PLUME ANALYSIS AND CFD MODELING FOR EFFECTIVE EAF MELTSHOP ENVIRONMENT CONTROL

BY

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SYNOPSIS:

Process gas emissions from Electric Arc Furnace (EAF)-based operations are frequently excessive and require improvement to meet environmental regulation standards applicable to the country where the operation is located in.

Gas Cleaning Technologies (GCT) has applied several techniques such as Computational Fluid Dynamics (CFD) and plume video analysis to quantify plume flow rates and to evaluate flow patterns and capture efficiencies. These techniques help optimize the exhaust requirements and capture efficiencies of hoods. Effective use of these techniques will result in not only emissions reductions but operational improvements which in turn lowers operating cost.

Plume video analysis is an essential tool to quantify the fume release rates into the meltshop over time for dynamic processes such as furnace charging. The results can then be used to optimize canopy hood storage capacity and exhaust rate.

GCT has also successfully applied CFD modeling for complex models of the entire meltshop. The modeling predicts fume and dust flow patterns through the building for various operating scenarios and wind conditions for the existing meltshop geometry and hood exhaust rates. The model can then be modified to evaluate the impact of building modifications, hood modifications, and hood exhaust rates on capture efficiencies and fugitive emissions rates.

This paper presents the use of video plume analysis and CFD modeling to evaluate and optimize EAF meltshop fume capture and use of other logged and measured data to calibrate the model to real world conditions.

Keywords: Electric Arc Furnace, Computational Fluid Dynamics, Process Improvements, Operational Cost Savings, Emission Reduction

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Introduction

Electric Arc Furnace (EAF)-based operations are of high intensity and are often associated with excessive fugitive gas emissions. Air pollution control (APC) in a steel meltshop typically relies on both fourth-hole direct extraction and roofline canopy hood capture. Recent work has been done to improve APC by enhancing the extraction efficiency at the fourth-hole[1] and optimizing canopy hood design and exhaust rate.

To better control and reduce the release of emissions, a good understanding of the plume flow rates and analysis of the canopy hood capture efficiency (the percentage of emissions generated by the EAF that are captured by the canopy hood) is required. Techniques such as video plume analysis and Computational Fluid Dynamics (CFD) modelling may be used to gain a better understanding of the specific process conditions in a meltshop and to provide results that allow adequate process improvement decisions.

A good understanding of the EAF operation is necessary to apply these techniques correctly. Literature on the modelling of the EAF is scarce but dynamic modelling has been considered[4,5]. CFD has been shown as a powerful tool to aid in the design of ventilation and fume control systems in high temperature metallurgical facilities such as meltshops and smelters[3].

The primary focus of the techniques discussed here is to reduce emissions; however, the application and adequate interpretation of the results obtained using these techniques allows for a meltshop air pollution control system design with better capture efficiencies and optimized exhaust conditions which in turn results in a reduction in operating costs. Two such case studies, one of which directly discussed air pollution control in an EAF meltshop with a 1.2 million ton per annum production rate, were presented at the Kazakhstan Growth Forum in 2007. This case study demonstrated that CFD modelling can be used to optimize the meltshop configuration as well as the canopy hood design[2].

Typical meltshop Fume Extraction Systems (FES) comprise of a Direct Evacuation Control (DEC) system to capture primary gases and a canopy hood to collect fugitive emissions associated with the EAF operation. These systems can also include a local capture hood for a separate ladle metallurgy furnace and can also include secondary emissions collection such as rooftop scavenger hoods. Modern meltshops have seen marked improvements in productivity, however, this also resulted in an increased demand on the FES. Els *et al.* cited a steel meltshop at which the productivity was increased by 30%, without modifying the APC which resulted in poor ambient air quality, dense fumes and low visibility[1].

This paper will address ways to improve the emissions capture to align productivity improvements with solutions to provide for better emissions control. Adequate use of the FES and improvements in the system operation will be discussed which ultimately also result in a reduction in operating cost due to more efficient scrap processing and often better draft control in the DEC.

Materials and Methods

In order to adequately model the EAF environment or even the entire meltshop, it is necessary to collect various data directly at the plant facility. Therefore, a site visit is conducted to observe EAF operations, collect logged data from the PLC, collect ductwork measurements, and conduct ventilation surveys of the meltshop. In order to obtain reliable results from a CFD model, it is crucial to set appropriate boundary conditions based on the data collected during the site visit to validate the model. During a typical plant site visit, the following data is collected:

- Drawings of building general arrangements and equipment layouts
- Notes of observations of the EAF operation
- Identification of various heat and fume sources throughout the building
- Photographs of building openings, internal equipment, and buildings or equipment outside of the meltshop adjacent to the meltshop building
- Temperature and velocity measurements at each major opening including ground level openings, building wall louvers, rooftop monovents and mechanical ventilators
- Flow rate and temperature data within the existing primary and secondary gas collection systems
- Plume videography.

After collection and analysis of data collected on site, the typical inputs into the CFD model include:

- Wind direction and speed based on conditions observed during site visit
- Exhaust conditions from canopies and other ventilation systems based on measurements collected during site visit
- Heat release from heat sources
- Ambient air temperature.

Computational Fluid Dynamic Model

A CFD model is a three-dimensional computer model that simultaneously solves the fundamental momentum, mass and energy equations under steady-state or transient conditions. The tool allows to quantitatively predict fluid flow in and around equipment, structures, ductwork and hoods. The complexity of the model varies and can be as simple as modelling a single collection hood or include an entire building, taking into account its surroundings, internal heat sources and external wind conditions, etc.

The use of CFD modelling allows for better evaluation and comparison of various scenarios which is then used to improve the ventilation system design.

The CFD modelling for this work is carried out using CHAM's Phoenics CFD Package. In this work, the CFD is used as a tool to supplement conventional engineering methods typically employed to design fume capture hoods and building ventilation. Figure 1 below demonstrates an example of a typical meltshop CFD model including the FES.
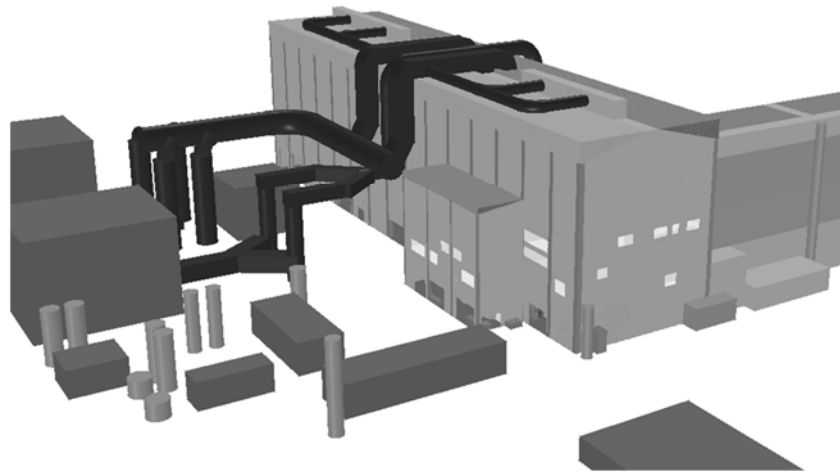
Figure 1. Meltshop CFD Model Including the Fume Collection System.

Once sufficient input data has been obtained, the CFD model can be developed for only selected equipment or the entire meltshop. For this particular model, details of major equipment for the entire meltshop with two EAFs were developed and its layout is presented in Figure 2.

Figure 2. Meltshop CFD Model Showing the Major Internal Equipment Layout.

Figure 3 below presents an elevation view taken from the CFD model showing the EAF, DEC duct, canopy hood and slag tunnel.
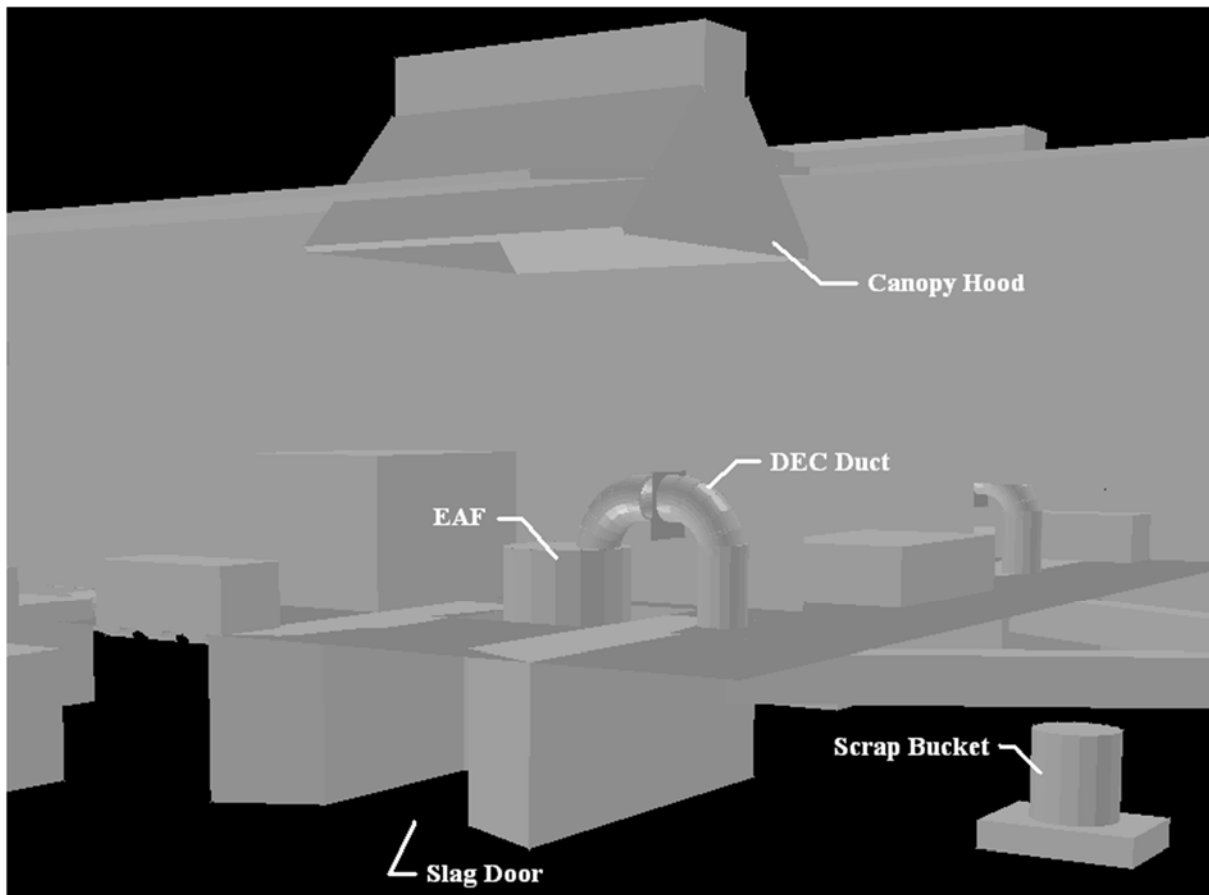

Figure 3. Meltshop CFD Model Showing Furnace Operating Floor and Canopy Hood.

The use of CFD modelling in the manner described allows the engineer to generate a range of outputs from the model including:

- Inlet or outlet velocity through building openings
- Temperature, velocity, and pressure profiles obtained in the meltshop
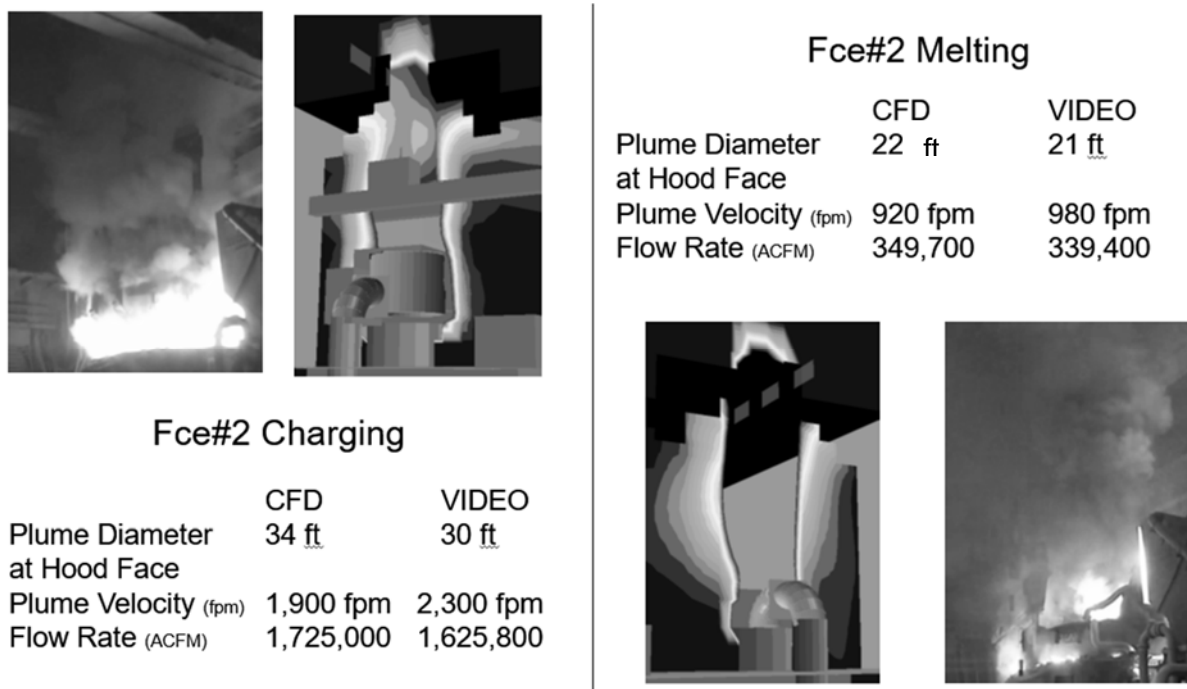- Fume profile in the meltshop.

However, in order to reliably use the CFD modelling results the model data must be first validated.

Model Validation

A CFD model must always be validated first at current operating conditions in order to ensure it can be used with confidence to make equipment and building design changes to achieve the desired improvements. Therefore, the following steps are taken to confirm that field observations and field measurements are in agreement with the model:

- Compare video plume photography results (plume analysis)
- Compare measured and model-predicted temperatures at various elevations and locations throughout the meltshop
- Compare meltshop inlet and outlet ventilation rates.

Plume analysis is a method of estimating the plume diameter and velocity in order to quantify the plume flow rate during various EAF operations. Video is used to track the plume frame by frame. For this work, video plume analysis is performed during melting and charging operations to establish the characteristics of the plume reporting to the canopy hood. The CFD model is then used to simulate the plume and allows for direct comparison with the video plume analysis. This is illustrated in Figure 4, were validation using plume analysis is shown by comparing the plume video with the CFD model. Validation is demonstrated for the EAF during both charging and melting conditions. As expected, the plume velocity is much larger during the charging stage. During both charging and melting, the flow rates obtained from the video plume analysis and the CFD model correlate sufficiently well.

Fce#2 Melting

	CFD	VIDEO
Plume Diameter at Hood Face	22 ft	21 ft
Plume Velocity (fpm)	920 fpm	980 fpm
Flow Rate (ACFM)	349,700	339,400

Fce#2 Charging

	CFD	VIDEO
Plume Diameter at Hood Face	34 ft	30 ft
Plume Velocity (fpm)	1,900 fpm	2,300 fpm
Flow Rate (ACFM)	1,725,000	1,625,800

Parameter	Furnace #2 - Charging		Furnace #2 - Melting	
Plume Diameter at Hood Face (m)	10.4	9.1	6.7	6.4
Plume Velocity (m/s)	9.7	11.7	4.7	5.0
Flow Rate (m^3/h)	2,930,794	2,762,252	594,144	576,644

Figure 4. Video Plume vs. CFD Model Calibration and Validation.

Under charging conditions, i.e. when the highest flow to the canopy occurs, the highest overall emissions inside the meltshop arise. Plume analysis can also be used to analyse the average plume characteristics of an EAF operation by averaging the average plume flow rate at the canopy face and the average plume heat release (in BTU/min or kW) during melting, charging and tapping, respectively.

Validation of field measurements versus the CFD model prediction for flow rates at each major opening of the meltshop is shown below in Table 1 for a representative meltshop facility with two furnaces.

Opening	Measured				CFD Predicted			
	Velocity (fpm)	Velocity (m/s)	Flow Rate (ACFM)	Flow Rate (m³/h)	Velocity (fpm)	Velocity (m/s)	Flow Rate (ACFM)	Flow Rate (m³/h)
#4 (EAF #1 Slag Door)	139	0.71	109,600	186,212	79	0.40	62,100	105,509
#6	284	1.44	198,600	337,424	243	1.23	170,300	289,342
#7	-	-	Closed	-	-	-	Closed	-
#8	306	1.55	65,200	110,776	345	1.75	73,800	125387
#9	184	0.93	230,100	390,942	134	0.68	168,000	285,434
#10	202	1.03	80,700	137,110	566	2.88	226,500	348,826
#11	-	-	Closed	-	-	-	Closed	
#12	637	3.24	227,800	387,035	570	2.90	204,000	346,598
#13	553	2.81	243,100	413,030	619	3.14	272,200	462,471
#14	456	2.32	398,600	677,226	609	3.09	532,700	905,063
#16 (EAF #2 Slag Door)	196	1.00	343,800	584,120	252	1.28	441,700	750,453

Table 1. Meltshop Model Calibration and Validation.

Table 1 illustrates that – in most cases – the flow rate at the various openings correlates reasonably well with the flow rate predicted by the CFD model, validating the model. If correlations are poor, adjustments need to be made to the CFD model to ensure that real conditions are more closely reflected.

On completion of the validation, additional modelling can be carried out with the CFD model to study various modification scenarios being considered to improve the operation which not only will result in emissions reduction but may also result in cost savings from operational improvements. Such scenarios include:

- Increasing the exhaust rate to the canopy hood or other hoods
- Modifying the existing canopy hood or other hoods to improve storage capacity
- Closing various openings around the building such as louvers and doors
- Provision of dedicated ventilation to 'clean heat' sources inside the meltshop.

Results

In this section the findings of this work are presented and analysed. In addition to using video plume analysis for direct comparison with the plume modelled by the CFD, as discussed in the previous section, plume video analysis can also be used to establish a profile of the change in plume flow at the canopy hood with time.

Video plume analysis is therefore performed for both melting and charging operations to establish the characteristics of the plume reporting to the canopy hood. In Figure 5 the plume volumetric flow rate profile is shown by plotting the change in plume flow rate reporting to the canopy hood face vs. time. The graph shows that the canopy hood currently provides an exhaust rate between 580,000 ACFM (985,430 Am^3/h) to 640,000 ACFM (1,087,370 Am^3/h) during charging and tapping. Standard EPA (Environmental Protection Agency, USA) hood design equations were also used to calculate exhaust requirements which were estimated at 720,000 ACFM (1,223,290 Am^3/h) demonstrating that the current exhaust rate, particularly during charging, is too low.

Measured flow rates over the 180 seconds period ranged from about 350,000 ACFM (594,700 Am^3/h) during melting to as high as 1,600,000 ACFM (2,718,500 Am^3/h) during charging. What this illustrates is that the peak flow rate experienced far exceeds both the exhaust rate currently provided by the hood as well as the requirement determined by EPA standard calculations. Generally, there is a trade-off required between designing for the storage volume of the canopy hood and the exhaust rate. The hood storage requirement increases with a low exhaust rate, hence – in the first instance – the recommended action is to take steps to increase the exhaust rate before re-designing the hood for a larger storage volume.
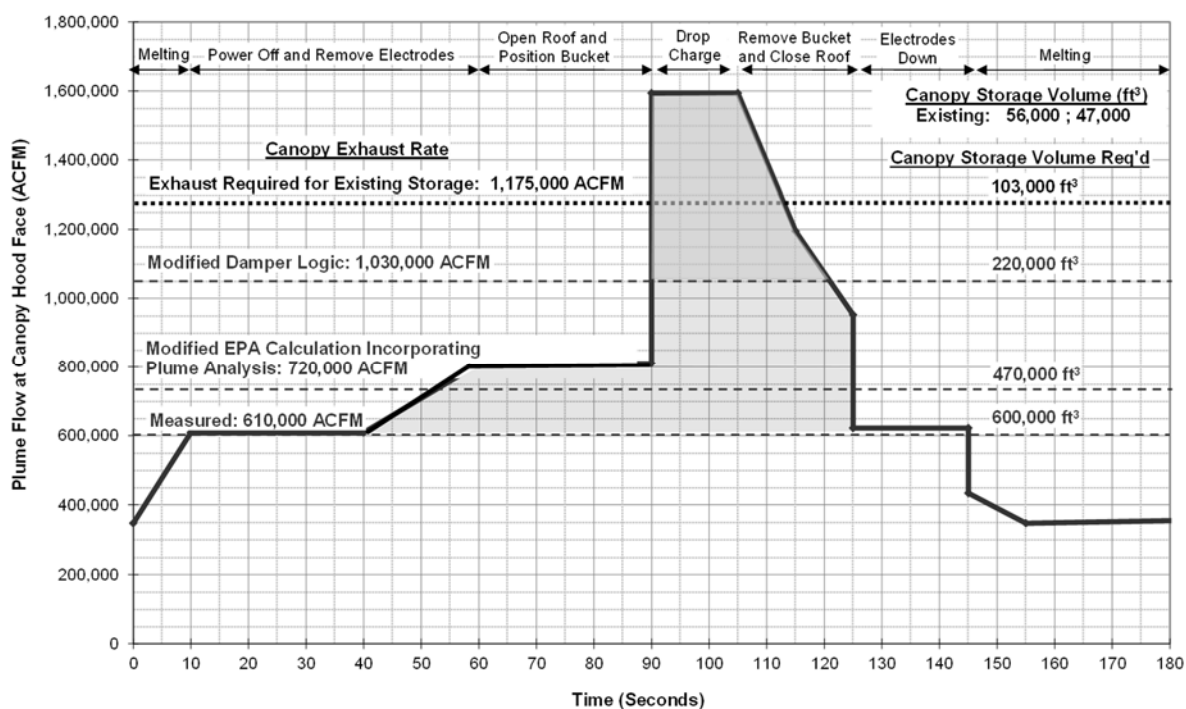

Figure 5. Charging and Melting Plume Flow Rate Profile.

Based on the CFD modelling results, a fume capture efficiency curve can be developed. A fume capture efficiency curve, or capture curve, is a helpful tool when trying to understand the relationship between hood exhaust rate and fume capture efficiency. The capture curve plots the canopy hood capture efficiency for various exhaust rates or optimized hood configurations. From the graph it is made possible to see at what point the canopy hood exhaust rate is increased sufficiently for optimal fume capture.
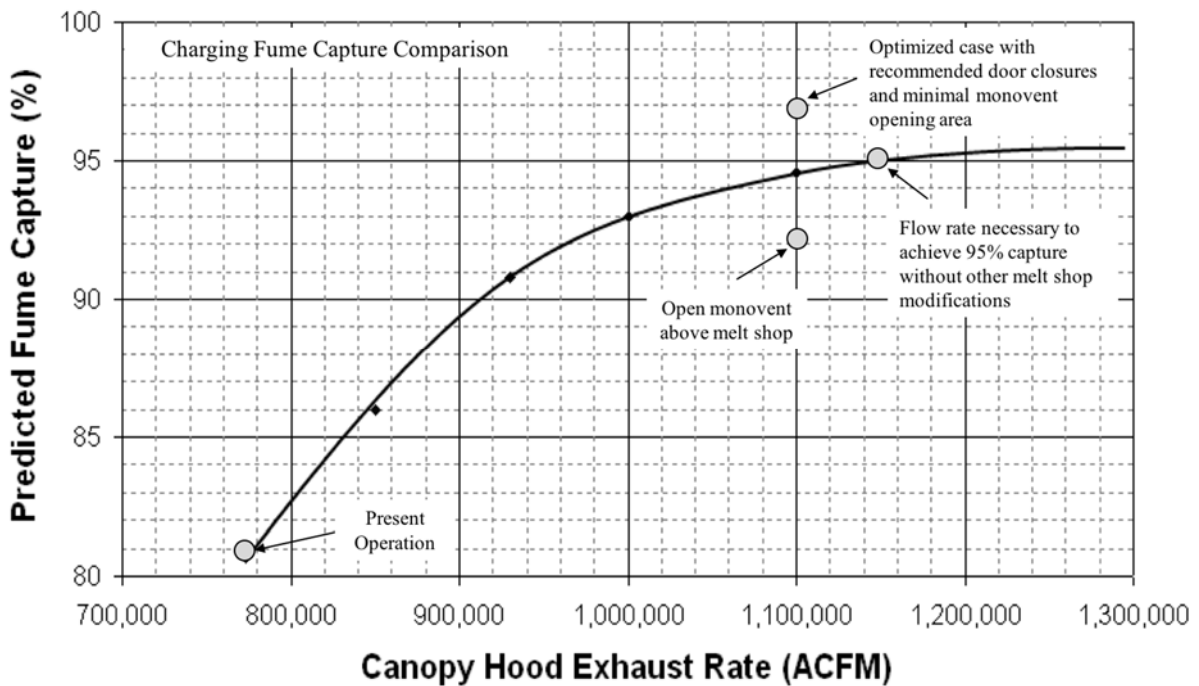

Figure 6. EAF Canopy Hood Capture Efficiency Chart.

Figure 6 shows that at a canopy exhaust flow rate of about 1,150,000 ACFM (1,954,000 m³/h) is required to achieve 95% fume capture. If appropriate meltshop modifications are made the exhaust flow rate requirement to accomplish 95% fume capture can be reduced. For the scenario in Figure 6, it is thus demonstrated that an exhaust rate of about 1,110,000 ACFM (1,869,000 m³/h) will suffice to achieve a fume capture greater than 95% if openings in the meltshop are minimized by reducing the monovent opening area and closing several doors at this facility.

Discussion

The use of a CFD model of the meltshop environment can greatly enhance the evaluation of the APC system efficiency. Typical canopy hood design techniques rely on assuming conditions which do not take account for the initial upward velocity of high temperature gases during charging and melting nor can they account for building openings and external wind conditions etc. In the Materials and Methods section it has been illustrated how these factors can be incorporated when using CFD modelling ultimately allowing one to make better design decisions.

However, as illustrated in the Materials and Methods section, it is critical to validate the CFD model to real-world conditions in order to be able to rely on the CFD model results. An example of the potential issues that may arise without validation has also been highlighted in the work by Els *et al.* who found that their assumed correlations for the off-gas modelling of a trombone cooler and its associated temperature drop did not correctly reflect temperatures measured during site testing. They had attributed this to the trombone cooler not operating continuously at high temperatures and subsequently modified the modelling procedure to obtain a more realistic correlation[1]. The same group, in their work, also found the extraction efficiency to reduce with an increase in the off-gas energy and temperature which resulted in higher emissions[1].

Earlier it was demonstrated how plume analysis, a method of estimating plume diameter, velocity and flow rate during EAF operations, was incorporated into the CFD model. If plume analysis is coupled with flow and temperature measurements it is also possible to estimate heat release into the meltshop during melting and charging operations. This information, in turn, can then be used to aid in the design of the canopy hood.

Adequately designed canopy hoods should include enough volume to store the fumes that are generated during charging. For many meltshops, however, the canopy hood is often grossly undersized, especially if productivity improvements were made to the EAF without re-evaluating the FES at the same time. As shown in Figure 5 earlier, the evaluated meltshop had a canopy storage volume capacity of 56,000 ft³ (1586 m³) for EAF #1 and 47,000 ft³ (1331 m³) for EAF #2 but analysis of the operation using field measurements and CFD modelling suggested that a volume of 103,000 ft³ (2917 m³) is required, which is why during charging the hood volume is insufficient.

For canopy hood design available data and measurements required are more substantial than those required to evaluate the DEC system. This is because it is required to characterize both the plume generated at the EAF during charging operations as well as the overall ventilation pattern within the shop. Care must also be taken not to design the canopy purely on the basis of storage volume requirements because a balance between a reasonable hood evacuation time and storage volume of the canopy is critical. This is because a canopy with a very large storage volume will have a long evacuation time and therefore allows fumes to cool off and settle back into the meltshop before these fumes can be effectively extracted into the gas handling system. Similarly, a canopy with a small storage volume, as found at the facility presented here, will not be able to capture all fumes and they will roll out back into the meltshop and possibly also building openings, before they can be evacuated by the gas handling system.

Once the CFD model of the entire meltshop has been established, it can also be used to identify any openings on the DEC system which can then be closed with the intention to reduce air infiltration. This provides another means to increase the EAF canopy flow without having to upgrade any equipment such as exhaust fans or a baghouse located downstream. Moreover, improvements to the DEC operation generally result in a lower system pressure drop and therefore reduced operating costs as a result of a lesser demand on the exhaust fan.

Summary

This paper provides an example of how GCT has carried out meltshop APC system evaluations utilizing not only conventional design and assessment techniques but also more modern tools such as plume video analysis and CFD modelling. Plume analysis was found to be particularly useful in evaluating the canopy hood capacity. It has been demonstrated that CFD modelling can be used to supplement the traditional approach of using theoretical design equations for the design of a FES to achieve a more optimized meltshop environment.

They key for adequate canopy hood design is to provide deep storage capacity, i.e. fumes that are generated during charging should ideally be stored in the canopy until they can be evacuated by the air pollution control system. This can be achieved by maximizing the hood exhaust rate so as to minimize storage volume requirements and retention time. The canopy storage volume should be such that the plume can be held until the fumes can be completely evacuated. The tools described in this paper provide the means to enable such a design based on the information deduced from the CFD modelling results.

Ideal capture efficiencies for a DEC system should be around 90 to 95% to achieve efficient EAF operation. Conventional capture hood and DEC system design techniques can be augmented by use of CFD modelling and through additional improvements based on field observations and measurements. Meltshops with lower than desirable capture efficiencies can be optimized to achieve the target efficiency thereby reducing emissions, improving the meltshop environment for the operators and ultimately reduce operating cost by means of better EAF operating and DEC drafting conditions.

References

1. Casper Els, Olof Vorster, Chris Coetzee, Timothy L. Fisher, May 2008, New Techniques in Steel Meltshop Air Pollution Control; *AISTech Iron & Steel Technology Conference and Exposition*.

2. Paykan Safe and Matt Russell; 2007, Metallurgical Gas Cleaning System Design for Emissions Control and Energy Efficiency, *Kazakhstan Growth Forum*.

3. Paykan Safe and Robert L. Stephens; 2000, Peirce-Smith Converter Hood Design Analysis using Computational Fluid Dynamic Modeling, *The Minerals, Metals & Materials Society*.

4. Sam A. Matson & W. Fred Ramirez.; November 1997, The Dynamic Modeling of an Electric Arc Furnace, In *55th Electric Furnace Conference Proceedings*, Iron and Steel Society.

5. S. Matson, W. Fred Ramirez, P. Safe; 1998, Modeling an EAF using Dynamic Material and Energy Balances, *University of Colorado*.