AIR POLLUTION CONTROL SYSTEM UPGRADE AT TUBATSE FERROCHROME

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ABSTRACT

Three electric arc furnaces (EAFs) were constructed by Union Carbide at Tubatse Ferrochrome (TFC) in 1975. This plant was expanded to four furnaces at the East Plant in 1985 and the gas cleaning system was enlarged without taking flow dynamics into consideration.

In order to improve competitiveness, TFC has increased furnace capacity, partially substituted coal for coke, and changed the charge mix. These changes increase the heat and dust load into the air pollution control (APC) system. TFC embarked on a project to improve the APC capacity by:

- *Quantifying the required off-gas capacity*
- *Optimising the aerodynamic flow through the system by means of Computational Fluid Dynamics (CFD)*
- *Converting the old Brandt Koyo top entry baghouses to bottom entry*
- *Upgrading the cleaning system*
- *Installing Gore-tex® ePTFE membrane filter bags*

The estimation of required off-gas capacity is traditionally done by rule-of-thumb methods such as specific extraction. A more elegant evaluation method was developed for simulating the effects of changes in charge mix on the furnace reaction gas volume and the APC system. Reaction gases are calculated by modelling the reactions taking place in the furnace and off-gas volumes are compared to both fan and baghouse capacity. This enables identification of bottle-necks in the off-gas system. CFD techniques were utilized to evaluate geometric imbalances and propose solutions to ensure optimal use of off-gas capacity.

The system modifications were completed over several months and the modified equipment went into service in May 2006.

1. INTRODUCTION

Tubatse Ferrochrome (TFC) was established in 1975 as a joint venture between Gencor and the USA-based company Union Carbide. As a result of its close proximity to the chromite mines, a site at Steelpoort, approximately 300 kilometres northeast of Pretoria and Johannesburg, was selected for the construction of the plant.

The original plant consisted of three furnaces with an annual capacity of 120,000 tons of high carbon chrome, known in the industry as Charge Chrome. Globally, around 85% of chrome production is used for metallurgical applications (primarily the production of stainless steels) with 8% used in chemical applications and 7% in refractory and foundry applications.

Salient features in the history of TFC are:

- 1985: Samancor bought the Union Carbide shareholding in Tubatse Ferrochrome.
- 1988 to 1990: Expansion of plant capacity to 300,000 tons (5 furnaces).
- 1993: Joint venture established with Nippon Denko and addition of 6^{th} furnace.
- 1997: Billiton acquired control
- 2002: Erection of a Pelletising and Sintering plant (520 000 tons per annum) to pelletise and sinter chromite fines. Introducing pellets into the submerged arc furnaces lowers the specific energy consumption by improving bed permeability and metallurgical changes achieved through the sintering process.
- 2005: TFC sold to the Kermas Group. The Kermas Group is a producer of and trader in ferrochrome and chrome chemicals, with activities in Russia, Germany and Turkey.

TFC made the following modifications to improve furnace ventilation:

- Converting the existing baghouse from top bag gas entry to the more common bottom bag entry
- Replacing the woven fiberglass bags with ePTFE membrane bags
- Significant duct and plenum modifications based on Computational Fluid Dynamic Modelling

The system modifications were completed over several months and the modified equipment went into service in May 2006. The result has been improved furnace evacuation preventing heat and fume from escaping into the building.

The layout of the off-gas handling system from Furnaces 1 to 4 is shown below.

A brief system description after conversion is:

- Each of the furnaces extracts to a trombone cooler.
- 4-off fans are installed after the coolers, one for each furnace.
- The fan inlets are interlinked by a header duct.
- A pressure type reverse air baghouse filters off-gas, with 2-off reverse air fans and 32-off compartments.
- After conversion each reverse air fan serves 16-off compartments (one each for the Northern and Southern rows of compartments). The reverse air fans discharge to the risers on the pressure side of the fans (vs current discharge to the fan inlets).

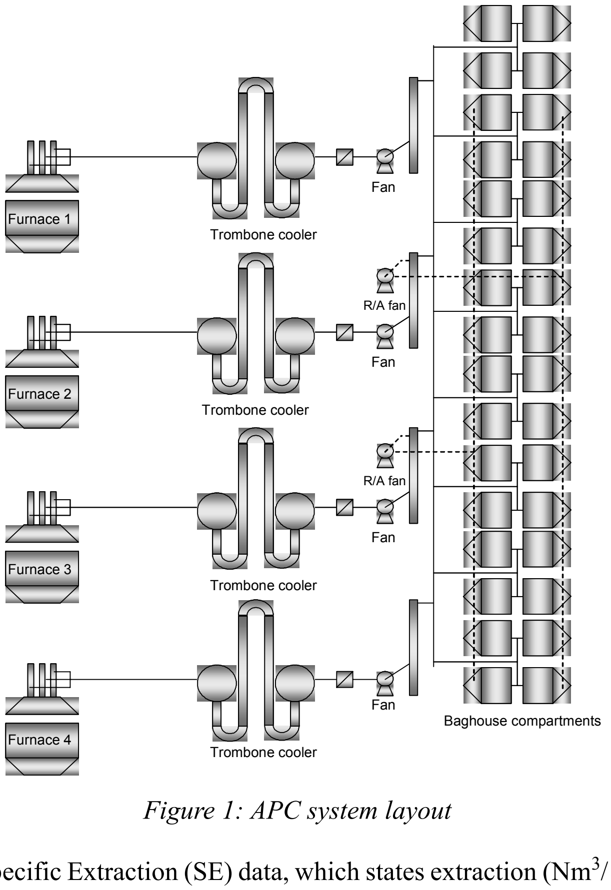

Figure 1: APC system layout

2. APC SYSTEM DESIGN REVIEW

A design review was done on upgrade options for the East plant (4 furnaces) off-gas system. Objectives of the study included determining the required extraction system capacity as well as the system design and operational weaknesses.

2.1 Design Methods Generally Used

In the past, off-gas system sizing was done using Specific Extraction (SE) data, which states extraction (Nm^3/h) per furnace energy input (kW), i.e. Nm^3/h/kW. Specific extraction was benchmarked by visually checking if a furnace is adequately ventilated and then extrapolating the SE value to other plants and industries. Design SE values were for example compared for various Samancor plants by Wall [1]. Rentz [2] did extensive work on reducing emissions from Ferroalloy furnaces and i.a. established required SE values for various feed material preparation regimes.

A more sophisticated method of sizing baghouse equipment is based on furnace heat extraction requirements – sometimes referred to as the "X" factor. According to this method, the heat content of the submerged arc furnace exhaust gas is directly proportional to the furnace load (influenced by the amount and type of raw materials and furnace operation). The ratio of Exhaust Gas Heat to Furnace Power input yields the "X" factor. Therefore, the relationship can be written as follows:

$$Q = X \times kW = m \times C_p \times [T_h - T_{amb}]$$

Where Q is the heat content of the furnace exhaust gas, X is the ratio of furnace off gas heat to furnace power input, m is the mass flow, T_h is the hood exhaust gas temperature and T_{amb} is the ambient temperature of the air drawn into the hood.

The X factor is unique for each application and is affected by furnace operating conditions and the make up of the charge mix. Factors that can influence the X factor include furnace energy consumption per alloy ton, fixed carbon in the charge mix, volatile matter in the charge mix, water content in the charge mix, reducing agent required per alloy ton and metal recovery from the raw ore feed.

Typical X values for some common ferroalloy processes are 1.3 for Si-Metal, 1.1 for 75% FeSi, 1.0 for SiMn and 0.7 for FeCr.

The X factor is normally estimated from experience, based on field testing and visual observations since each application is unique. If heat and fume are spilling from the hood during the field testing the furnace heat extraction is not adequate and provisions must be made to increase the furnace draft.

2.2 Furnace Reaction Gas Modelling

In response to problems with above methods in adequately estimating the effect of various process and operational factors on design of APC systems, a more thoroughly process-based method was developed. Furnace reaction gas modelling is done in two steps: furnace reaction gas is estimated by doing a carbon balance over the furnace, whereafter the reaction gas is combusted and diluted with ambient air. Varying amounts of dilution air are used to calculate off-gas temperatures at the furnace and baghouse inlet.

The reaction gas is the gas evolved from the reactions in the bath between ore and reductant as well as volatiles released by the reductant. Details of how the reaction gas is estimated are given below:

- Carbon in the reductant is handled in one of three ways: fixed carbon is assumed to react with ore in the bath, producing carbon monoxide, excess fixed carbon is assumed to be released into the off-gas as pure carbon and is combusted in the next phase. Part of the carbon contained in the volatiles is assumed to be combusted to carbon monoxide by oxygen contained in the coal. The remainder is assumed to come off as carbon for later combustion.
- Hydrogen in the reductants is assumed to come off as H_2.
- Moisture in the reductants and ore is assumed to report to the gas phase as H_2O and is not dissociated to oxygen and hydrogen.
- Whatever nitrogen there is in the reductants is assumed to report to the gas phase.

Carbon, carbon monoxide and hydrogen in the reaction gas (calculated above) are combusted with air assumed to be drawn into the furnace hood, providing an off-gas temperature after combustion and dilution.

Heat loss at the furnace ducting and trombone cooler is calculated to determine the baghouse inlet gas temperature and volume flow based on off-gas volumes and temperatures calculated with the above carbon mass balance. A standard trombone cooler design procedure was used, as proposed in the EPA's Air Pollution Engineering Manual[3]. The calculation model makes use of correlations by Sieder and Tate[4] for convection heat transfer on the trombone cooler tube inside, McAdams[5] for radiation heat transfer and McAdams[5] for convection heat transfer on the trombone cooler tube outside.

2.3 Furnace Operating Base Data

Furnace design power input is 28MW for Furnaces 1 to 3 and 32MW for Furnace 4. Reductants fed to the furnaces include coal, coke and anthracite. The fixed carbon requirement is made up of 60% coke, 20% anthracite and 20% coal. Approximately 63% of ferrochrome feed material is in the form of pellets, with 32% lumpy ore and 15% concentrate. Quartz and dolomite are fed as fluxes.

2.4 Design criteria and Assumptions

The criteria used for off-gas system design are that, at the design off-gas volume, furnace hood temperature must be below 450°C and baghouse inlet temperature has to be kept below 240°C. The furnace hood temperature limit ensures that equipment in the furnace roof is not exposed to high temperatures which result in short working life. The criterion is kept relatively low at 450°C, as radiation heat caused by running a furnace with an open bath can boost temperatures significantly. The baghouse inlet temperature limit ensures that bags are not exposed to over-temperature.

In reality, one finds that temperatures measured on site differ from modelling calculation values in that furnace hood temperatures tend to be a bit higher, caused by radiation heat, while in-leakage of ambient air along the off-gas system causes furnace hood temperatures to be still somewhat higher (less gas is actually extracted from the furnace) and baghouse inlet temperature to be lower (further dilution air is introduced by in-leakage).

2.5 Off-gas Estimation Results

2.5.1 Individual Furnaces

The furnace off-gas conditions at furnaces 1 to 3 (28MW) and furnace 4 (32MW) were estimated for a baghouse inlet temperature of 220°C. The values are summarised in table 1 below.

Table 1: Off-gas estimation results

Furnaces 1 to 3			*Furnace 4*		
Parameter	Unit	Value	Parameter	Unit	Value
Reaction gas	kg/h	7443	Reaction gas	kg/h	8090
Furnace off-gas temperature	°C	403	Furnace off-gas temperature	°C	379
Furnace off-gas volume	Am^3/s	113.5	Furnace off-gas volume	Am^3/s	136
Normalised volume	Nm^3/s	42.3	Normalised volume	Nm^3/s	49.9
Baghouse inlet temperature	°C	220	Baghouse inlet temperature	°C	220
Baghouse volume	Am^3/s	82.8	Baghouse volume	Am^3/s	97.7
% CO_2	% (v/v)	3.73	% CO_2	% (v/v)	3.44
X-factor		0.80	X-factor		0.77
Specific extraction	$Nm^3/h/kW$	5.44	Specific extraction	$Nm^3/h/kW$	5.62

At furnace 1 to 3, at a baghouse normalised flow of $42.3Nm^3/s$, a furnace off-gas temperature of 403°C and a baghouse inlet temperature of 220°C is predicted. At furnace 4, at a baghouse normalised flow of $49.9Nm^3/s$, a furnace off-gas temperature of 379°C and a baghouse inlet temperature of 220°C is predicted.

To indicate the effect of varying furnace off-gas volume on off-gas temperatures, the temperatures were calculated over a range of volumes. Figures 2 and 3 give furnace off-gas and baghouse inlet temperatures for varying off-gas volumes. The above results form a single point on each of the curves.

The baghouse temperature line can be seen as the process extraction requirement – i.e. what baghouse temperatures are produced by the process at which extraction volumes. The line does not give any clues as to at which temperature the APC system will operate. To obtain the operating point, the fan(s) and baghouse capacities have to be compared with the process extraction requirement. On the graph, two further curves are plotted: fan and baghouse normalised extraction capacity as a function of temperature. The fan capacity curve is estimated by using the design fan curve and taking into account the effect of gas density on fan performance. Fan laws are used to adjust the fan performance accordingly. The baghouse capacity curve is estimated by taking the design actual filter volume and at each temperature calculating the corresponding normalised volume for a constant actual inlet volume (i.e. to ensure that the actual baghouse volume remains constant).

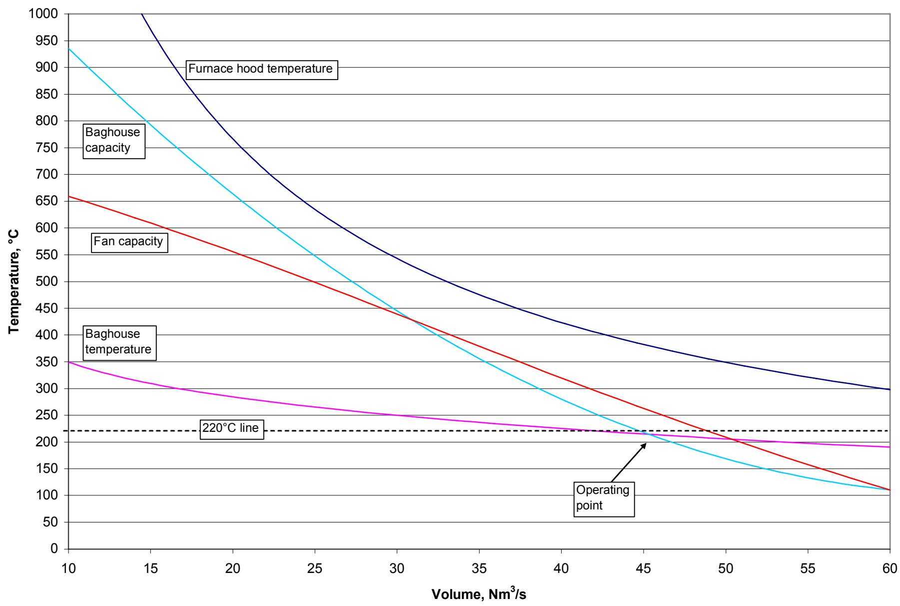

Figure 2: Extraction volume vs Temperature – Furnaces 1, 2 or 3

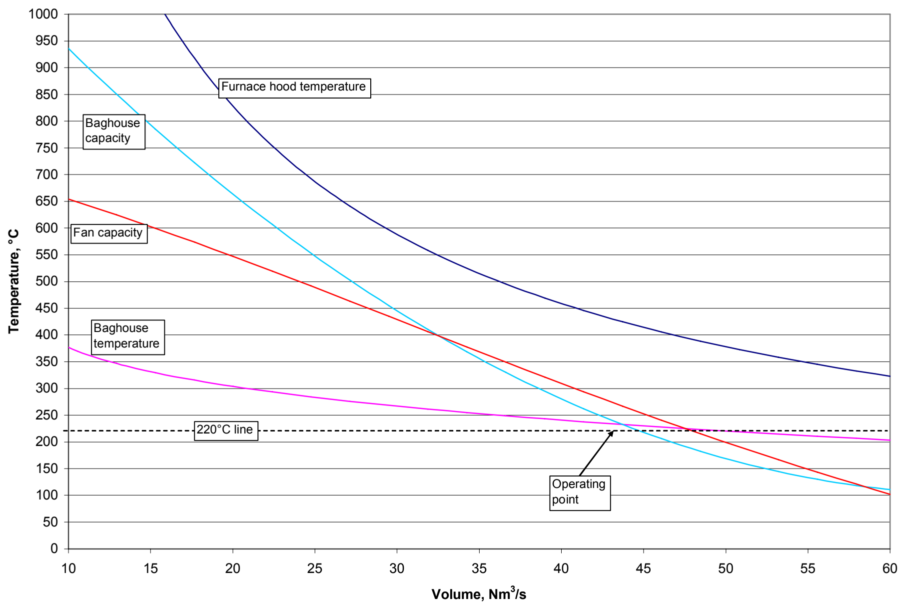

Figure 3: Extraction volume vs Temperature – Furnaces 4

The range of temperatures for varying off-gas volumes can be appreciated from the graphs, as can the importance of maintaining the off-gas system in good condition: decreasing volumes result in rapidly increasing furnace hood temperatures as well as baghouse inlet temperatures.

In order to compare process requirement with fan and baghouse capacities, the baghouse and fan capacity are viewed vs the baghouse temperature curve. If the baghouse and fan capacity curves are above the baghouse temperature curve, then the off-gas system (fan and baghouse) have sufficient capacity to adequately ventilate the system. The first point of intersection of the fan or baghouse capacity curve with the baghouse temperature curve shows the maximum off-gas operating capacity. If the above point of intersection is at a normalised volume where both the baghouse temperature and the furnace temperature are within design criteria, then the off-gas system is adequately sized for the application.

For furnaces 1 to 3, the point of intersection of the baghouse capacity curve with the baghouse temperature curve is at 45Nm^3/s. At this volume, the furnace temperature is below 400°C and the baghouse temperature below 220°C. The conclusion from the curve is therefore that the off-gas system has sufficient capacity for the application.

For furnace 4, the baghouse capacity curve is the first to intersect with the baghouse temperature curve – i.e. the baghouse capacity is limiting. The point of intersection is at a baghouse temperature of 233°C, which is above the operating guideline of 220°C. The fan capacity intersects the baghouse temperature curve at 223°C, which is marginally above the operating guideline. The conclusion drawn from the curve is that the baghouse capacity is limiting and the system will not be able to operate at 220°C.

However, furnace 4 does not operate in isolation and the combined effect of all 4 furnaces on the fans and the baghouse was viewed.

2.5.2 Combined APC System Modelling

The graph below combines the process impact of the four furnaces and the capacities of the 4-off fans and 32-off baghouse compartments. Curves shown are combined average furnace temperature (all 4 furnaces), com-

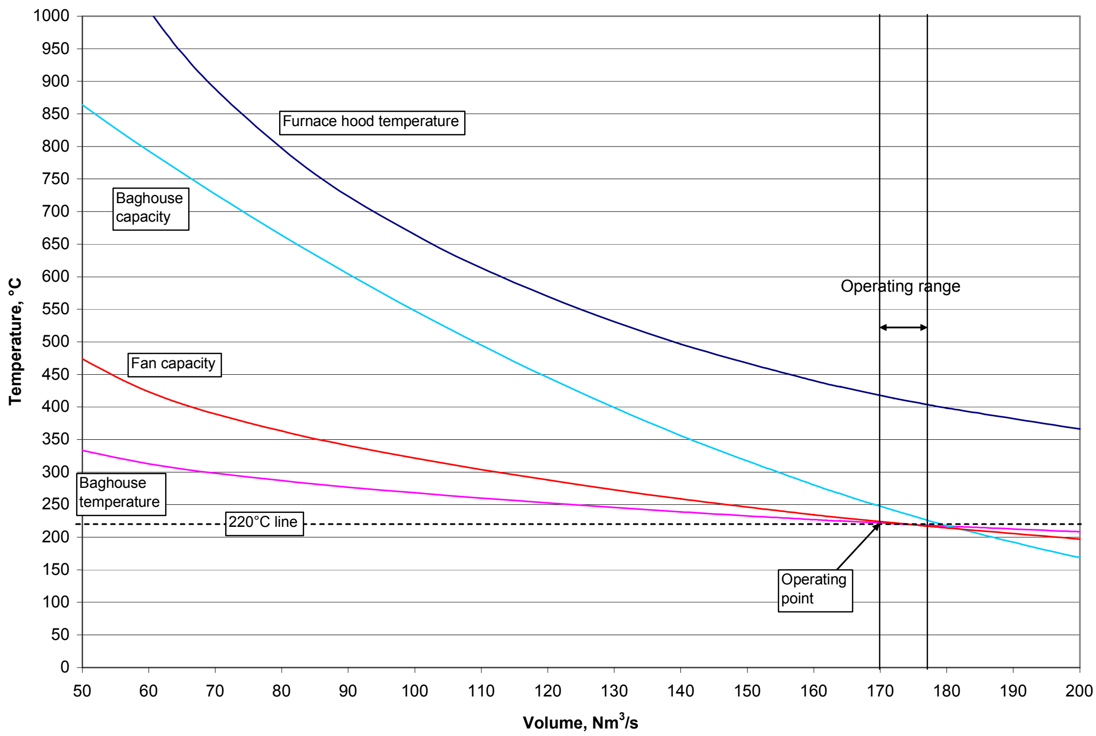

Figure 4: Combined Furnaces Extraction volume vs Temperature

bined average baghouse temperature (total baghouse), baghouse capacity curve for all 32 compartments and combined fan capacity curve for all 4 fans. To indicate the impact of system in-leakage, a 5% air in-leak was assumed close to the fans.

The combined graph indicates the following:

- At a total extraction volume of 170Nm^3/s, a baghouse inlet temperature of 220°C is achieved.
- The furnace stack temperature can be maintained at 420°C at this extraction volume.
- The fan and baghouse capacity is sufficient to operate at 170Nm^3/s at a temperature of 220°C.
- The specific extraction required is 5.5Nm^3/h / kW with an X-factor of 0.79.
- Installed baghouse and fan design capacities (after baghouse conversion) are sufficient to achieve the required extraction volume.

The effect of in-leakage on the system was to establish an operating range: without in-leakage a volume of 177Nm^3/s is required to main a baghouse inlet temperature of 220°C. The negative effect of in-leakage is that furnace off-gas temperatures rise with increasing in-leakage down the line. The average furnace off-gas temperature increased from 400°C at 177 Nm^3/s to 420°C at 170 Nm^3/s.

3 AERODYNAMIC OPTIMISATION AND BAGHOUSE CONVERSION

In the not so distant past computational fluid dynamics (CFD) was restricted to very powerful computers and highly specialized users. The quantum leap in computer processing power has made CFD analysis accessible to the engineering industry in general as opposed to the NASAs of the world.

TFC is one of the enlightened companies that used this quantum leap in technology to their benefit to optimize the aerodynamic flow through their gas cleaning system. A number of proposed ducting layout modifications were simulated in EFD.Lab 6.0 to find an optimized/balanced resistance through the system. An optimized system will result in an increase in production capacity and a balanced system will ensure uniform wear through the system and ultimately longer operational life. With the addition of furnace 4 in the 1980s flow dynamics was not taken into consideration as can be seen from the increased pressure drop through furnace

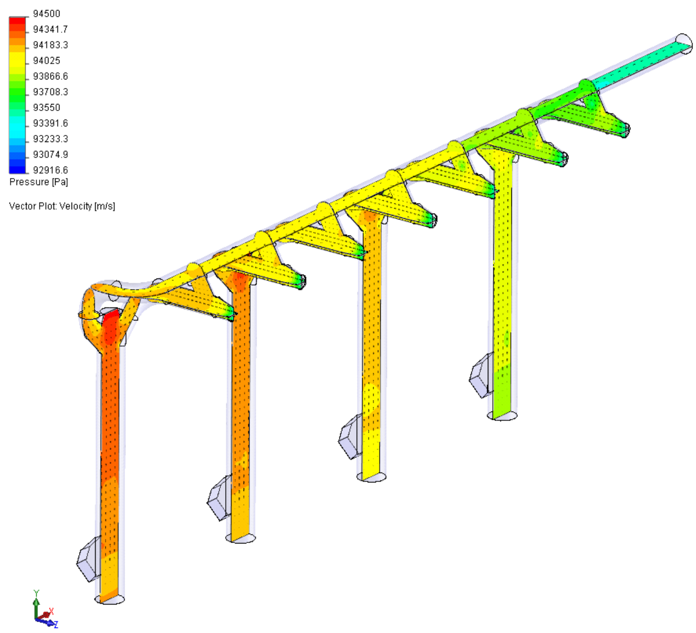

Figure 5: Baghouse inlet duct configuration: before

4 in Table 1. The difference in pressure drop was due to the addition of bends not present in furnaces 1-3. The proposed optimized layout consisted of four new ducts that will result in flow symmetry as indicated by the pressure drop in Table 1. The unbalance in the system was therefore reduced from 417Pa to less than 21Pa. Due to the fact that numerous simulations can be performed in a relatively short time, the design can be optimized before construction starts. CFD makes up only a fraction of the total project cost, yet it could result in significant improvement of profits due to higher efficiency and lower maintenance costs to the system.

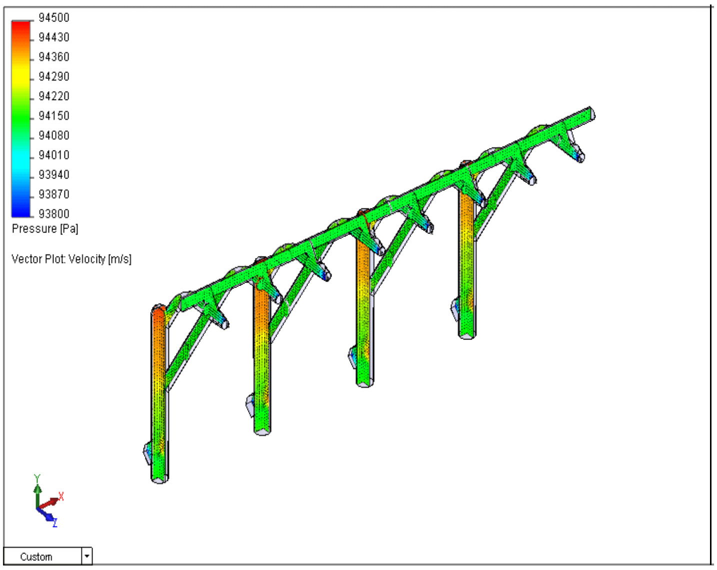

Figure 6: Baghouse inlet duct configuration: after

Table 2: Ducting pressure drop before and after modification

Location	*Pressure Drop Before (Pa)*	*Pressure Drop After (Pa)*
Furnace 1	553	452
Furnace 2	561	469
Furnace 3	451	455
Furnace 4	868	449

With the new bottom entry conversion the gas was directed into the hopper and through the bags as opposed to through the bags and into the hopper with the original design. A CFD simulation was done to ensure uniform flow into the hopper and ultimately entering the bags. This avoids velocity abrasion of the filter bags and re-entrainment of dust from the hopper. The following two pictures illustrate the velocity profile through the new ducting as well as the hopper before entering the bags.

4. CLEANING SYSTEM UPGRADE

There are many factors that affect the performance of a baghouse, especially the filter bags. Earlier experience has shown the following variables affect the pressure drop across the filter bags.

- Dust generation rate
- Humidity of the gas
- Electrostatic attraction between the bag and the dust
- Bulk density of the dust
- Dust particle size

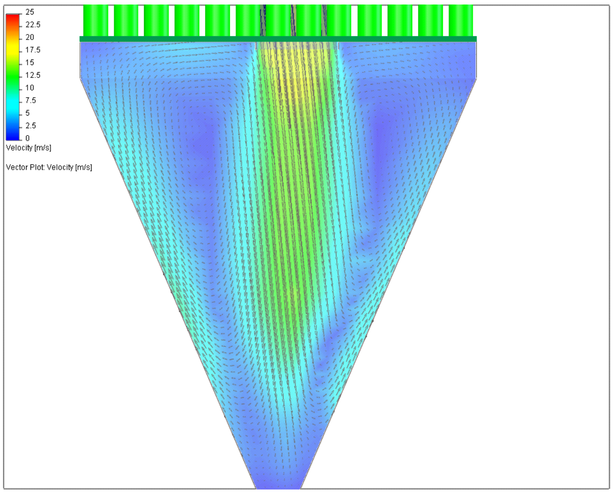

Figure 7: Flow distribution through hopper

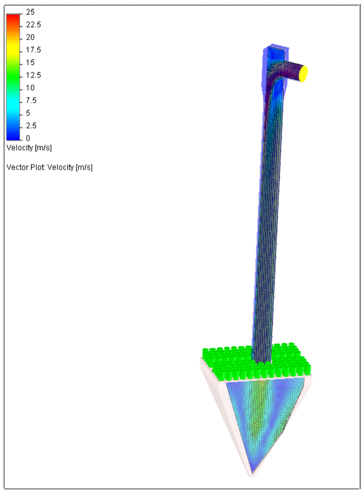

Figure 8: New bottom entry conversion

- Chemical composition of the dust
- Filter velocity (the air to cloth ratio)
- Effectiveness of the cleaning system

While most of these factors are beyond the control of the baghouse operator the effectiveness of the cleaning system can be improved by computerized control of the cleaning cycle. This computerized technique is now often referred to as "smart cleaning".

There is direct relationship between gas flow through the bags and the pressure drop across the bags during reverse air cleaning. This is true up to a threshold point where the additional reverse air pressure does no more good and needlessly increases the baghouse pressure drop since the reverse air must re-filtered by the on line compartments.

Since each compartment is a different distance from the reverse air fan inlet and some compartments capture more dust due to the inherent flow imbalance within the baghouse it is best to vary the reverse air volume to maintain a consistent pressure drop across the bags during cleaning. The most practical approach in most cases is to use a variable speed drive (VSD) on the reverse air fan motor based on the output of a pressure control loop. This requires each compartment to be fitted with a pressure transmitter to measure the tubesheet pressure drop and for those signals to be logged by the baghouse programmable controller (PLC).

If the pressure set point is not achieved the PLC signals the VSD to increase or decrease the motor speed the next time that particular compartment comes up for cleaning. Attempts to readjust the reverse air fan motor speed while the reverse air damper is open have not been successful.

5. FILTER BAG REPLACEMENT

Tubatse previously utilized woven fiberglass filter bags. Fiberglass material is known to have many advantages [7]:

- Non combustible because it is completely inorganic
- Zero moisture absorption; therefore, it is not subject to hydrolysis
- Dimensional stability (low coefficient of linear expansion)
- Very high strength but poor resistance to flex and abrasion; however, there are chemical surface treatments that improve the flex and abrasion characteristics of fiberglass
- Woven fiberglass can operate continuously up to 260°C and depending on the surface treatment withstand up to 288°C for short periods.

Person [8] has explained the relatively high filter drag of conventional woven fiberglass material when applied to metallurgical fume. Additionally, one could reasonably expect higher particulate emissions through the conventional fiberglass filter media since the filter cake must be sacrificed to maintain airflow. While aramid material (good to 204°C) in shaker cleaning applications shows lower filter drag than woven fiberglass material, there is limited experience with aramid in EAF baghouses. Furthermore, in the limited cases where aramid had been used in EAF applications, the results have not been encouraging.

Eriksen [9] and Stordahl [10] reported that GORE-TEX® membrane/fiberglass filter media has substantially lower filter drag than conventional media in metallurgical fume applications. Previous work by Hall, et al [11] demonstrated the improved filtration efficiency of GORE-TEX® membrane filter bags in a steel EAF application at British Steel when compared to the results with various woven synthetic filter media at the same installation.

Difference Between Conventional and Membrane Fabric Filtration Technologies

When fabric filter dust collectors became a viable technology years ago, the available fabric filter media included wool and cottons, then progressed to polyester, aramid, fiberglass, etc. This method of filtration was and is referred to as conventional depth filtration. W. L. Gore & Associates, Inc. (Gore) introduced expanded polytetrafluoroethylene (ePTFE) membrane surface filtration, offering significant advantages over conventional depth filtration. The comparison of these two filtration methods has been explained a number of times in the literature including the paper by Yerkes [6] comparing the performance of polyester and GORE-TEX® filter bags at Corus Tuscaloosa Steel.

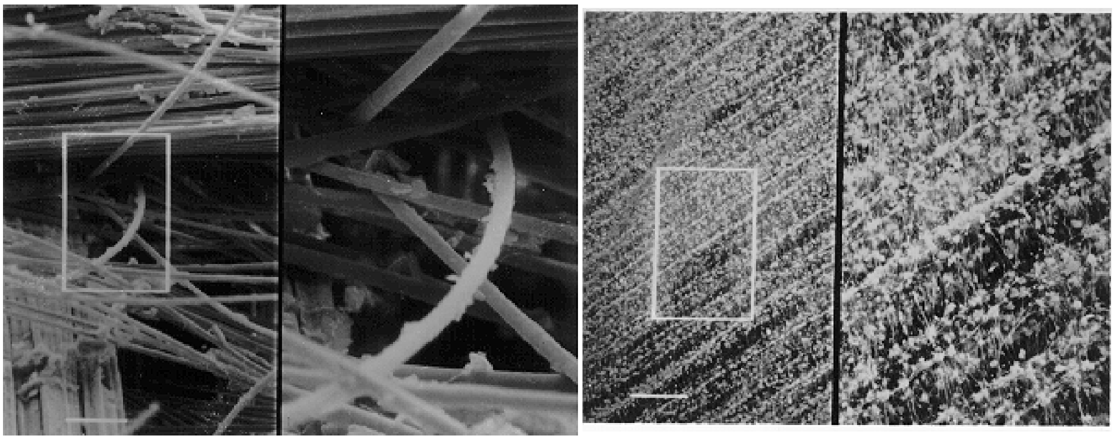

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Figure 9: Scanning Electron Microphotograph: Fiberglass Fabric vs ePTFE Membrane

The lower filter drag typical of GORE-TEX® membrane filters reduces the system resistance and allows increased gas flow through the baghouse. With proper inspection and maintenance, GORE-TEX® membrane/acid resistant fiberglass fabric filter bags operate effectively for many years. In most cases, even after five years, the GORE-TEX® membrane filter bags do not show a drop in gas flow capability or filtering efficiency. Elverd, et al [6] documented the improved furnace evacuation, longer bag life, lower maintenance cost, and decreased particulate emissions at Tennessee Alloys Corporation after the installation of GORE-TEX® expanded PTFE (ePTFE) membrane/fiberglass filter bags in 1993. Substantially all of those filter bags were still in service after eight years.

Water leaks are a common problem in EAF fume treatment systems. These water leaks, if carried over to the baghouse, will blind conventional filter media in a short time period. Since the airflow through conventional media does not recover after an extended water leak, new bags are required. Due to the hydrophobic nature of the membrane, GORE-TEX® membrane filter bags have proven their ability to recover from water leaks.

GORE-TEX® expanded PTFE (ePTFE) membrane/fiberglass filter bags offered TFC a cost-effective way to deal with the demands of increased furnace productivity, leading to a higher required furnace extraction volume to the system.

6. CONCLUSIONS

At the time of writing (July 2006), Tubatse had restarted only the No 2 and No 4 furnaces. It was thus difficult to assess the whole system effectiveness. Initial indications are, however, positive:

- Emissions from the baghouse have been significantly reduced.
- Pressure drops across the filter bags are as predicted during design.
- Inlet temperatures are lower, but this is due to in leakage of ambient air from the furnaces that are still idle.

This paper makes a contribution by presenting Furnace Reaction Gas Modelling as an alternative to previously used design methods.

DEDICATION

This paper is dedicated to the memory of Casper Els who died on the 7th of November 2006 after the initial paper was submitted. His invaluable contribution to the field of air pollution control is hereby acknowledged.

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