Improving Steel Plant Work Environment

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SYNOPSIS:

NatSteel Holdings operates a Direct Current (DC) finger shaft electric arc furnace at its meltshop in Singapore. The Meltshop Fume Extraction System (FES) includes a Direct Evacuation Control (DEC) system to capture the primary fumes, a canopy hood to collect the fugitive emissions associated with the Electric Arc Furnace (EAF) operations, and a local capture hood for the ladle furnace. Over the years, with improvement in Meltshop productivity, demand on the FES had increased. Several changes had been made to the FES in the past in order to meet the emission control requirements of the EAF. However, in some areas, the addition of system components has resulted in in-efficiencies, preventing the FES from operating at full potential.

Gas Cleaning Technologies (GCT) recently completed an engineering study with NatSteel Holdings to evaluate the performance of the existing FES and to improve the FES operating performance and efficiency. The evaluation included CFD modeling of the Meltshop to optimize ventilation and fume capture in the Meltshop and reduce fugitive emissions.

This paper will discuss the evaluation of the FES and the recommended plan of action in order to improve the efficiency and effectiveness of the FES.

Keywords: Fume Extraction System (FES), Direct Evacuation Control (DEC), Gas Cleaning Technologies (GCT), NatSteel Holdings, CFD modeling, fugitive emissions

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INTRODUCTION:

NatSteel Holdings operates a Direct Current (DC) finger shaft electric arc furnace producing approximately 750,000 tonnes/year of steel at its meltshop in Singapore. The meltshop Fume Extraction System (FES) includes a Direct Evacuation Control (DEC) system to capture the primary gases generated at the Electric Arc Furnace (EAF), a canopy hood to collect the emissions associated with charging and tapping operations and a local capture hood for the ladle furnace. The combined process and secondary gasses are sent to a baghouse system for particulate removal. The plant was originally equipped with three, 381,000 Am^3/hr, negative pressure, reverse-air baghouse systems for three smaller EAFs. They have since been combined into one baghouse system to handle emissions from the finger shaft electric arc furnace. Figure 1 shows the schematic of the FES before modifications and improvements

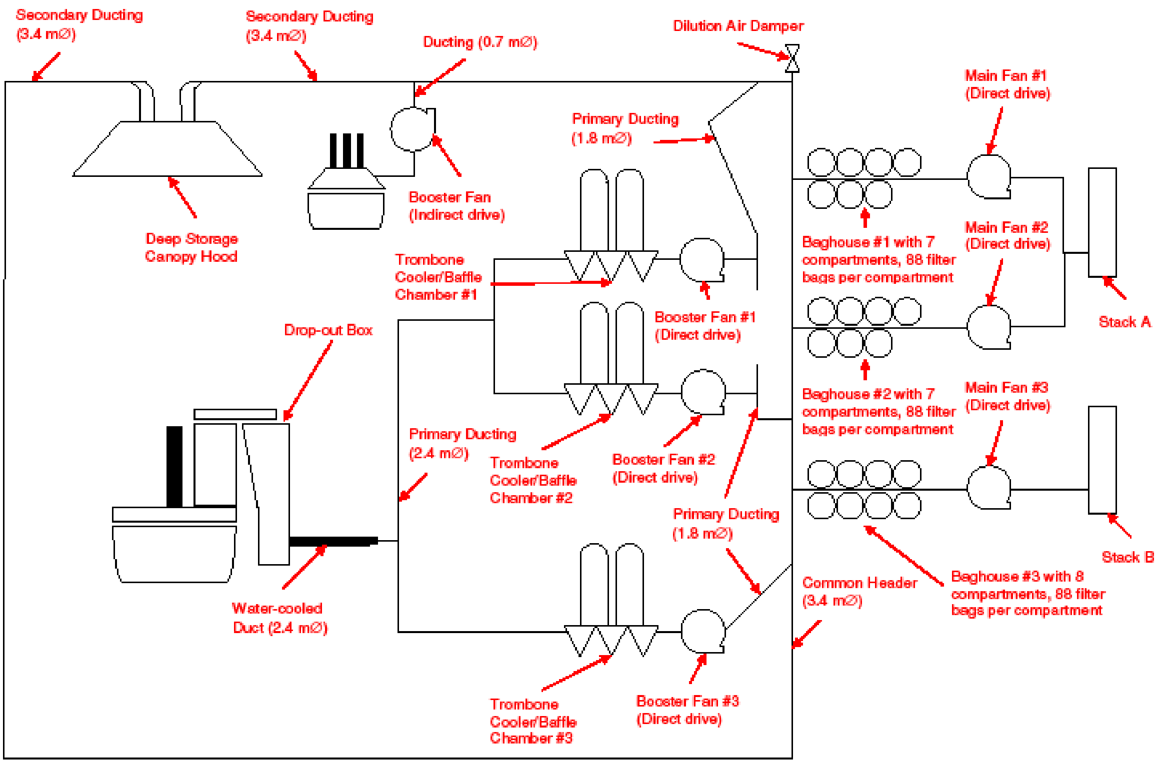


Figure 1 –Schematic of FES before Modifications and Improvements

Over the years, as meltshop productivity increased, the demand on the FES has also increased. Several changes had been made to the FES in the past in order to meet the emission control requirements of the EAF. However, in some areas, the addition of system components has resulted in in-efficiencies, preventing the FES from operating at full potential.

Gas Cleaning Technologies (GCT) recently completed an engineering study with NatSteel Holdings to evaluate the performance of the existing FES and to improve the FES operating performance and efficiency. The primary objectives of the study were as follows:

- Evaluate the performance of the current fume extraction system.
- Develop a CFD model of the meltshop to optimize ventilation and fume capture in the meltshop and reduce fugitive emissions.
- Implement modifications to improve performance of the fume extraction system and minimize meltshop fugitive emissions.

OFF-GAS SYSTEM EVALUATION METHOD:

The key components of a modern EAF FES are the Direct Evacuation Control (DEC) system and the Canopy Hood.

DEC System

The purpose of the DEC system is to collect emissions generated by the EAF during melting operations. A well designed DEC system should therefore provide the following functions:

- Capture EAF melting emissions effectively
- Minimize operator exposure to dust
- Destroy carbon monoxide & hydrogen (CO & H_2) efficiently
- Minimize generation of NO_x
- Cool the off-gas for handling by a downstream gas cleaning system

The off-gas generation rate, composition, and heat content exiting the furnace determines the sizing of the DEC system and depends on several parameters including:

- Active electrical power
- Total burner input
- Total oxygen flow rate to burners and injectors
- Total carbon injection rate
- Furnace freeboard pressure (furnace draft)
- Size and position of furnace openings and slag door operations
- Slag and bath conditions
- Recovery efficiencies of carbon, oxygen, and burner energy

The key to designing the DEC system is understanding the effect of the electrical and chemical inputs into the EAF. Electrical energy is much more efficient than chemical energy in heating and melting the scrap. Therefore, the amount of electrical energy input into the EAF has a relatively small impact on the DEC requirements while the rate of chemical energy input into the EAF impacts the DEC requirements tremendously. To complicate matters, the chemical energy efficiency can vary from heat to heat. For these reasons, the recommended approach to analyzing EAF off-gas systems includes utilizing both theoretical design equations as well as practical experience including knowledge of what has and has not worked in other similar shops.

Collection of measurements in the field is critical in order to understanding the present performance of a meltshop DEC system. The act of collecting measurements can be labor-intensive, but the data collected is useful not only for the evaluation of potential improvements but also as a reference point for the performance of the FES as further improvements are made.

At NatSteel Holdings, continuous flow rate, temperature, and static pressure measurements were collected at the exit of the DEC system for several heats. In addition, EAF operating data was collected and used to develop a furnace heat and mass balance. The EAF balance was used to predict the furnace off-gas flow rate and heat content profiles at each major step of the heat. The assumptions made in the EAF balance are as follows:

- Total slag volume is estimated from flux additions and furnace yield
- For energy outputs, energy in the steel is calculated based on the steel tap temperature and tap weight
- Energy in slag is based on slag volume, slag composition and tap temperature
- Miscellaneous losses are based on the difference between energy inputs and outputs

Figure 2 shows the relative percentages each source of energy contributes to the overall heat balance of the furnace.

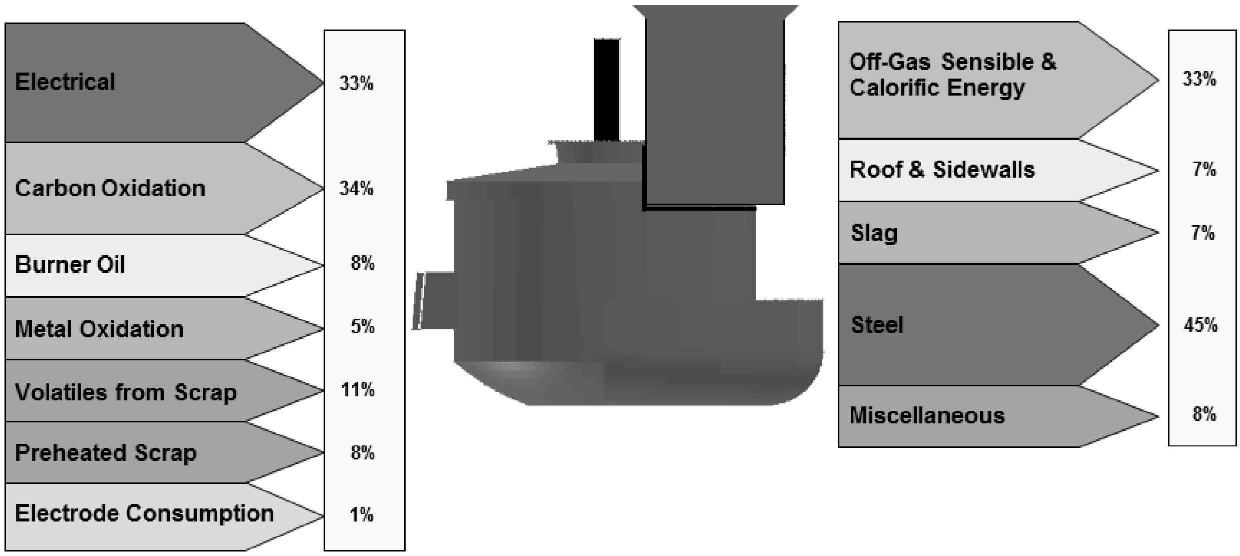
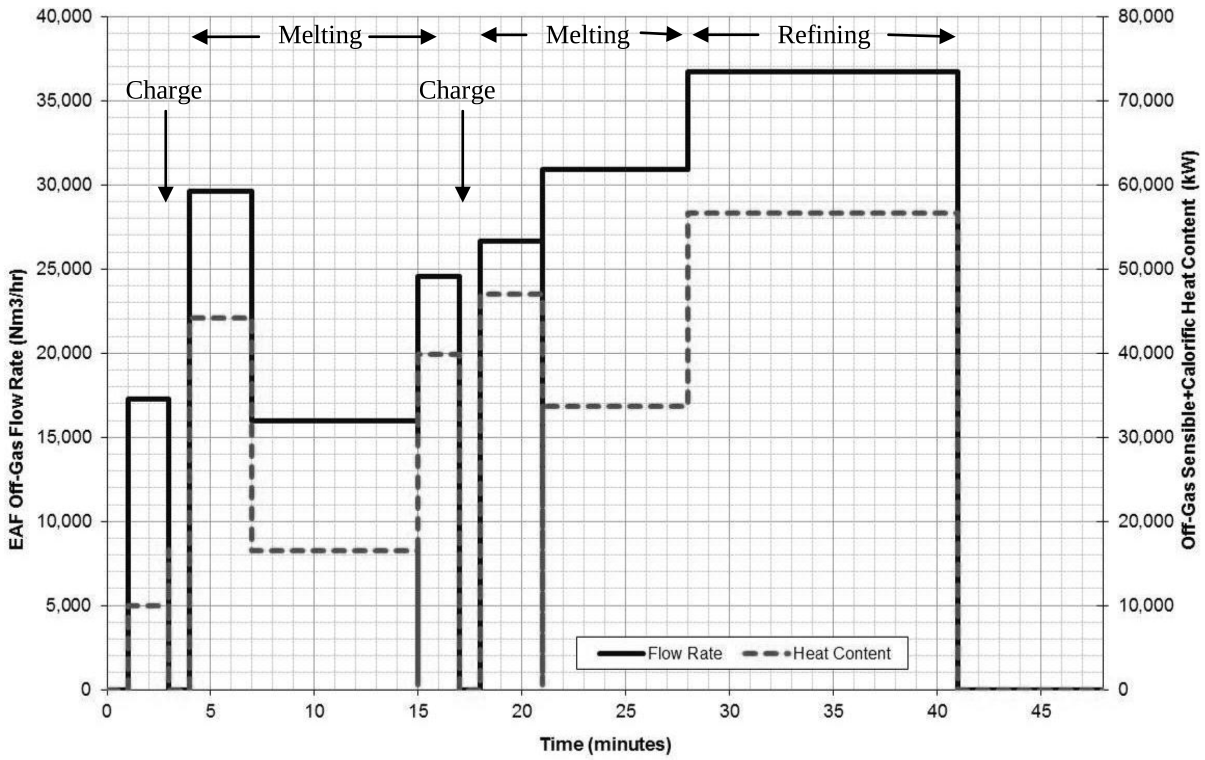


Figure 2 –EAF Energy Balance

Figure 3 shows the calculated off-gas flow rate and heat content for each operation period.



Note: Nm3/hr refers to gas volume occupied at normal temperature and pressure which are 273.15 K and 100 KPa while Am3/hr refers to gas flow rate at actual operating conditions of the process.

Figure 3 –EAF Off-Gas Flow Rate and Heat Content

A mass and energy balance of the entire FES system was generated using the calculated EAF off-gas flow rate, temperature, and gas composition as an input. The mass and energy balance was calibrated using the measurements that were collected at the exit of the DEC system. Once calibrated, the balance could be utilized to assess the performance of the DEC system.

Based on the site measurements, the mass and energy balance, and observations of the EAF operation, it was estimated that only 70% of the off-gas generated in the EAF was captured by the DEC during the peak period of off-gas generation. For proper operation of an EAF, a DEC capture efficiency between 90-95% is considered ideal.

The performance of the DEC system is generally dependent on several factors which include both the effectiveness of the EAF draft control strategy as well as the level of air infiltration entering into the system. A typical draft control strategy includes maintaining a constant draft set-point at the EAF roof of less than 2 mm.w.g. by modulating a draft control damper located in the DEC system ductwork. This ensures that the EAF receives adequate draft during periods of high off-gas generation to prevent significant fugitive emissions from the EAF. This also ensures that during periods of low off-gas generation, the EAF is not over-drafted which can result in increased energy losses and higher NO_x generation. At NatSteel Holdings, the EAF draft was not modulated to maintain a set-point at the EAF which lead to a large variation in capture efficiency for periods of varying off-gas generation rates.

EAF off-gas typically contains up to 30 to 50% CO. The CO needs to be fully combusted to reduce the risk of explosion in the FES and to minimize CO emissions to the atmosphere. This is done by introducing ambient air into the DEC near the furnace off-take while gas temperatures are high. To ensure maximum combustion of CO, 100% stoichiometric excess air is recommended. At NatSteel Holdings, a high level of air infiltration beyond the 100% excess requirement was entering the DEC system at various locations. High rates of air infiltration reduce the draft available to the EAF to provide effective capture of emissions and can also quench the off-gas resulting in incomplete combustion of CO.

Canopy Hood

Modern meltshops utilize a canopy hood located at the shop roof level that is centered over the EAF to provide collection of secondary emissions generated by the EAF. The canopy hood serves the following purposes:

- Collect the emissions generated during EAF charging and tapping operations
- Collect emissions that are not collected by the DEC during melting operations
- Minimize operator exposure to dust
- Maintain acceptable temperatures in the shop for operators and equipment
- Prevent fugitive emissions from escaping out of shop openings

The NatSteel Holdings meltshop is equipped with a single deep-storage canopy hood, exhausted by four off-takes. At the time of the evaluation, the total canopy hood extraction rate averaged approximately 200,000 Am^3/hr at 40°C. This was well below the typical exhaust rate required for this size furnace, and as a result, the canopy hood performance was generally poor during both melting and charging operations. In addition, the inconsistent DEC capture during melting operations resulted in heavy furnace emissions reporting to the canopy hood throughout the heat. This prevents the canopy hood from being completely free of emissions and can result in spillage from the hood and fugitive emissions from the meltshop.

The canopy hood exhaust rate is selected based on several parameters including:

- Distance from EAF shell to face of canopy hood
- Furnace inside diameter
- Charge weight
- Scrap volatiles content
- Wind/cross-drafts in meltshop
- Shop cross-sectional area

Theoretical equations have been developed to compute the required exhaust rate for a canopy hood under reasonable conditions taking into account some of the above parameters. However, the equations generally do not reflect the effect of various components on canopy hood performance such as flow patterns within the shop, partitions or walls near the EAF, or the configuration of the canopy hood. Therefore, a multi-step approach that combines the standard design equations, field measurements, benchmarking, and computational fluid dynamic modeling to design and optimize canopy hoods and establish hood exhaust rate requirements is recommended. This approach accounts for the well understood design parameters as well as the less obvious factors affecting the performance of the canopy hood.

The measurements required for canopy hood design are more extensive than those required to evaluate the DEC system and require characterizing both the plume generated at the EAF during charging operations as well as the overall ventilation pattern within the shop. The measurements collected in the canopy analysis include:

- Video of the melting, charging, and tapping plume

- Measurements in the canopy ductwork
- Meltshop ventilation surveys

At NatSteel Holdings, video of the EAF operation was collected in order to perform video plume analysis of the melting and charging operations to establish the characteristics of the plume reporting to the canopy hood. Plume analysis is a method of estimating the plume diameter and velocity in order to quantify the plume flow rate during various EAF operations. Coupling plume analysis with ductwork flow and temperature measurements makes it possible to estimate the heat release into the meltshop during various furnace operations.

The plume volumetric flow rate and heat content profiles are shown in Figure 4. The flow rate and heat release rates spike for approximately 20 seconds while the charge is dropped and then decrease back to the melting level in a relatively linear fashion. The total charging operations at NatSteel Holdings take approximately 60 to 90 seconds on average.

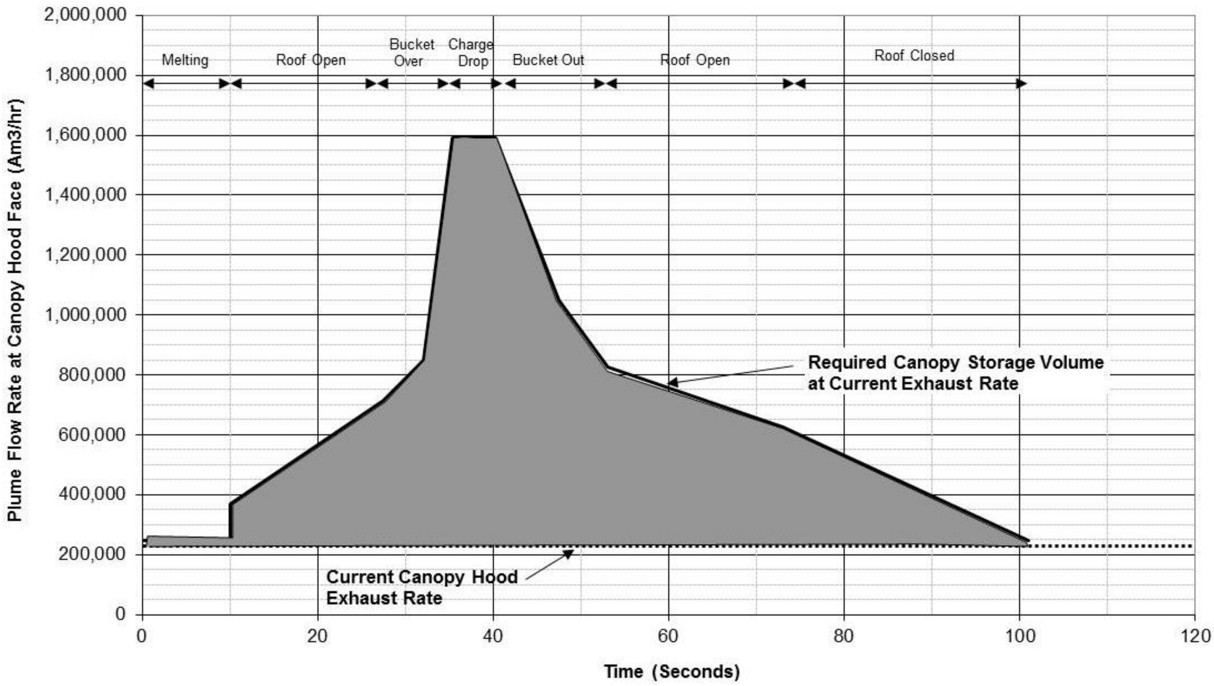


Figure 4 –EAF Charging Plume Flow Rate

The four major design parameters for canopy hoods are listed below:

- Exhaust rate (Am^3/hr)
- Storage volume (m^3)
- Face velocity (m/s)
- Evacuation time (s)

Exhaust Rate

Based on the standard canopy hood design calculation method approved by the United States Environmental Protection Agency (US-EPA), the canopy hood exhaust rate requirement at NatSteel Holdings is approximately 1,275,000 Am^3/hr for charging operations, much greater than the measured exhaust rate of 200,000 Am^3/hr.

Storage Volume

The canopy hood storage volume determines the amount of fume that the canopy hood can store when the fume generation rate (plume flow rate) exceeds the canopy hood exhaust rate. For an EAF operation, this typically occurs during charging. Figure 4, previously shown, shows the charging plume flow rate profile estimated using plume analysis. The total amount of fume generated by the furnace during charging can be determined by calculating the area beneath the profile. Likewise, the total amount of fume collected by the canopy hood can be determined by multiplying the canopy hood exhaust rate by the duration of the charge. The difference between the two is the minimum canopy hood storage volume required to prevent fume spillage out of the canopy hood.

The required canopy hood storage volume at NatSteel Holdings was nearly 20,000 m^3 to capture the plume with the current measured extraction rate, which was would require an impractically large canopy hood.

Face Velocity

The canopy hood face velocity is the average speed at which that the gas enters the hood. It is calculated by dividing the exhaust rate (Am^3/s) by the face area of the canopy hood (m^2). A canopy hood face velocity of over 0.5 m/s is generally recommended to prevent fume stored in the canopy hood from escaping the hood. The canopy hood at NatSteel Holdings was operating at a face velocity well below 0.1 m/s.

Evacuation Time

The evacuation time refers to the amount of time required to remove fumes from a full hood at a given exhaust rate. The canopy hood evacuation time is calculated by dividing the storage volume (m^3) by the exhaust rate (Am^3/s). Evacuation times of 10 to 15 seconds are generally acceptable in order to maintain an appropriate balance between the hood exhaust rate and the storage volume. Evacuation times of less than 10 seconds are not a disadvantage but times greater than 15 seconds can lead to settling and spillage of the fumes from the canopy hood even with appropriate face velocities and storage volumes. The evacuation time of the canopy hood at NatSteel Holdings during charging was well over 15 seconds.

COMPUTATIONAL FLUID DYNAMIC (CFD) MODELING:

A computational fluid dynamic model is an effective tool to supplement conventional engineering calculation methods typically used in the design of fume capture hoods and overall building ventilation systems. CFD provides a means to quantitatively predict the fluid flow behavior in and around equipment and structures, accounting for fluid dynamic, heat release, and other physical effects.

CFD analysis was performed by developing a model of the NatSteel Holdings shop using the Phoenics CFD package. Phoenics enables the designer to create a model of the system divided into thousands of three-dimensional cells. Each cell within the model solves the fundamental equations (momentum, mass and energy balance) for the specific conditions in the cell. Boundary conditions are entered for the model and the program solves the equations, simultaneously, for each cell in the domain. The program iterates until the entire domain obeys the momentum, mass, and energy balance criteria. The domain of the model can be as simple as a fume source and collection hood, or complex, such as a building and its

surroundings to account for the effects of adjacent equipment, door openings and external wind conditions.
The meltshop CFD model inputs and outputs include the following:

Inputs
- Wind direction and speed
- Exhaust conditions from canopies and other powered ventilation systems
- Heat release rate from heat sources

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

CFD modeling also allows the engineer to evaluate and compare various scenarios and thereby optimize the ventilation system design. As with any theoretical method, good engineering judgment, practical considerations, and prior experience must also be considered in the configuration and evaluation of a CFD model to ensure the final design is effective.

A CFD model of the NatSteel Holdings meltshop was developed to:
- Predict the fume capture efficiency of the existing EAF canopy hood during melting and charging operations.
- Predict flow patterns and fume concentration profiles within the meltshop.
- Predict temperature profiles within the meltshop.
- Make recommendations to improve the EAF canopy hood capture efficiency.
- Determine the minimum EAF canopy hood exhaust rate required to achieve the desired fume capture efficiency for melting and charging operations.

The domain for the NatSteel Holdings Model, as shown in Figure 5, includes the meltshop and portions of the surrounding structures that have an impact on ventilation patterns within the meltshop.
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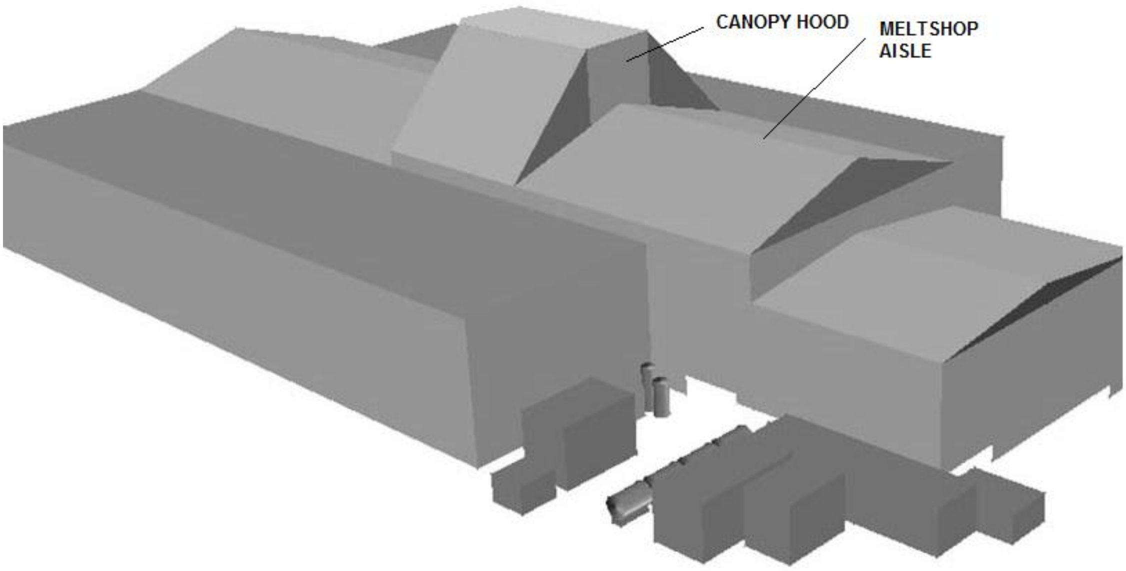


Figure 5 – CFD Model Domain

Validation of the meltshop CFD model consists of comparing the CFD predictions with site measurements and observations. The validation criteria include agreement between model predictions and field measurements/observations for the following:

- Flow rate through meltshop openings
- Temperatures at various locations in the meltshop
- Furnace charging and melting plume characteristics
- Meltshop fume migration patterns

Ventilation surveys were conducted by measuring ambient air temperature with a thermocouple and air velocity with a propeller anemometer at each major opening in the meltshop building to quantify the air flow rate into and out of the building and heat release rate in the meltshop. The measured flow rates through each doorway are compared to the flow rates predicted by the CFD model, and small adjustments are made to the model until the measured values match reasonably well with the CFD model results.

Temperatures measured at the operating floor and charging crane rail elevations were also compared to those predicted by the CFD model in order to validate the heat release rates specified in the model with those measured on site. Figure 6 shows the contribution of each heat source within the shop to the overall shop heat release based on the ventilation survey measurements.

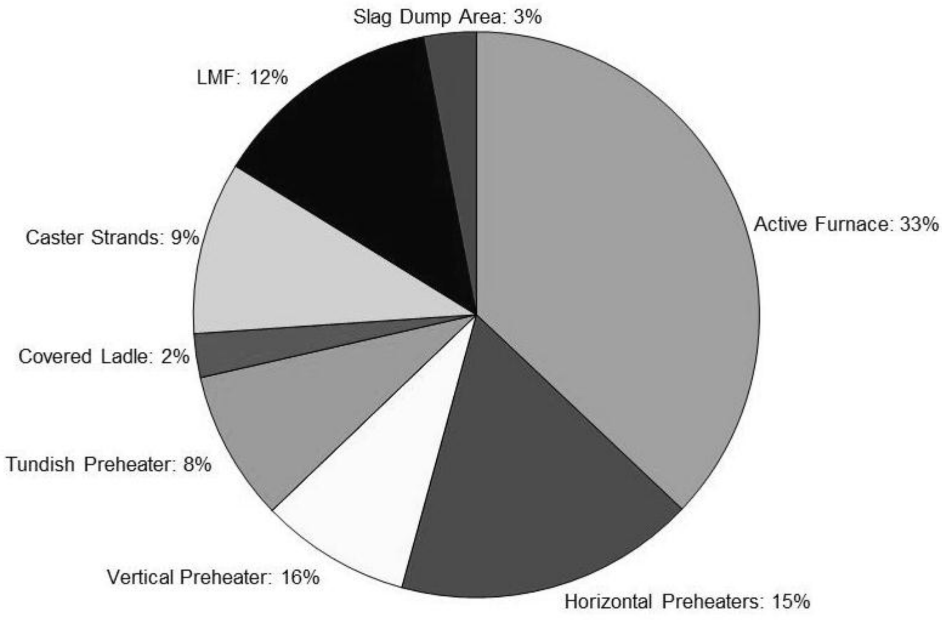
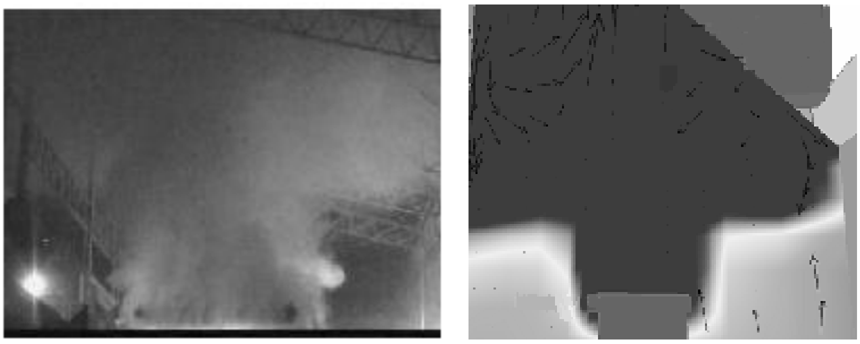


Figure 6 - Meltshop Heat Release Distribution
Total Shop Heat Release Approximately 11 MW

The plume characteristics are validated by comparing the conditions at the canopy hood face measured from the plume video to those predicted by the model. Figure 7 shows a comparison of the observed EAF charging plume with the plume predicted by the CFD model. As shown, the plume characteristics predicted by the CFD model are similar to the plume photography analysis performed during the site visit.



Plume Photograph
Plume Diameter: 12.3 m
Plume Velocity: 2.4 m/s
Plume Flow Rate: 1,051,000 Am^3/hr

CFD Predicted
Plume Diameter: 13.7 m
Plume Velocity: 1.9 m/s
Plume Flow Rate: 1,027,000 Am^3/hr

Figure 7 – CFD Charging Plume Validation

Once the model has been successfully calibrated, the model can be used to evaluate the effect of various modifications on the capture efficiency of the EAF canopy hood. The canopy hood is modeled at a range of exhaust rates, and the capture efficiency (the percentage of emissions generated by the EAF that are captured by the canopy hood) of the canopy hood is calculated for each exhaust rate. As a result of this exercise, a capture efficiency curve can be generated that compares canopy hood capture efficiency to the canopy hood exhaust rate, as shown in Figure 8 below.

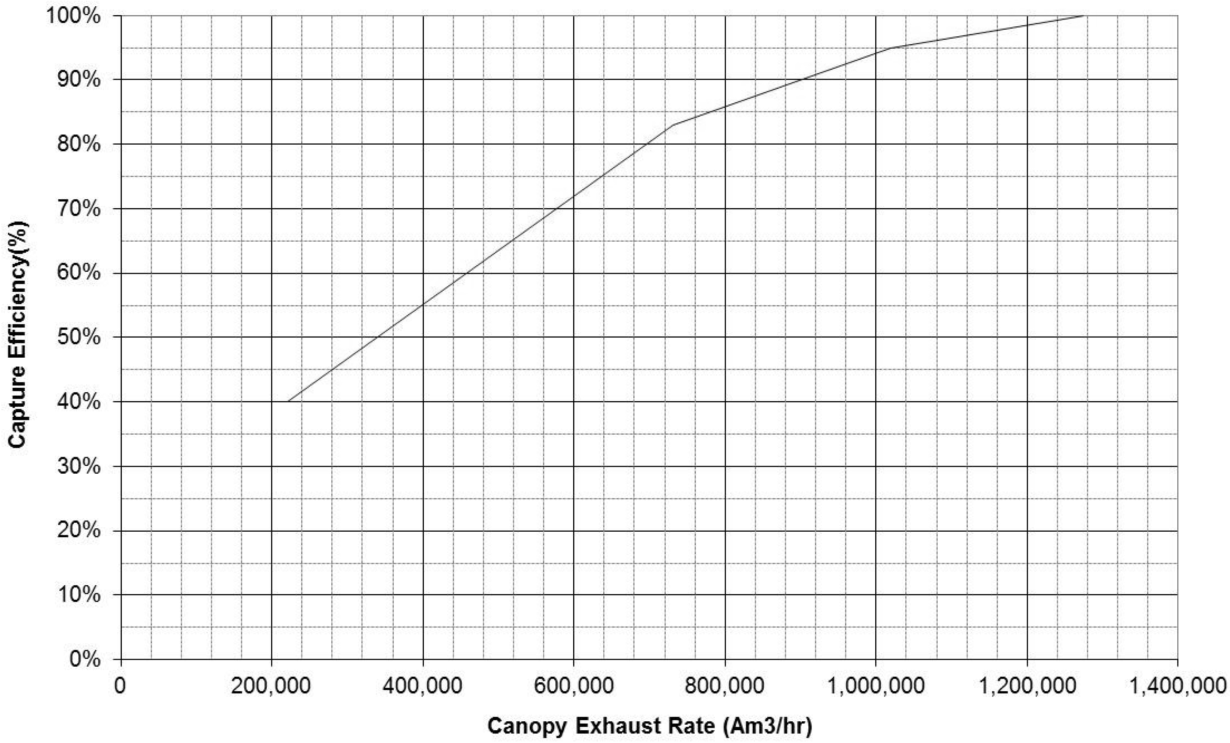


Figure 8 – Canopy Hood Capture Efficiency vs. Exhaust Rate

The results of the CFD modeling are then compared with the results of the standard theoretical calculations and benchmarked against other similar operations. Using these three data sources, a recommended exhaust rate can be defined in order to achieve the desired performance of the EAF canopy hood.

RESULTS:

As a result of the evaluation, the following major recommendations were presented to NatSteel Holdings:

- Increase the canopy hood exhaust rate during charging operations to 1,275,000 Am^3/hr
- In order to achieve the required canopy hood exhaust rate during charging operations, install a new 825,000 Am^3/hr baghouse dedicated solely to the EAF canopy hood resulting in a total baghouse capacity of approximately 2,000,000 Am^3/hr
- Reduce air infiltration into the DEC system by sealing gaps in the ductwork and drop-out box to increase draft available to the EAF and increase gas temperature to promote complete combustion of CO
- Maintain a set draft at the EAF to ensure capture of emissions during all periods of the heat and prevent over drafting of the EAF
- Increase the diameter of the ladle furnace ductwork diameter to allow an increased exhaust rate to the ladle furnace hood

Following the completion of the study, NatSteel Holdings proceeded to implement several of the recommendations. A new 820,000 Am^3/hr pulse-jet baghouse was installed that was dedicated to the canopy hood. Figure 9 shows the schematic of the FES after modifications and improvements.

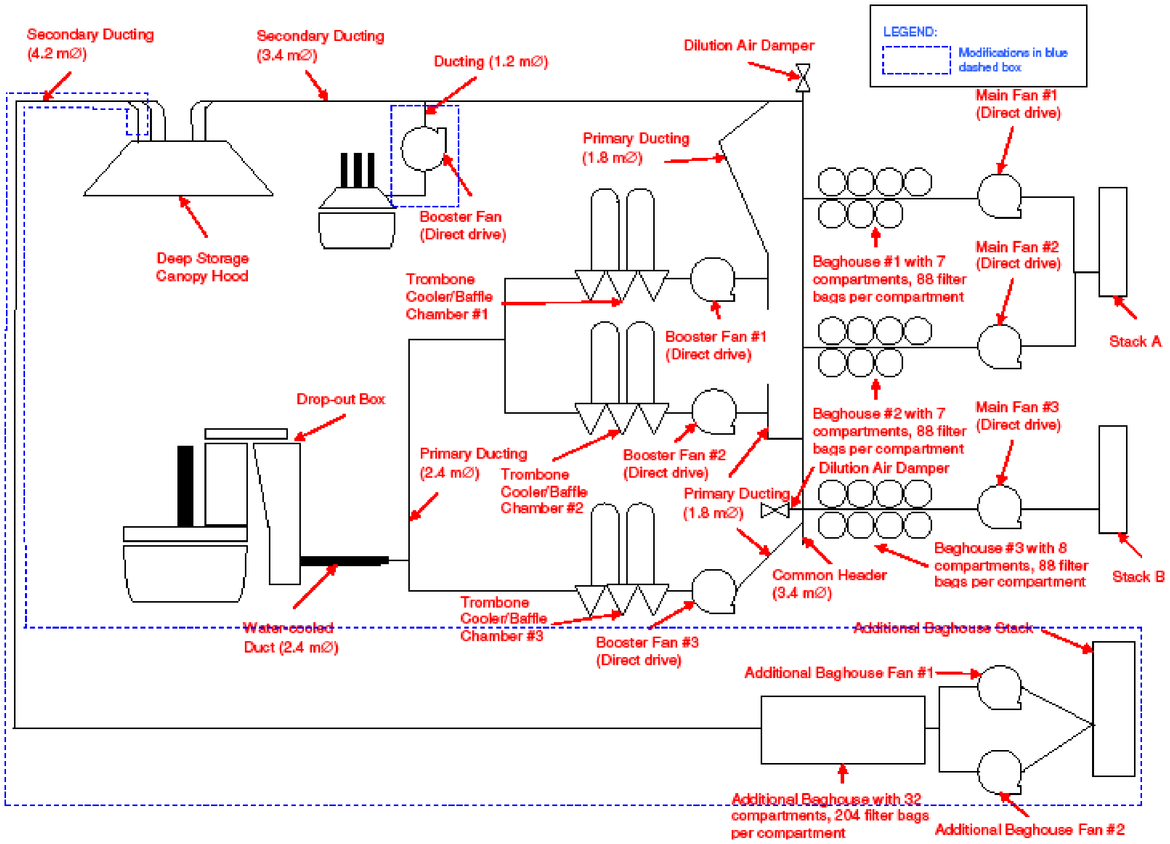


Figure 9 –Schematic of FES after Modifications and Improvements

In addition, NatSteel Holdings modified the design of the DEC system's drop-out box to significantly reduce the openings in the system that allowed large amounts of air infiltration to enter the system, increasing the draft available to the EAF. The ladle furnace ductwork was also increased in size, from 0.7 m diameter to 1.2 m diameter.

With the new baghouse installed, the FES now has sufficient capacity to provide the DEC and canopy hood exhaust rates required for meltshop operations. Based on observations recently collected at NatSteel Holdings, the modifications have resulted in greatly improved capture of EAF emissions by the DEC and canopy hood system. The increased exhaust rate at the canopy hood has greatly improved visibility within the shop and has resulted in much cleaner conditions within the shop during all phases of operation. In addition, the larger ductwork installed at the ladle furnace hood has allowed the exhaust rate from the hood to be increased from approximately 8,000 Am^3/hr before the modifications to 48,000 Am^3/hr after the modifications, resulting in a marked increase in performance and fume capture.

NatSteel Holdings is continuing to assess additional improvements to further optimize the FES. Air infiltration rates into the DEC system are still relatively high, and the DEC system draft is not modulated to maintain a constant furnace pressure. Implementation of a draft control strategy should lead to even further improvements in DEC system performance and emissions capture.

CONCLUSIONS:

CFD modeling can be used to augment the traditional approach of theoretical design equations to achieve optimized design parameters for meltshop fume extraction system upgrades. Combining this with field measurements and benchmarking of similar operations provides the engineer with a robust set of data on which to base their recommendations. Using this methodology, NatSteel Holdings has greatly improved the performance of the FES resulting in improved working conditions in the shop and reduced environmental impact.