PROCESS MODELING AND TESTING METHODS FOR EVALUATING FERROALLOY FURNACE OFF-GAS WASTE ENERGY

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ABSTRACT

This paper details test work and process modeling activities done to profile ferroalloy furnace off-gas systems for the design and implementation of waste energy recovery systems. Studies were done at three ferroalloy smelters, considering the following waste energy recovery technologies:

- *Flue-gas to air heat exchanger for the supply of hot, clean air to both a fluidised bed ore and rotary reductant dryer, utilizing the waste heat in the off-gas from a semi-open furnace*
- *An Organic Rankine cycle (ORC) for the generation of electricity from a semi-open furnace.*
- *Steam boilers and turbine for the production of electricity using the waste heat in the off-gas from semi-open furnaces.*
- *Internal combustion engines for the production of electricity using the energy available in the CO-rich off-gas from a set of 4 closed furnaces.*

Semi-open and closed furnaces have different requirements for test work and modeling to evaluate waste energy, since gas compositions and temperatures are dissimilar. Common activities for evaluation are the following:

- *Furnace predictive process modeling and off-gas optimization.*
- *Test work to validate the off-gas model in terms of gas flow, composition and temperature.*
- *Additional test work to assess energy quality, including isokinetic sampling, VOC (Volatile organic compound) testing, and moisture content determination.*
- *Continuous testing over longer periods under varying furnace operating conditions to ensure that the design work considers all furnace operating modes.*

Study deliverables formed the basis for detailed energy recovery equipment design and provided inputs to project economic evaluation. Steam boilers are being implemented at one smelter, while drying, ORC and gas engine technologies have been found to be feasible at the other smelters.

KEYWORDS: *Ferroalloy, furnace, off-gas, energy recovery, ORC, gas engines, Rankine.*

1. INTRODUCTION

The implementation of waste energy recovery on ferroalloy furnace off-gas is not a new concept and has been completed at several plants with varying degrees of success. Steam generation, drying and gas engine technologies have been utilised in the past and organic Rankine cycle (ORC) is being evaluated by several vendors for future use. This article discusses test work and process modeling done on three projects. The suitability and optimal design of steam generation at a semi-open furnace application, drying and ORC on a second semi-open furnace application and gas engines on a closed furnace application was evaluated. The project for steam generation is currently being implemented, while the other projects await capital funding.

The capital cost associated with energy recovery projects necessitates proper evaluation of both the application and the energy recovery technology to optimise efficiency, operation and project economics. The furnace process has a considerable variation with regard to the energy content and usability of the off-gas stream. Site test work, the compilation of a validated process model and statistical analysis provide reliable, longer-term data regarding energy quantity and quality and result in a sound approach to project technical and economic evaluation.

2. SEMI-OPEN FURNACES

2.1. Ferrochrome SMELTER

An energy recovery study was conducted on a 54 MVA semi-open submerged arc furnace to evaluate available energy, energy quality and recovery options. The gas cleaning layout and test results are displayed in figure 1.

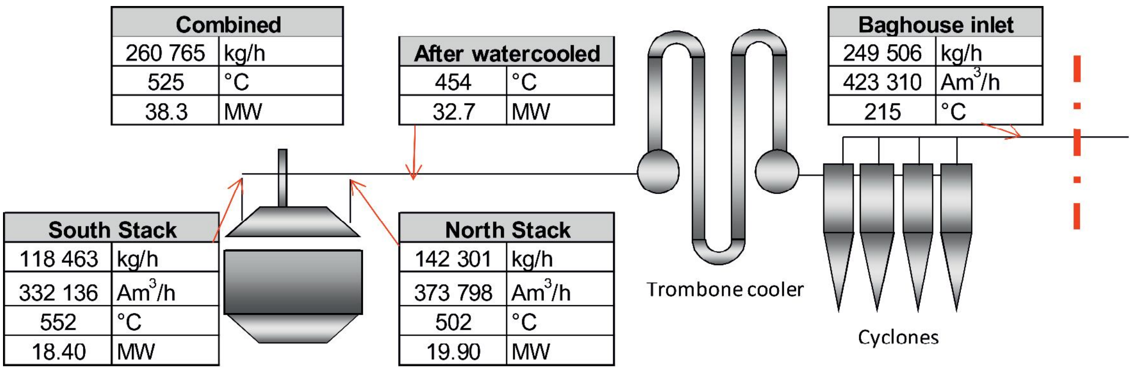

Figure 1: Test results

The test points at the off-takes are approximately 10 m away from the furnace hood, which means that some energy was lost over the water-cooled duct. A process model of the furnace was developed, as previously detailed in Koekemoer and Els et al [1, 2], to predict off-gas parameters. The additional water cooled ducting was added to the furnace model and compared to measured values. The comparison between the furnace model and test results is displayed in table 1.

Table 1: Comparison between furnace model and test results

Parameter	Unit	Measured	Model	Variance
Mass Flow rate	kg/h	260 765	260 669	0.04 %
Combined Off-gas temperature	°C	525	533	1.52 %
Temperature after cooled ducting	°C	454	461	1.54 %
Main fan inlet temperature	°C	215	233	8.37 %

The measured temperatures correlate well with predicted temperatures of the furnace model with a variance of below 2 %, thereby verifying the proposed furnace model.

Statistical analysis was used to evaluate available off-gas energy. The histogram in figure 2 indicated that long-term off-gas energy data corresponded with the validated model.

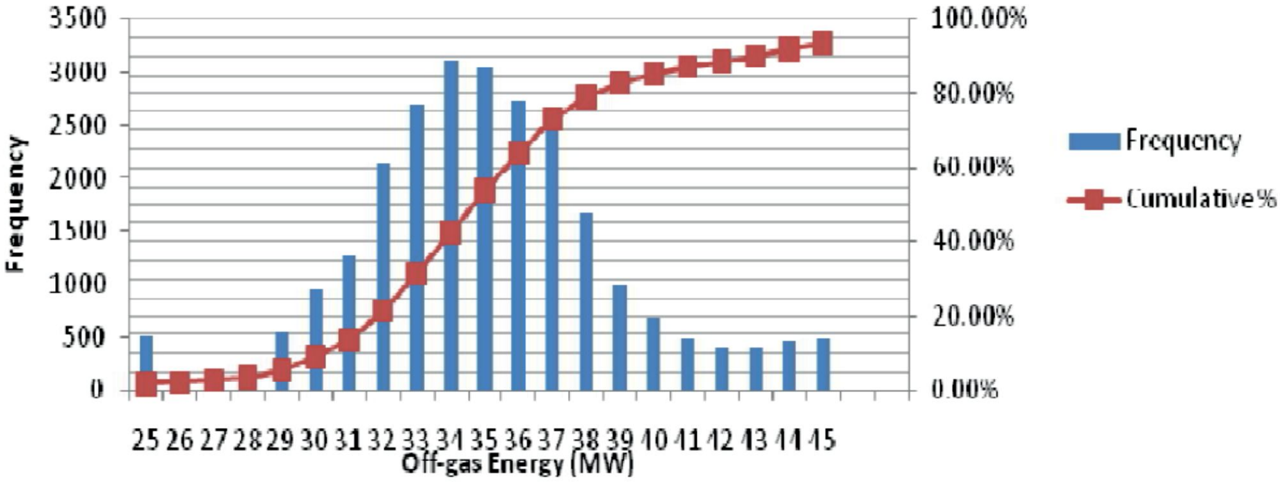

Figure 2 : Histogram indicating off-gas energy

The following conclusions are drawn from the available data and analysis:

- Off-gas energy of 38.3 MW was produced for a furnace electrical energy of 43 MW. The off-gas temperatures matched up with the furnace model with a variance of less than 2.5 %.
- The design temperature can be increased by approximately 50°C and the energy by 5.0 MW if the water-cooled ducting length is reduced.
- The test results showed an increase of 5 MW in off-gas energy when charging the furnace with more coal and less coke. If this forms part of the long term batching plan more off-gas energy will be available to harvest.
- The off-gas parameters were subsequently used as a basis for evaluating reductant and ore drying as well as organic Rankine cycle (ORC) energy recovery.
- Drying could utilise 17.4 MW or 45 % of the 38.3 MW off-gas energy. The ORC could utilise 22.9 MW (60 %) of the off-gas energy and generate 4MW electrical energy.
- The payback period for drying was less than 3 years and the ORC around 7 years, the project is currently awaiting funding.

2.2. Tubatse Ferrochrome

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”. 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. This previous off-gas system has been described in detail by Koekemoer et al. in [1].

Subsequently the furnace transformers were upgraded, and currently the gas cleaning system is being extended and waste heat recovery boilers for electricity generation are being installed. The future gas cleaning and boiler layout is shown in figure 3.

The off-gas system was designed to operate at a boiler inlet (cyclone outlet) temperature of 500°C (±20°C). 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.

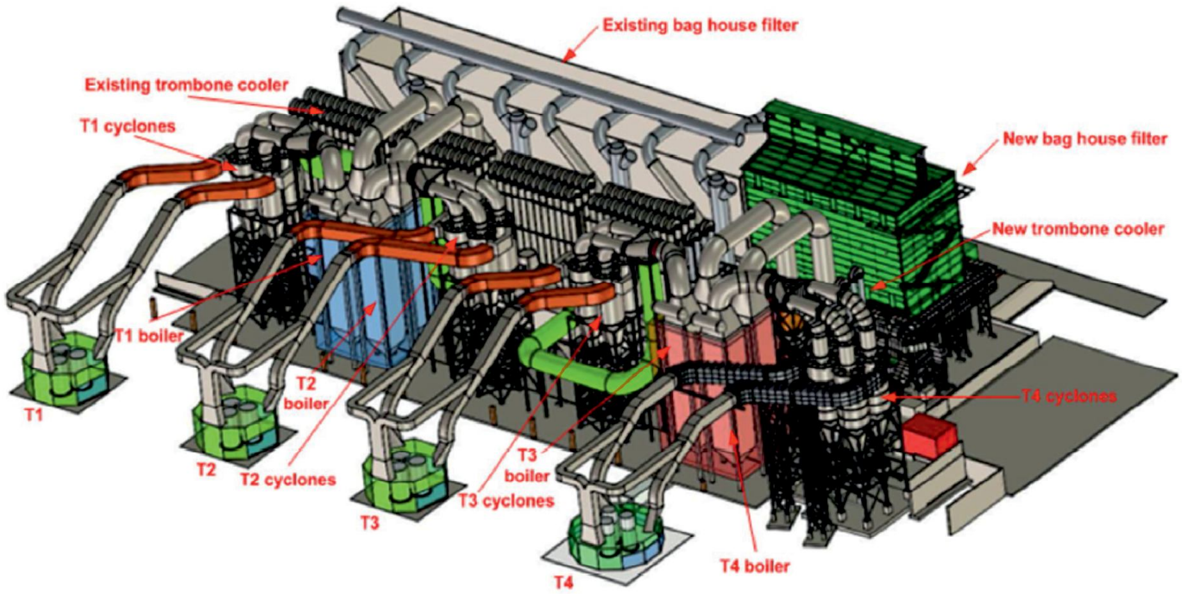

Figure 3: east plant layout

2.2.1. Furnace Predictive Model

To accurately predict the off-gas in terms of volume, temperature and composition, a furnace predictive model was developed, as described in several previous articles [1, 2]. Three scenarios were specified, namely Design gas, Low gas and High gas, which varied according to the quantity and type of reductants in the charge mix. The design off-gas temperature and flow profiles, assuming 100 % fume capture at the furnace hood, for the three scenarios is shown in figure 4.

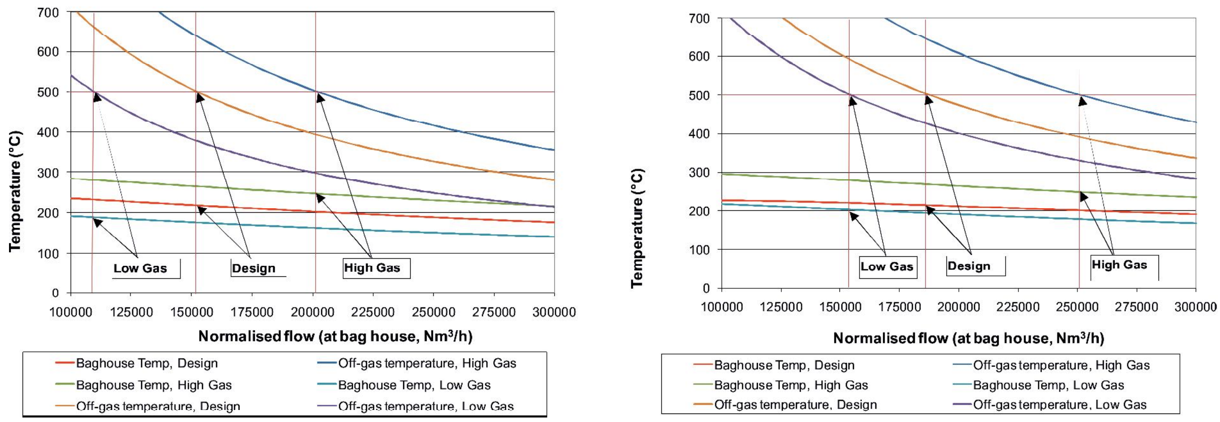

Figure 4: Off-gas profile along system for scenarios for furnaces 1-3 (left) and 4 (right)

2.2.2. Furnace Off-Gas Testing

The off-gas system was tested 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 was done in accordance with the prescribed EPA methodologies [3]. The tested results were then compared to the design values, considering actual operating conditions such as furnace recipe and input MW.

The comparison between the design values and the tested data are shown in figure 5.

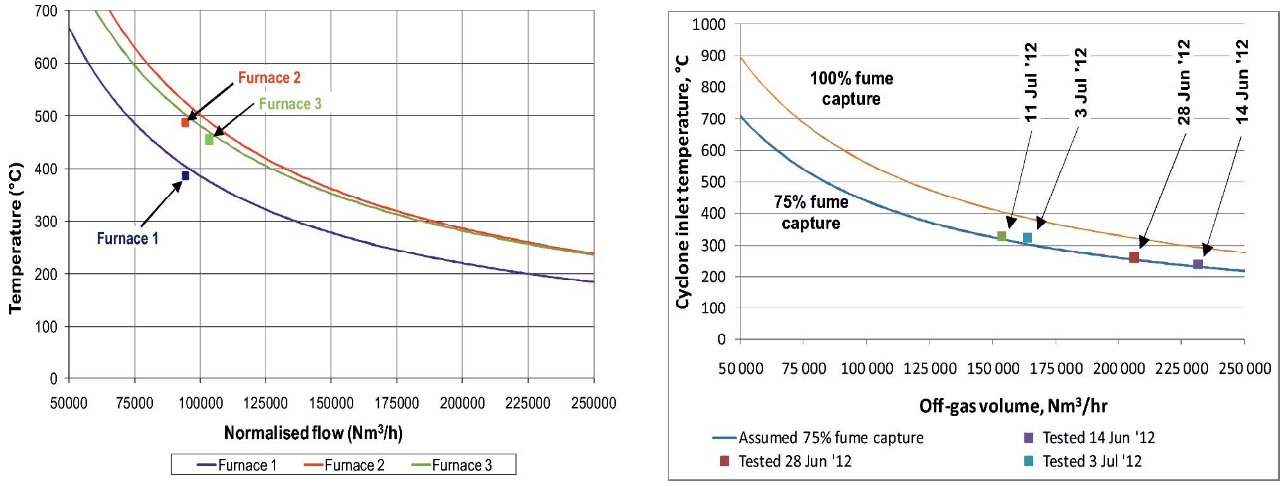

Figure 5: Off-gas design vs. tested conditions for furnaces 1-3 (left) and 4 (right)

As is evident in the figure, the tested data ties up well for furnaces 1 to 3. At furnace 4, fume leakage was found at the hood during testing due to furnace doors being left open. The test results compared well with an estimated fume collection efficiency of 75 %, this value was verified using CFD modeling as described in the next section.

2.2.3. Furnace CFD Model

A computational fluid dynamics (CFD) model was built of the furnace and furnace hood. The simulations were run using FloEFD 11.3.0. 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.

The CFD model was run for 3 scenarios: no furnace doors open, 1 door open and 3 doors open. The furnace hood configurations for the 3 scenarios considered are shown in figure 6. The CFD results are illustratively shown in figure 7 and figure 8.

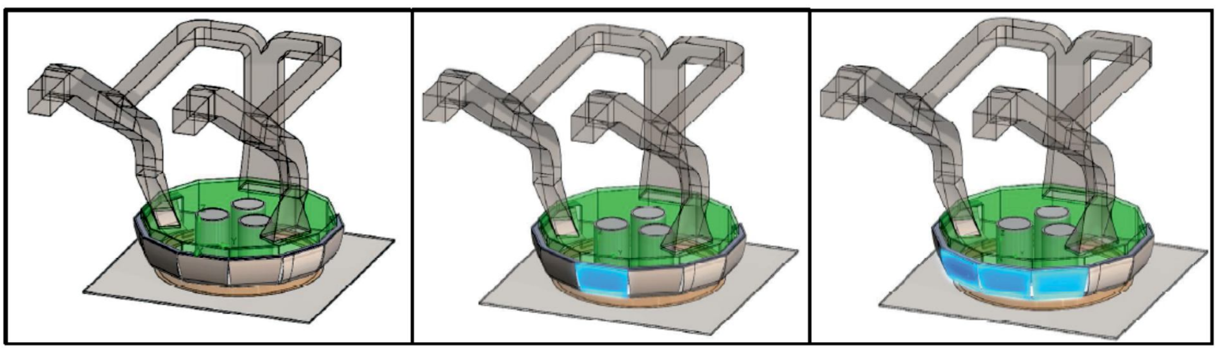

Figure 6: Furnace hood configurations for CFD scenarios

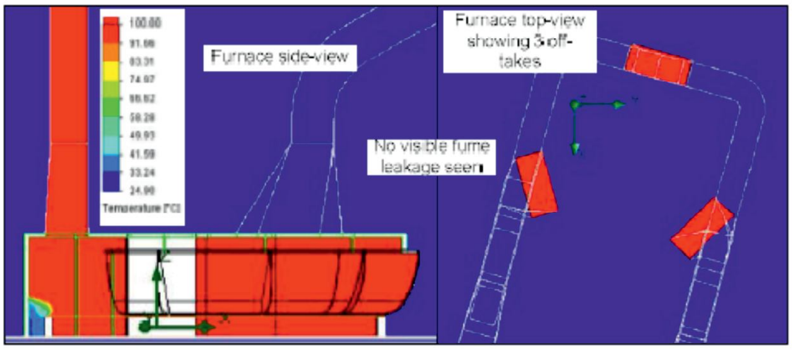

Figure 7: CFD results for 0 doors open

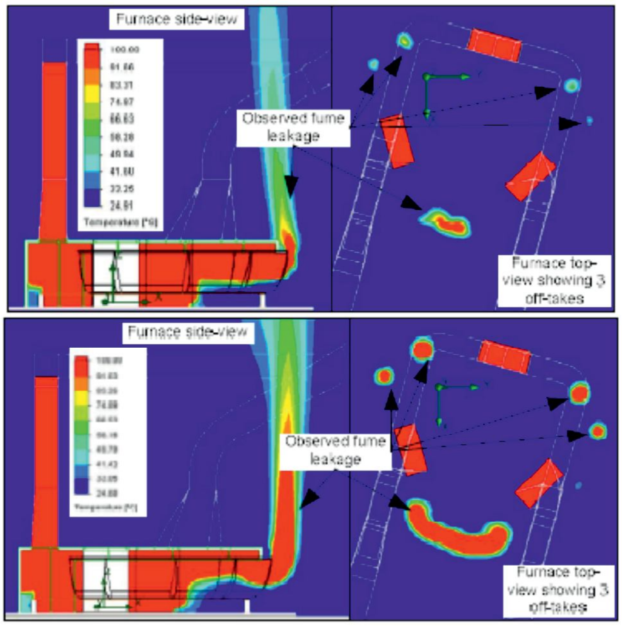

Figure 8: CFD results for 1 door open (left) and 3 doors open (right)

2.3. Conclusions

The following conclusions are drawn:

- 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 model shows good correlation to the results obtained from the furnace predictive model, which has in turn been validated by site test work.
- For all 4 furnaces, total off-gas energy of 160 MW is predicted under High gas conditions and 121 MW under Design conditions.
- Under High gas conditions, 64 % or 103MW of the off-gas energy is transferred to steam and the turbine installed capacity is 30 MW. The project is currently under construction, first steam and electricity generation is envisioned for December 2013.

3. CLOSED FURNACES

A six month test campaign was completed to evaluate the feasibility of using gas engines for energy recovery at Hernic Ferrochrome. Four furnaces are located at Hernic, rated from 37 to 78 MVA. The scope of test work, test and verification methods as well as confidence level are summarised in the table below.

Parameter	Method of measurement	Verification method(s)	Confidence level [High - Med - Low]
Gas volumetric flow	Pitot tube measurements, EPA approved method.	Mass and energy balance, completed by independent parties, based on Hernic furnace feed mixes.	High
Gas analysis	Tedlar bag GRAB or BOMB samples analysed by Gas Chromatograph (GC)	Calibration gas tests performed by a third party	High
	Sperosens portable analyser	ORSAT analysis	
	Siemens online analyser (SCADA)		
	ABB analyser		
Gas particulate loadings	Isokinetic testing, EPA approved method.	Repeat testing	High
VOC and PAH content of gas	Tedlar bag GRAB or BOMB samples and analysis.	Repeat testing	High
Moisture content	Silica gel absorption tube	Mass and energy balance	High

Gas volumetric flow had to be measured to determine the number of engines required, gas analysis determined the engine type, gas composition variability was compared to engine limitations, gas particulate loading and VOC content was required to compare with engine specifications. From the gas testing study, the following average combined gas properties were defined:

Combined MEASURED gas flow to energy recovery plant	Nm^3/hr	41 235
Combined PREDICTED gas flow to energy recovery plant	Nm^3/hr	40 644
Total PREDICTED combined gas flow from furnaces (before off-takes)	Nm^3/hr	49 044
Overall combined gas availability	-	89%
Combined gas CO%	% vol	57.90%
Combined gas H_2%	% vol	3.30%
Combined gas calorific value	MJ/Nm^3	7.72
Total furnace power	MW	171
Combined gas energy	MW	88
Average rate of change of calorific value per 30 seconds	%	0.50%
Combined gas temperature	°C	42.0
Combined gas average particulate loading	mg/Nm^3	197
Combined gas VOC and PAH content	-	negligible

The calorific value of the gas, as well as the rate of change of calorific value per 30 seconds, was assessed for the combined furnace gas, to assess the engine requirement of fluctuation of less than 2 % per 30 seconds. A histogram and OGIVE curve for the calorific value fluctuations is shown in figure 9. As indicated on the curve, the average calorific value fluctuation was 0.5 % and it exceeds the 2 % per 30 seconds limit 0 % of the time.

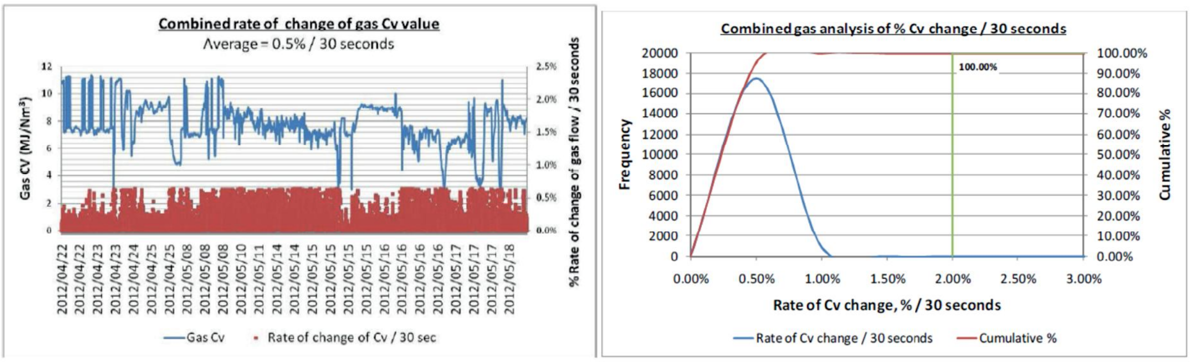

Figure 9: Calorific value assessment and Cv rate of change histogram and OGIVE curve

Mass and energy balance calculations were done to verify the gas volumetric flow and analysis. The calculations considered the following:

- Carbon monoxide (CO) and hydrogen (H_2) gas formed by furnace reactions.
- In-leakage and partial combustion of CO and H_2
- Boudouard and water-gas shift reaction

Volumetric flow was calculated to within 5% of measured values at the measured gas analysis.

Using the above information and daily MWh data for the test period, the following analysis was done to determine the number of engines which can be run at a specific instance in time:

$$Gas\ Energy = (Furnace\ input\ MW)(X - factor)$$

$$Usable\ Gas\ Energy = (Gas\ Energy)(Gas\ Quality\ Factor)$$

Engine selection is done based on measured gas analysis. Fuel parameters of importance are carbon monoxide (CO) and hydrogen (H_2), as illustrated in the typical selection chart compiled by Jenbacher. After selection of the most appropriate engine for the gas composition, the gas quality factor in the above usable energy equation was calculated by determining the quantity of gas not falling in the operating range of the selected engine.

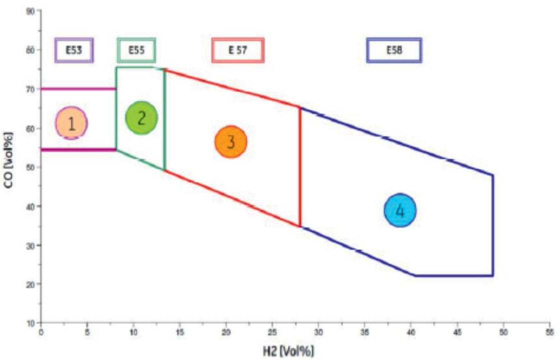

Figure 10: Engine selection chart

The individual engine utilisation factors are shown in the graph in figure 11 below. The overall engine utilisation factor for the installation of 15 engines is 92.4 %, whilst that for the installation of 16 engines is 88.4 %, as shown in figure 11 below.

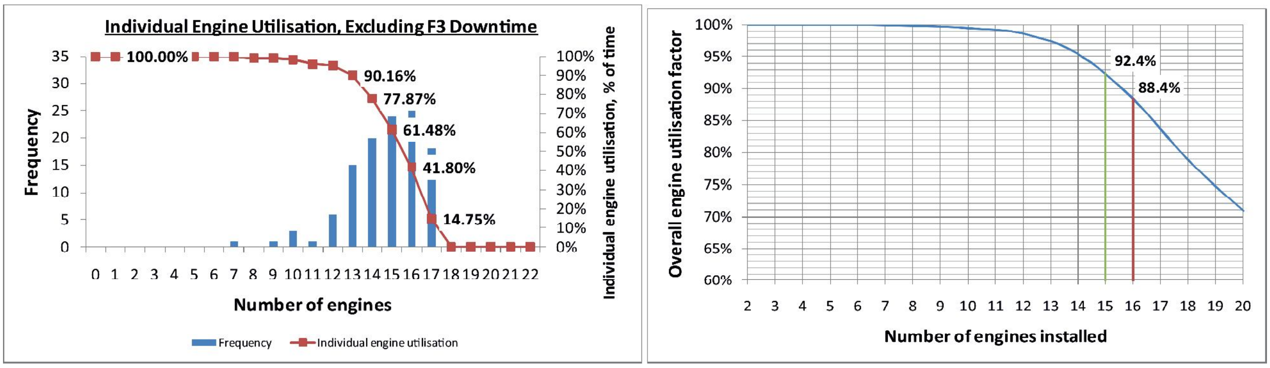

Figure 11: Individual engine utilization and overall engine utilization

Conclusions of the gas test study were:

- Gas Analysis: Multiple gas analysis methods and analysers were used to ensure an accurate and representative result was achieved.
- Gas Volumetric flow: volumetric flows could be accurately measured by pitot tube method and results verified using mass and energy balance calculations.
- Pollutant levels were determined and the need for secondary filtration of particulates confirmed.
- Gas analysis and volumetric flow measurements have been validated to ensure good confidence of input parameters to the BFS.
- The optimum number of engines could be selected using a combination of verified test results and statistical analysis of plant data.
- Usable average off-gas energy of 88 MW was produced and for 16 engines installed at an overall utilization factor of 88.4 %, this would lead to 24 MW of electrical energy generation. The project shows good economic potential and is currently awaiting funding.

4. CONCLUSIONS

Process modeling and test methods were used to evaluate three energy recovery applications at ferroalloy smelters:

- The quantity of energy was accurately tested in various environments (low/high temperatures, combustible/high temperature gases).
- Test results were validated using process models developed specifically for these applications.
- Energy quality was determined by testing contaminants including dust concentration, tars and trace elements.
- Long-term energy variability was determined for optimum capacity selection of energy recovery equipment and short-term energy variability was determined to evaluate the impact on selected energy recovery equipment.
- Successful integration of energy recovery equipment in existing brown-fields sites was assisted by evaluation of the furnace processes and energy recovery requirements.

- The availability of high quality data helped ensure accurate economic analysis of energy recovery feasibility.

5. REFERENCES

[1] Air Pollution Control System Upgrade at Tubatse Ferrochrome. Koekemoer, R, et al. 2007. INFACON XI.

[2] Major Ferroalloy Producer Improves Fume Control System by Installing Baghouse with Membrane Filter Bags. Els, L, Fereday, F, Vorster, O. s.l. : INFACON XII.

[3] US EPA Testing Methods, http://www.epa.gov/region1/info/testmethods/pdfs/testmeth.pdf.