Ferrochrome Off-gas System Design, Implementation and Verification for Eventual Waste Heat Recovery

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This paper details the process followed in the design, implementation and verification of a new off-gas system implemented for a Ferrochrome furnace at Tubatse Ferrochrome in Steelpoort, South Africa, in 2012, which is part of a larger project which will include a boiler and steam turbine for waste heat recovery and electricity generation. The newly designed and installed off-gas system includes a set of 4 cyclones, a trombone cooler and a reverse air bag house filter. Detailed design work for the new off-gas system at Tubatse Ferrochrome was completed, which included

- Complex furnace modeling leading to an off-gas volume and temperature – dependent on the amount of air ingress at the furnace.
- Furnace modeling led to a system specification and equipment design.
- The off-gas volume was selected to ensure an optimal bag house size, whilst providing a high enough hood face velocity to keep the fume within the hood.
- Detailed structural, electrical and C&I design of the off-gas system was completed.
- Computational Fluid Dynamics modeling was done to confirm the hood extraction volume.

The off-gas system was built and commissioned. System testing and verification was then done with the objectives of providing design verification, proving that the boiler operating conditions will be met in terms of off-gas flow and temperature, and equipment assessment. This paper describes the design, testing and verification processes, as well as reports actual field results and design value comparisons.

Keywords: off-gas system design, furnace predictive model, design verification. Off-gas system testing, reverse air bag house filter

Notation:

CFD	Computational Fluid Dynamics
EPA	Environmental Protection Agency

1 Introduction

Tubatse Ferrochrome, located in Steelpoort, South Africa, produces ferrochrome in 6 open electric arc furnaces. There are 4 furnaces located on “East Plant” and 2 furnaces located on “West Plant”. The work described in this paper focuses on “East Plant”, specifically on furnace number T4. Previously, all 4 furnaces were extracted to a single bag house filter, via a common trombone cooler and set of 4 fans linked via an inlet header, as shown in Figure 1. This previous off-gas system has been described in detail by Koekemoer *et al.* in [7].

The furnace T4 transformer was upgraded, increasing the furnace capacity from 37MVA to 45MVA, which led to the requirement for a new, separate off-gas system for furnace T4. This off-gas system upgrade is linked to the implementation of waste heat recovery boilers which will generate steam from the hot furnace off-gas, which will in turn be utilized to drive steam turbines, generating electricity. The new off-gas system for furnace T4 was therefore designed with the boiler in consideration to ensure that suitable off-gas temperatures and flows would be achieved for optimal waste heat recovery, whilst ensuring that the furnace extraction remains optimal with little to no fume escaping the furnace hood.

This paper details the design method followed and the steps taken to validate and verify the design work after the system was implemented, thereby ensuring optimal system operation in terms of fume capture and the eventual waste heat recovery system.

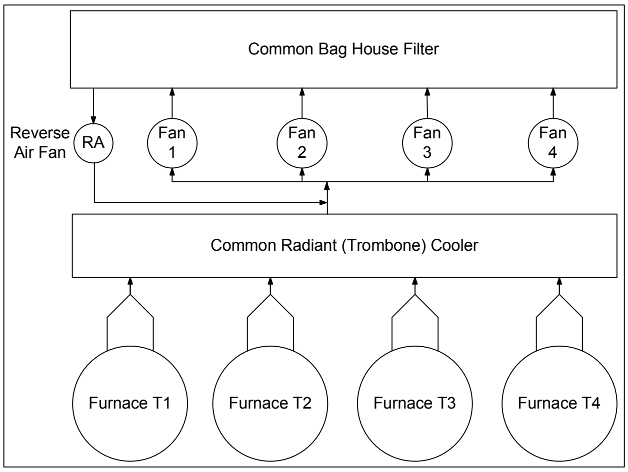

Figure 1: Previous East Plant process flow

2 Process Description

The off-gas system layout is shown in Figure 2. The off-gas system was designed, implemented and commissioned and is currently being continuously monitored to ensure optimal operation.

The off-gas system was designed to operate at a boiler inlet (cyclone outlet) temperature of 500°C (±20°C). This design specification is based on a specific furnace batch recipe and a furnace input power of 41.5MW. As the boilers are not yet implemented, but currently under construction, the data presented pertains to the off-gas flow via the radiant cooler.

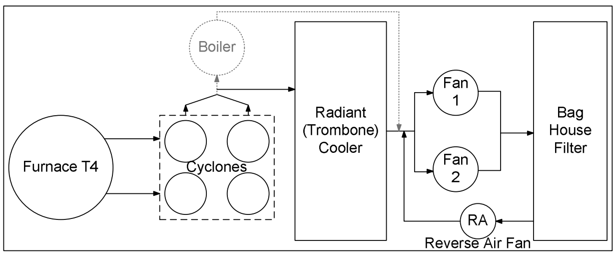

Figure 2: Basic off-gas system layout

The off-gas system had to be designed such that it would cater for variations in the furnace feed mixture, specifically with regards to reductant type and quality, leading to variations in the off-gas volume, temperature and composition. Three scenarios were specified, namely Design gas, Low gas and High gas, briefly differentiated in Table 1.

The design of an off-gas system for these three possible future scenarios needed to address the following main points;

1. The duct system needed to be specified at a diameter which ensured that the low gas case has a velocity which is high enough to prevent dust drop-out, while the low gas case has a velocity low enough to prevent high abrasion rates and high system pressure losses.
2. The cyclone design was optimized to ensure adequate efficiency for the low gas scenario, and optimal pressure losses for the high gas scenario.
3. The main air fans were specified to be flexible enough to compensate for the different gas scenarios and their associated system pressure losses.
4. The bag house filter design was done such that the air-to-cloth ratio (filter velocity) is manageable at the high gas flow rate and optimal at the design gas flow rate, making the filter an optimal size.
5. The use of PTFE-membrane lined filter bags within the bag house filter allows for large variations in filter velocities, up to 50% higher than for conventional filter bags (0.65m/min gross for conventional bags), as described by Els *et al.* in [9].
6. Each scenario was assessed such that at a boiler inlet temperature of 500°C, the furnace extraction volume was adequate to ensure that no fumes escaped the furnace hood.

The design off-gas temperature and flow profiles, assuming 100% fume capture at the furnace hood, for the three scenarios is shown in Figure 3.

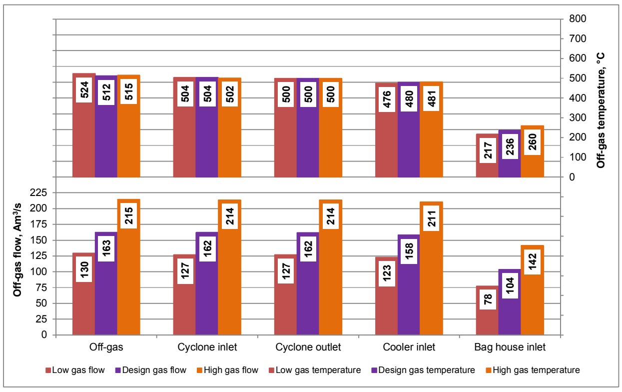

Figure 3: Off-gas profile along system for scenarios

Table 1: Three off-gas scenarios considered

	Low gas	Design gas	High gas
% Ore	70%	71%	67%
% Reductant	22%	20%	25%
% Fluxes	8%	9%	8%
Reductant type			
% Coke	60%	40%	40%
% Anthracite	20%	25%	30%
% Coal	20%	35%	30%

3 Methodology

3.1 Furnace Predictive Model

In order to accurately predict the off-gas in terms of volume, temperature and composition, a furnace predictive model is generated which takes the following into consideration;

1. Furnace reaction gas is estimated through the utilization of a carbon balance over the furnace.
2. The reaction gas is combusted and diluted with ambient air. Various amounts of dilution air are used to calculate the off-gas temperature profile.
3. Heat transfer correlations are used to determine the temperature profile of the off-gas system.

The off-gas temperature must be designed to be within set limits; the upper limit is set to protect the furnace hood and off-gas ducting, whilst the lower temperature is governed by the specific acid dew point of the gas. It is important to consider both winter and summer conditions when assessing this low limit, as cold winter ambient temperatures will affect the gas temperature.

The use and development of such a model has been described in the following articles, references as [7], [8] and [9], respectively;

- “Air Pollution Control System Upgrade at Tubatse Ferrochrome”.
- “New Techniques in Steel Meltshop Air Pollution Control”.
- “Major Ferroalloy Producer Improves Furnace Fume Control System by Installing Baghouse with Membrane Filter Bags”.

3.2 Furnace CFD

A computational fluid dynamics (CFD) model is constructed of the furnace in order to verify that the volume specified by the furnace predictive model is adequate to ensure that all furnace fume is captured, considering the specific furnace hood configuration. The CFD model also indicates the predicted off-gas temperature, which should correspond with that predicted by the furnace predictive model.

3.3 Furnace Off-Gas Testing

The off-gas system is tested after implementation in order to validate and verify the design. Off-gas testing includes gas flow measurements, gas temperature measurements and gas composition measurements at various points along the off-gas ducting. All testing is done in accordance with the prescribed EPA methodologies.

The tested results are then compared to the design values, considering actual operating conditions such as furnace recipe and input MW.

4 Current Furnace Operation

The furnace is currently operated at a lower input MW rating than design, averaging at 30MW. This is due to electricity supply limitations, as well as a hot spot on the furnace shell which must be repaired.

The off-gas system is at present not controlled to operate at a cyclone outlet temperature of 500°C due to the following main factors;

- Furnace MW input is lower than design, so in order to increase the furnace off-gas temperature such that the cyclone outlet temperature is 500°C, a lower-than-design off-gas volume must be extracted which leads to large amounts of fume escaping at the furnace hood.
- The boilers are not yet installed, so there is at present no need for high temperature operation.
- Current furnace practices during stoking are not optimal for high temperature operation as all furnace doors are opened at once, leading to off-gas temperature drops. An operation regime change must be implemented to reduce the number of doors open at any time during furnace operation.

Figure 4 shows a comparison of the off-gas flow and temperature along the off-gas system for the design case of 41.5MW and the current operational case of 30MW (both for the design gas scenario). The figure shows the vast reduction in off-gas flow required if the boiler inlet temperature (cyclone outlet temperature) of 500°C is to be met.

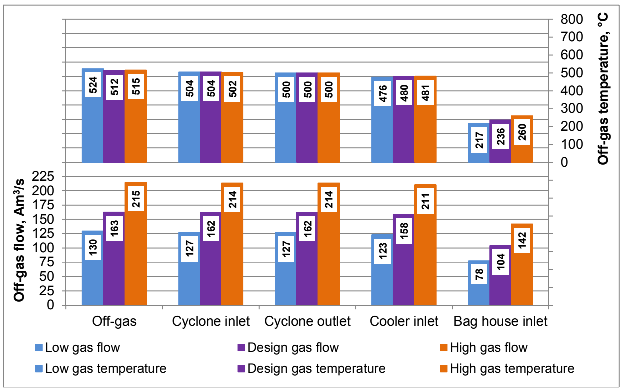

Figure 4: Off-gas system profile for 41.5MW and 30MW

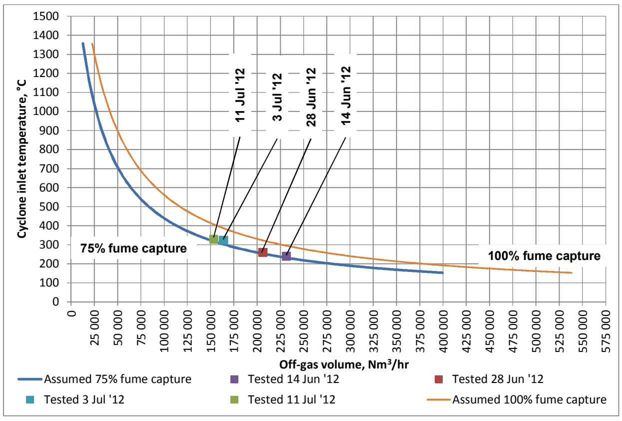

Figure 5: Off-gas design vs. tested conditions

5 Results

The off-gas system has been tested in order to provide a validation of the system design, providing a level of confidence for the boiler implementation phase. Due to power supply limitations, the furnace was tested at an operating power of 30MW.

An estimated fume collection efficiency of 75% is utilized in the calculation, which is a result of the furnace door configuration, as well as of the furnace operating philosophy whereby the furnace doors are left open for long periods of time.

The system is currently controlled such that the current drawn by the motors of the 2 main fans is maintained within the motor design range, typically at a value of 90 Amps.

5.1 Predictive Model Validation

The comparison between the design values (for 100% fume capture and 75% fume capture) and the tested data are shown in Figure 5, and noted in Table 2 with the calculated X-factor (which is the ratio of off-gas energy to furnace electrical energy). As can be seen in the graph, the tested data ties up with the 75% fume capture assumption made.

Table 2: Off-gas testing results

Test Date	Off-gas Volume, Nm^3/hr	Cyclone Inlet Temperature, °C	X-factor
14 June 2012	231 700	239	0.69
28 June 2012	206 300	260	0.67
03 July 2012	163 900	323	0.67
11 July 2012	153 600	328	0.64

5.2 Furnace CFD Model

A computational fluid dynamics (CFD) model was built of the furnace and furnace hood. The CFD model illustratively shows whether fume leakage is expected for the given extraction mass flow, as well as predicts the furnace off-gas temperature. Figure 6 shows the furnace hood configuration.

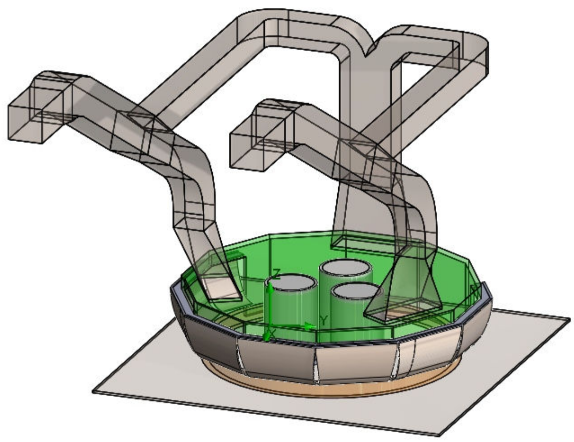

Figure 6: Furnace hood configuration

The CFD model was run for 3 scenarios, described below. The results of the CFD model, compared to the furnace predictive model, are given in Table 3.

1. No furnace doors open.
2. 1 furnace door open.
3. 3 furnace doors open.

The furnace hood configurations for the 3 scenarios considered are shown in Figure 7. The CFD results are illustratively shown in Figure 8, Figure 9 and Figure 10.

Table 3: CFD model results

No. furnace hood doors open	CFD Model Results		Predictive Model Results	
	Temperature	Fume leakage seen?	Temperature	% fume captured
0	404 °C	No	410 °C	0%
1	400 °C	Yes	393 °C	95%
3	356 °C	Yes	355 °C	85%

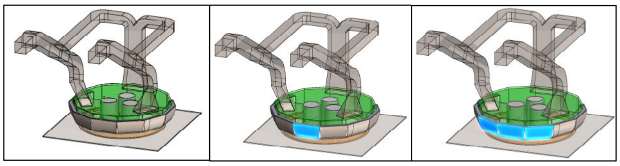

Figure 7: Furnace hood configurations for CFD scenarios

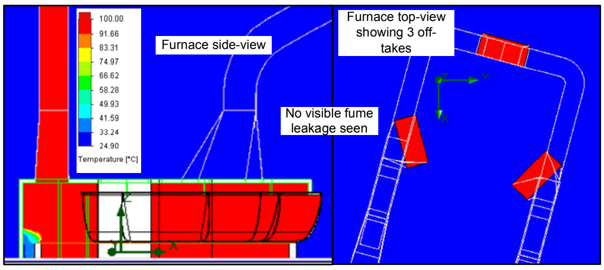

Figure 8: CFD results for 0 doors open

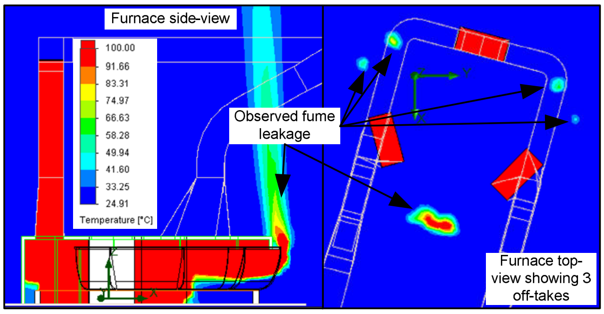

Figure 9: CFD results for 1 door open

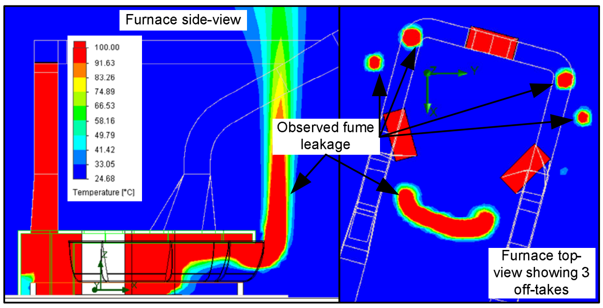

Figure 10: CFD results for 3 doors open

5.3 Steam Generation

The furnace off-gas flow and temperature was continuously tested over a period of 24 hours in order to assess the variability of the furnace over time with regards to furnace operations, as well as with regards to the furnace input MW variations. These variations have a direct impact on the steam generation rate from the waste heat boiler. The collected data is shown in Figure 11.

If the collected data is manipulated in the following manner, the theoretical steam generation rate may be predicted;

- Furnace MW data points are increased by 8.3MW, bringing the maximum furnace input MW for the 24-hour period to 41.5MW, and the average to 35MW.
- Furnace off-gas flow and temperature are theoretically predicted from the furnace input MW's and utilized to assess the steam generation rate with time.
- It is assumed that 100% of the furnace fume is captured.

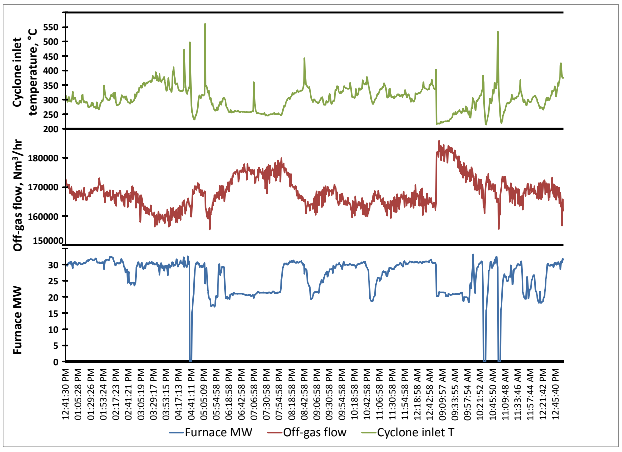

Figure 11: Collected off-gas data for a 24 hour period

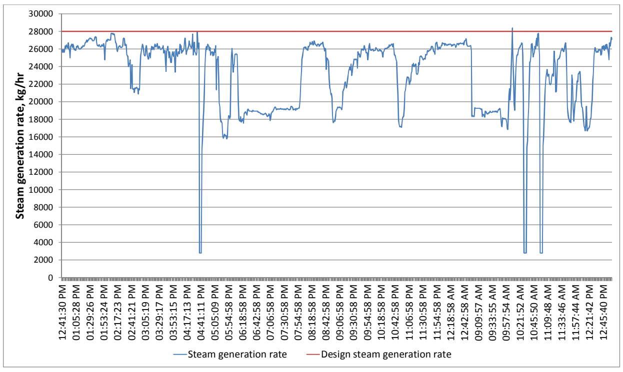

Figure 12: Theoretical steam generation rate

6 Discussion

6.1 Predictive Model Validation

The furnace predictive model was adjusted for actual operating conditions (specific batch recipe and furnace input MW), and then compared to the tested data as shown in Figure 5. A good correlation is seen between the model and the tested results when a furnace fume capture efficiency of 75% is applied to the calculation model. The small variations which can be seen on the graph, between the design values and the tested values are due to factors such as measurement errors and furnace instability.

6.2 Furnace CFD Model

The furnace CFD model is well correlated with the furnace predictive model, which in turn has been validated by site test work. The CFD models also show a correlation to the fume capture efficiency observed on site and implemented into the furnace predictive model.

6.3 Steam Generation

The typical furnace variation is illustrated by the data collected over a 24-hour period of continuous testing. This data was manipulated such that the theoretical steam generation rate could be predicted over time considering the furnace variations. As can be seen from the graph presented in the results section, the steam generation rate will fluctuate with time, and this must be taken into consideration when implementing a waste heat recovery system. The predicted average steam flow rate is lower than the design as the average furnace input MW is 34MW, while the design is for 41.5MW. For the case of Tubatse Ferrochrome, the steam fluctuations will also be smoothed due to the implementation of 6 boilers, feeding steam into a single turbine system.

7 Conclusions

The following conclusions are drawn;

- Off-gas systems can be optimally designed for a various number of furnace batch-mix scenarios, leading to variations in off-gas flows and temperatures. Careful consideration must be given to;
  - The design of ducting such that dust settlement does not occur at the various off-gas flow rates.
  - Selected off-gas temperature in order to ensure that the furnace hood is optimally extracted with no fume escaping the hood.
  - Design of equipment items such as cyclones, fans and bag house filters to ensure optimal sizing, pressure losses and operation over the entire range of off-gas volumes.
  - Selection of the filter media – membrane lined filter bags offer a wider flow variation at a smaller filter size by allowing up to 50% higher filter velocities than conventional bags.
- The furnace predictive model has been successfully validated against site data, collected through an on-going testing campaign.
- CFD analysis provides an efficient tool to ensure that the furnace fume is adequately contained in and extracted from, the furnace hood.
- The CFD modeling done shows good correlation to the results obtained from the furnace predictive model, which has in turn been validated by site test work.
- The fluctuating nature of a furnace leads to variable steam generation rates within the waste heat recovery boiler. These fluctuations must be taken into consideration when implementing a waste heat recovery system such as a boiler and steam turbine.

8 References

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