation phases of StarBags™ [5] was used for rapid pulse testing various prototypes of new designs. However, with the observation that long length ESB exhibited more apparent design limitations, a new 9 m long, horizontal test apparatus was constructed, Figure 5. This apparatus was equipped with flow meters at one-metre increments along the length in order to examine differences in gas flow profiles between different designs of ESB filters. A differential pressure monitor was used to test the pressure drop across the filter cell plate.

Figure 5. Pilot filters, Left: 1 m rapid pulse unit, Right: 9 m gas flow analyser.

5. A New Filter Design Methodology

With the understanding that the observed application limitations were a result of the previous single-minded focus on maximizing filter area, a new and more balanced design methodology was adopted. Design developments were undertaken and tested individually and separately to ensure the efficiency gains from each modification were understood and quantified.

The filter cage was modified [12] in order to minimize the cross-sectional area of the horizontal support components to minimize the gas flow path deviations and drag along the length of the internal structure.

The filter bag was redesigned with the aim of optimizing the increased surface filtration area whilst maximizing the internal diameter and free space on the clean side of the filter. This was done mathematically by optimizing the equivalent internal diameter (D_{equiv}) and the filtration surface area, and then confirmed in the pilot filters.

$$\Delta P_{internal} = \lambda \frac{L}{D_{eqiv}} \frac{\rho {v^2}_s}{2} + k_s \frac{\rho {v^2}_s}{2} \tag{3}$$

$$D_{equiv} = 2\sqrt{\frac{A_{XS} - A_{SP}}{\pi}} \tag{4}$$

where:

v_s, ρ, λ, k_s, L are defined in Equation (2)

D_{equiv}	Equivalent diameter of the star shaped support (m)
A_{XS}	Cross sectional bag area (m^2)
A_{SP}	Cross sectional area of the cage star shaped support (m^2)

A new filter medium was then designed using various blends of fine denier and multilobal fibres, and the optimal fibre blend, maximizing fine particle capture and minimizing filter media pressure drop, was obtained by using a filter media efficiency rapid pulse aging tester and a micro-particle filtration efficiency tester, Figure 6.

Figure 6. Filter media efficiency testers, Left: rapid pulse unit, Right: micro fine dust unit.

This new design system now enables the ESB design to be optimized in a multifaceted manner, now registered as the PrimaFlow® [13] system, rather than the previously single faceted manner focused solely on maximising filtration area.

6. Pilot Filter Test Results

A limited quantity of test results is included below (Figures 7, 8), which highlight the differences in gas flow distribution along the length of the filters comparing 7.5 m long conventional round filters to 7.5 m long ESB filters installed on the two different cage designs.

The distance from the cell plate is indicated on the y-axis with position zero being the actual flow through the cell plate. The x-axis is the gas flow rate in cubic metres per hour, with the solid shaded bars representing the gas flow on the clean side (inside) of the filter bag and the shaded bars representing the measured flow on the outside of the filter bag. While tests were conducted at several different flow rates, depicted here are just two different flow rates for illustrative purposes.

The differential pressure across the cell plate for each test is illustrated in the heading on each chart.

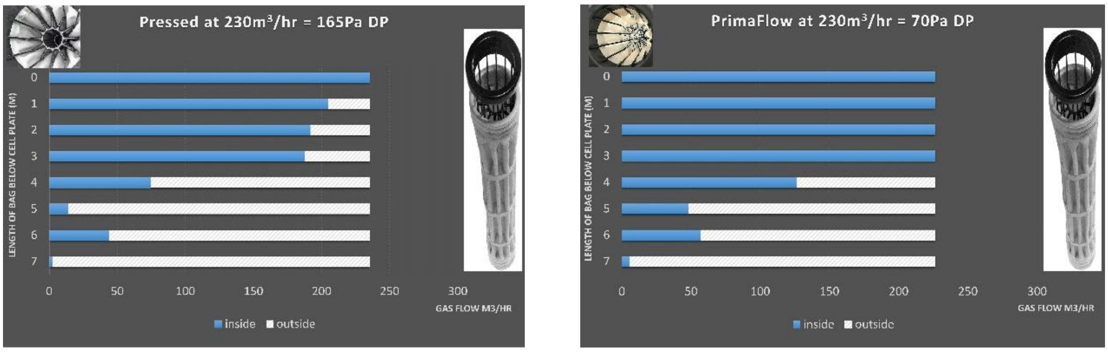


Figure 7. Gas flow distribution,
Left: conventional 12 pleat ESB filter, Right: PrimaFlow® filter.

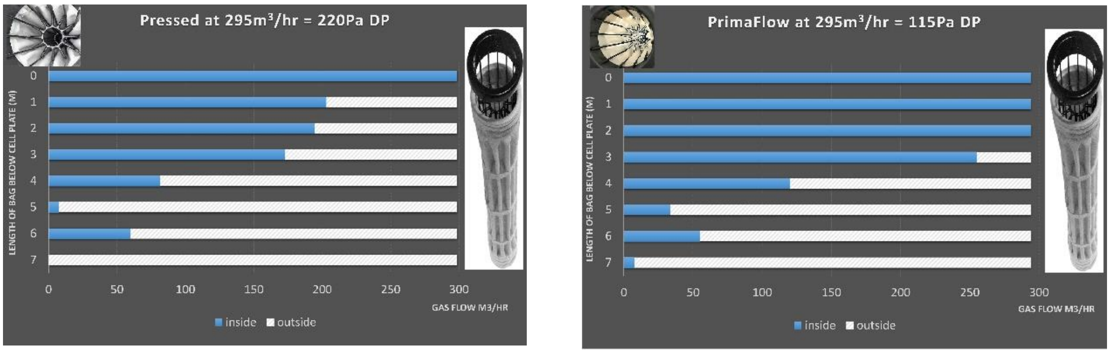


Figure 8. Gas flow distribution, Left: conventional 12 pleat ESB filter, Right: PrimaFlow® filter. The blue shaded area indicates flow inside the filter.

On a direct comparative basis, the newly designed PrimaFlow® filter had between 40 % to 65 % lower pressure drop than the conventional ESB filter over the whole range of different tested gas flow rates. While this indicates a lower resistance to cleaned gas flow, it also could indicate a lower resistance to pulse cleaning gas flow down the cage.

Also, on a direct comparison basis in the test apparatus described, the conventional ESB filter consistently had a different flow profile than that of the PrimaFlow® filter. The majority of the gas flow had passed through the filter in the bottom half of the bag with the Primaflow® filter. In contrast, there was still gas remaining on the outside of the filter in the top section and some still not entering the conventional ESB filter until the last top metre of the filter bag.

In all the tests conducted with this apparatus, the gas flow distribution of the PrimaFlow® filter was more comparable to the conventional round filter bag and cage, but with a lower differential pressure in all cases.

A limitation to this study was that it was conducted in the absence of particulate in the inlet gas. While an expanded polytetrafluoroethylene (ePTFE) membrane was used to simulate an evenly distributed dust cake, in application the dust cake will form according to the gas flow distribution. Since this gas flow distribution has proven to vary up the height of the filter bags, so too will the dust cake deposition in the early stages of the filtration cycle. Figure 9 represents the localized face velocity of filtration calculated from the measured gas flow and initial dust cake formation on the filter is likely to follow the gas flow.

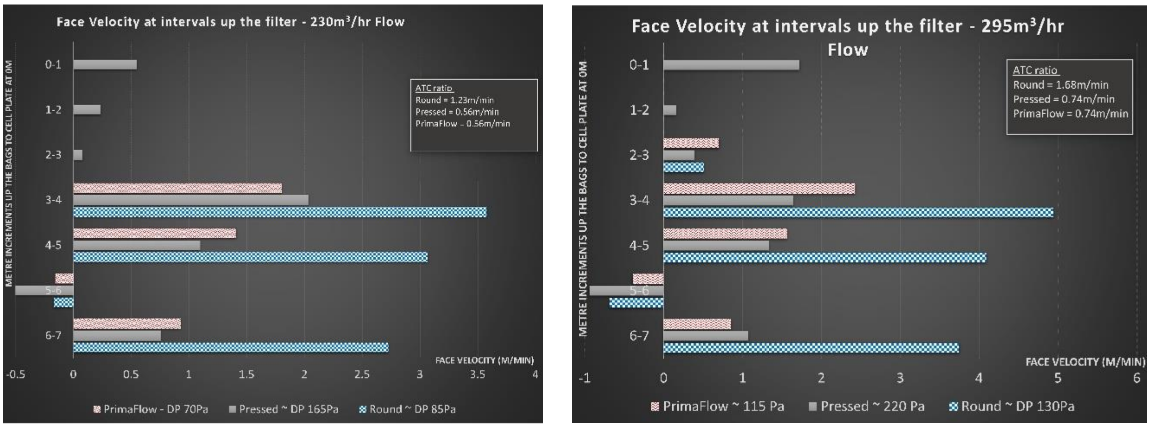


Figure 9. Face velocity incrementally up the filters,
Left: 230 m^3/h flow, Right: 295 m^3/h flow.

At least in the initial stages of filtration, it can be seen that the conventional ESB filter bag will result in a greater amount of dust cake formation at the top of the filter. This higher elevation filter cake has further to fall into the hopper with pulse cleaning. Furthermore, it is likely that the higher DP pressed spider cage will inhibit the flow of cleaning air down the filter to a greater extent than the low DP PrimaFlow® filter. The PrimaFlow® filter should therefore provide less gas flow restriction, yielding a lower cage differential pressure, a dust cake that will form initially around the bottom half of the filter, and result in a filter system that is easier to pulse clean.

This improvement should then provide a lower overall GTC differential pressure that is easier to maintain with filters that clean more effectively. Furthermore, the improved process gas and cleaning airflow distribution in longer filters should address the observed limitations of ESB particularly in longer length filters with high process gas flow.

7. Case Studies

Presented below are three separate case studies. Case study 1 and 2 are in aluminium smelter GTC applications, and case study 3 is in an aluminium smelter FTC carbon bake fume treatment centre (FTC application. These case studies are presented here to illustrate that the results are both repeatable and applicable across different applications.

7.1 Case Study 1 – Emirates Global Aluminium (EGA) Jebel Ali Smelter, United Arab Emirates (UAE)

In 2015/16, EGA's Jebel Ali smelter attempted to retrofit a GTC with ESB filters within an amperage increase program [14]. The desired outcomes were not all achieved, particularly in regards to the gas flow rate and filter differential pressure. Investigations into causes and remedies highlighted the need to focus on the importance of internal gas flow resistance as a primary cause of inadequate performance. This extended study resulted in the development of the PrimaFlow® system.

In 2019/20, the first trial cells of PrimaFlow® filters were installed and the performance was compared to that of other previous designs of ESB filters, Figure 10. The trial cell demonstrated the PrimaFlow® system was able to achieve significant performance improvements compared to the competitor's ESB filters, Table 1.

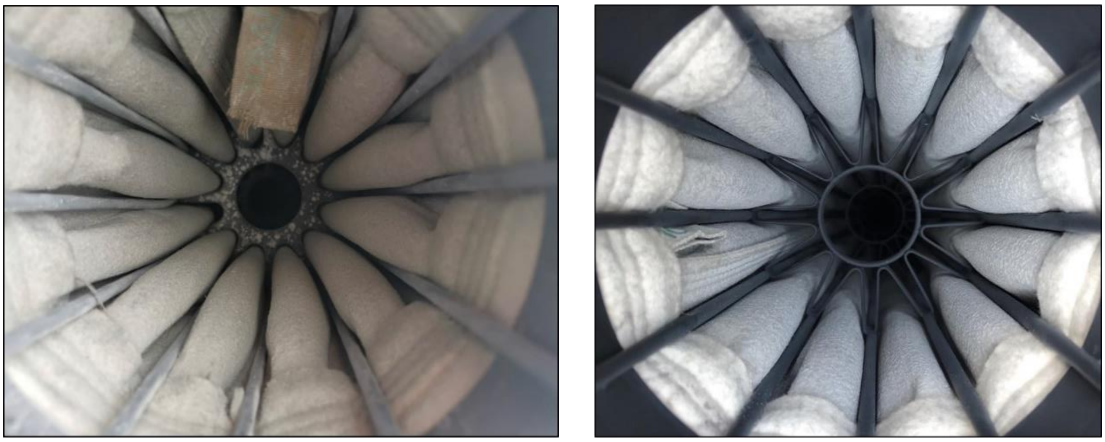


Figure 10. Clean side of the used trial filters,
Left: pressed metal component ESB filter, Right: Primaflow® filters.

Table 1. Trial cell initial startup comparison results.

Process parameter	**GTC Cell 7 - PrimaFlow®**	**GTC Cell 3 – Pressed metal cage**	**GTC Cell 5 – Wire cage**
Hours to pre-coat (h)	26.5	10.4	15.1
DP after offline cleaning (Pa)	700	1000	1100
Time to reach 1500 Pa DP (s)	270	210	235
Operational DP dampers fully open (Pa)	1850	2200	2200
Inlet static pressure (Pa)	2120	1880	1950
Static pressure below cell plate (Pa)	2290	1980	2080

The trial cells demonstrated that the PrimaFlow® filters were easier to clean and had lower gas flow resistance, which yielded longer time to pre-coat, lower filter DP and higher static pressure below the cell plate. The higher static pressure below the cell plate is indicative of a higher gas flow rate to the PrimaFlow® filters.

In late 2020, the full GTC 6B was converted to PrimaFlow® filters (6 000 filters in 10 filter cells). GTC 6B was then compared to the previous GTC 6B data obtained with pressed metal spider component ESB filters. After 18 months operation of PrimaFlow® filters, this comparison has been summarised in Table 2.

Table 2. Full GTC conversion comparison results.

Process parameter	GTC 6B - PrimaFlow®	GTC 6B – Pressed Metal Component ESB filters
Reverse pulse cleaning pressure (kPa)	350	350
Reverse pulse cleaning interval (s)	75	30
Reacted alumina recirculation (rpm)	46	21-36
Process gas flow (Nm³/h)	750 000-770 000	680 000-720 000
Filter cell DP (Pa)	1900-2100	2800-3100
Note: previously the DP with conventional round filters was also 2800-3000 Pa		

Both, the trial cell and the full GTC conversion have demonstrated that the lower gas-flow resistance characteristic of the PrimaFlow® system yields measurable and significant advances in lower pressure drop and reduced cleaning frequency. Operational savings are therefore expected in induction fan electricity use, cleaning air compressed air use, and longer filter bag life with respect to reduced flexural fatigue of the filter media.

7.2 Case Study 2 – Alcoa Fjarðaál Aluminium Smelter, Iceland

Alcoa Fjarðaál, which started operations in 2007, is one of the most modern and technologically advanced smelters in the world and is a model in terms of environmental protection. In 2018, Alcoa trialed a GTC retrofitted with ESB filters within an amperage increase program at the Fjarðaál smelter. This retrofit aimed at increasing the gas flow from the pots and lowering the filter DP whilst increasing the potline amperage. The smelter installed 7 m long, pressed metal component ESB filters. Again, this project failed to meet its design targets with older technology pressed metal component ESB filters.

In late 2020, this smelter installed one trial cell of 960, 7 m long PrimaFlow® filters to assess the merits of reduced clean-side gas flow resistance. The results to date from this trial cell have met and exceeded the targets established for the trial cell test. The results are summarized in Table 3.

Table 3. Trial cell results.

Process parameter	Pre-ESB trial 2017	Post ESB trial 2018	Trial cell Targets	PrimaFlow® Trial cell Results
Filter DP (Pa)	2200	> 2200	< 1800	1600
Filter cell gas flow (per 960 bag cell) (Nm³/s)	36.4	37.5	40.0	41.9
Pulse pressure (kPa)	250	340	-	170
Pulse frequency (pulses/h-bag)	6	> 6	< 6	3.75

This trial cell study has demonstrated that the low gas flow resistance of the PrimaFlow® system achieved a 27 % reduction in DP when compared to conventional cylindrical filters as well as the ESB filters previously trialed in 2018. It also achieved a DP that was 10 % lower than the trial cell target, and allowed operation at a low pulse frequency level not previously achieved at this smelter. The reduction in pulse air pressure and pulse cleaning frequency has yielded the potential for a 75 % reduction in compressed air in the GTC operations. The PrimaFlow® system also achieved the highest ever-recorded single cell gas flow in this modern aluminium smelter GTC. Even with the lower differential pressure, the gas flow rate is on average 12 % higher than achieved by any other technology and 5 % higher than the project target flow.

7.3 Case Study 3 – Rio Tinto Aluminium Alma Smelter, Canada

Rio Tinto Aluminium’s Alma Smelter in Canada have been using 8-ray ESB filters and cages since 2010 in both GTC and FTC applications. While the conversion to ESB filters brought many operational benefits [6], the filter installation crew have always reported difficulties and excess time required with filter cage insertion and removal in their FTC.

In order to test the PrimaFlow® concept and assess the merits concerning ease of installation, two filter cells within the carbon-bake fume treatment baghouse have been fitted with PrimaFlow® filters. The performance has been compared over the first 12 months of operation to the performance of the 8-ray ESB filters also used in the FTC baghouse.

The customer reported satisfaction with the ease of installation and they observed three measurable performance benefits of the PrimaFlow® filter over the 8-ray ESB filters. The customer observed a significant and sustainable reduction in differential pressure, a significant reduction in pulse cleaning frequency, and a higher process gas flow over time, Figure 11. They also see the measured reduction in pulse cleaning as a means to lower emissions and extend filter bag life.

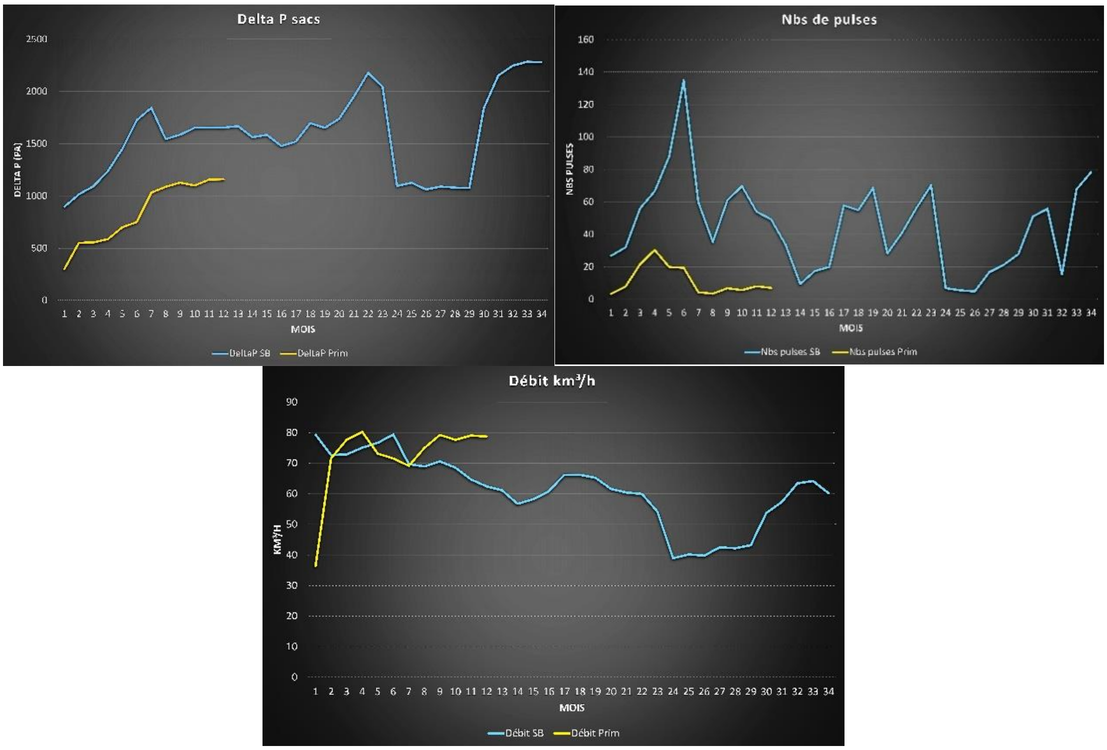


Figure 11. PrimaFlow® conversion, Left: comparison of differential pressure, Right: comparison of cumulative cleaning pulses per month, Bottom: comparison of total gas flow on a monthly basis.

8. Further Work

There are many different applications and reasons for upgrading a filter baghouse to ESB filters. The scope and design of such upgrades is governed by the customer’s application problem and desired upgrade outcome. Therefore, it is essential to consider as many of the process application aspects as possible when undertaking such an upgrade and designing the solution accordingly, rather than just simply maximizing filtration area for all application upgrades.

SOLAFT Filtration Solutions are in the process of creating a CFD modelling system in order to both optimize and expedite the PrimaFlow® design system for each application that is being considered for a process technology upgrade.

9. Conclusions

Application limitations in the implementation of older design ESB filters have been identified with respect to long filters and high gas flow. When older design ESB filters are applied in a process that is approaching these limits, it is not possible to achieve the performance gains previously experienced in applications with lower gas flow rates. This limitation and lower than expected performance has been observed at several major industrial sites.

A new system of ESB filter design has been undertaken. Rather than single mindedly focusing on maximizing filter area, a new and more balanced design methodology has been adopted. The new PrimaFlow® system considers and optimizes the filtration area of the ESB filter, the filter internal gas flow resistance and a new generation of high capture low resistance filter media.

The PrimaFlow® system has demonstrated, in both single cell and full baghouse conversions, to provide significantly higher gas flow and lower differential pressure than any previous embodiment of the ESB filter concept.

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