Project Report

March 10, 2020

AK Steel
Dearborn Works - Basic Oxygen Furnace

Computational Fluid Dynamic Modeling

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1. Introduction

Hatch was retained by AK Steel's Dearborn Works to perform an evaluation of the capture efficiency at their Basic Oxygen Furnaces and their Hot Metal Reladling Hood. This evaluation is required by AK Steel as part of their permit.

AK Dearborn operates a basic oxygen furnace (BOF) shop complete with two (2) 250 ton furnaces, known as Vessel "A" (North Furnace) and Vessel "B" (South Furnace), both a primary and secondary emission control system, a hot metal reladling station and a desulfurization station. Ancillary equipment includes an overhead crane, ladle preheaters and all other necessary equipment required for the conversion of iron into steel. The hot metal (molten iron) arrives from the blast furnace casthouse in torpedo cars. These torpedo cars are parked next to the reladling hood where the hot metal is transferred from the torpedo car to an awaiting ladle. When the ladle is full, the hot metal reladling hood is retracted and the ladle is moved to the desulphurization station. When the desulphurization process is completed, the hot metal is charged into one of the awaiting furnaces. Upon completion of the hot metal charge, the vessel is rotated to the "blow" position where oxygen is blown into the vessel at high velocity to convert the iron into steel. When the process is completed, typically 20-30 minutes, the vessel is rotated, and the molten steel is tapped into an awaiting ladle. When the tap is complete, the vessel is rotated 180 deg to pour the slag into an awaiting ladle. Once the slag is emptied, the furnace is rotated to 320 deg to await the next charge.

This report summarizes the Computational Fluid Dynamic modeling for the hot metal reladling station and the furnaces during both charging and tapping.

2. Computational Fluid Dynamic (CFD) Modeling Methodology

2.1 Introduction to CFD Modeling

Computational Fluid Dynamic (CFD) Modeling is the science of predicting fluid flow and heat and mass transfer. CFD models are used to simulate flow conditions for a variety of applications by numerically solving coupled balance equations for mass (Conservation Equation), flow (Navier-Stokes Equation of Motion) and heat (heat transfer equations). The numerical approach taken by CFD is to break a given geometry (in this case, the geometry of a basic oxygen furnace shop) into many smaller, geometrically simple pieces or elements. The equations can then be solved for each element with each element communicating with its neighboring element. The individual solutions for each element are then combined to give a solution for the overall volume (or domain).

2.2 Geometry

The first step in developing this CFD model is to set up the geometry of the BOF shop to describe the physical boundaries and internal blockages to fluid flow. The geometry of the model includes the physical bounds of the basic oxygen furnace shop and includes the furnaces, overhead crane, hot metal ladle, interior sheeting, transfer cars, reladling station, ladle preheaters and all associated ductwork. Figures 2-1 through 2-12 represent the various geometries utilized for this project.

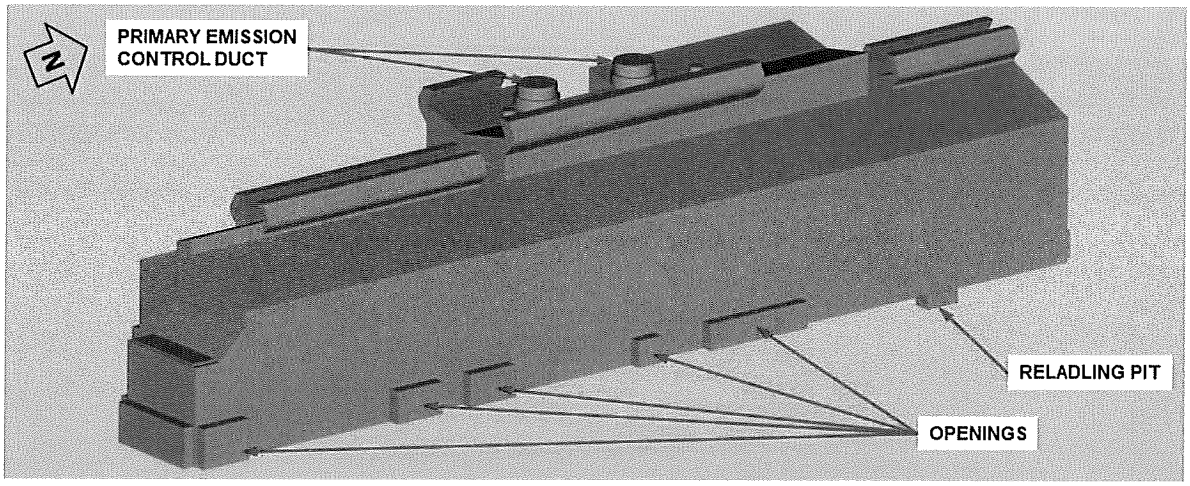


Figure 2-1 – Basic Oxygen Furnace Shop Exterior

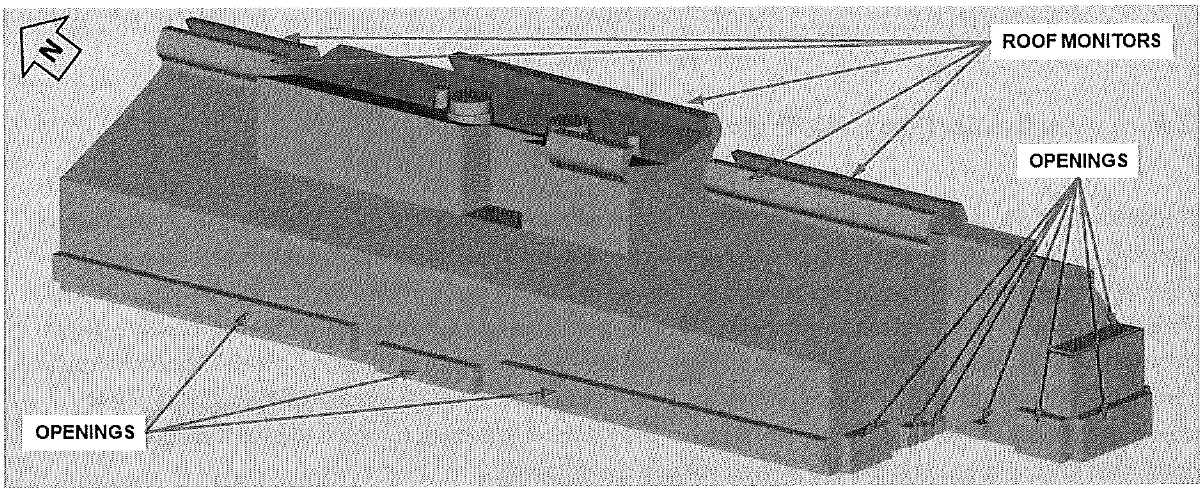


Figure 2-2 – Basic Oxygen Furnace Shop Exterior

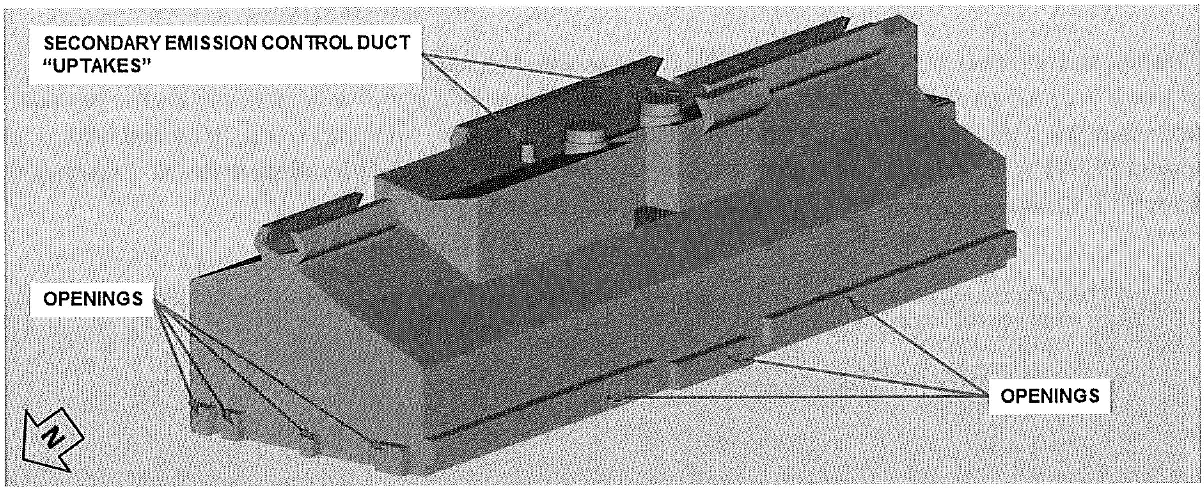


Figure 2-3 – Basic Oxygen Furnace Shop Exterior

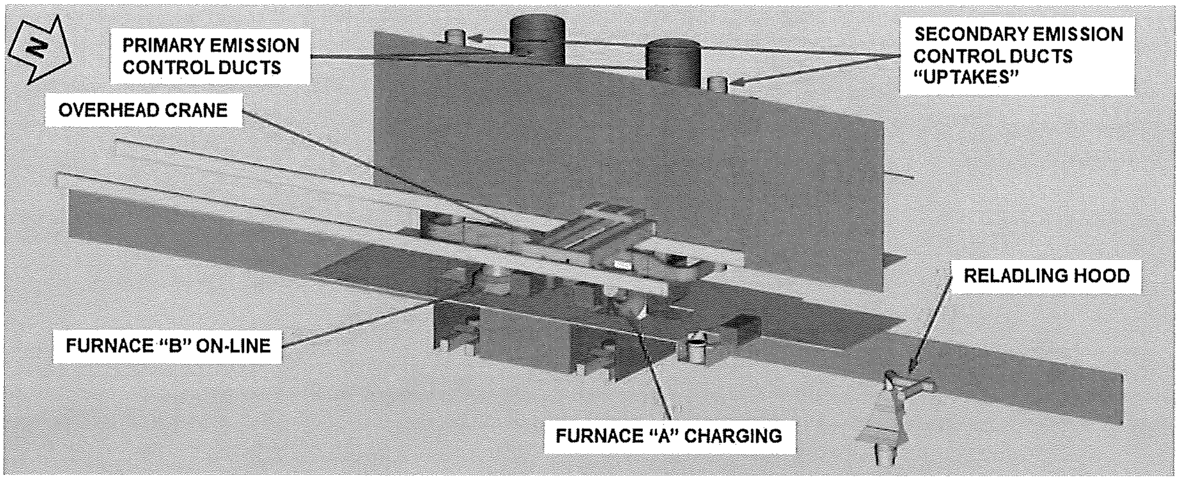


Figure 2-4 – Basic Oxygen Furnace Shop Exterior

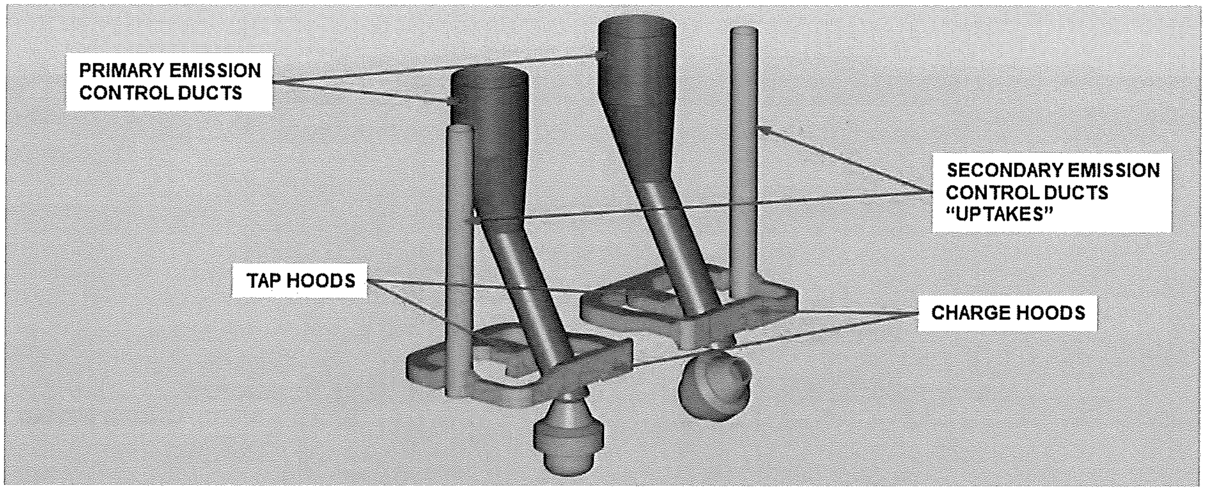


Figure 2-5 – Basic Oxygen Furnace Shop Emission Control Duct

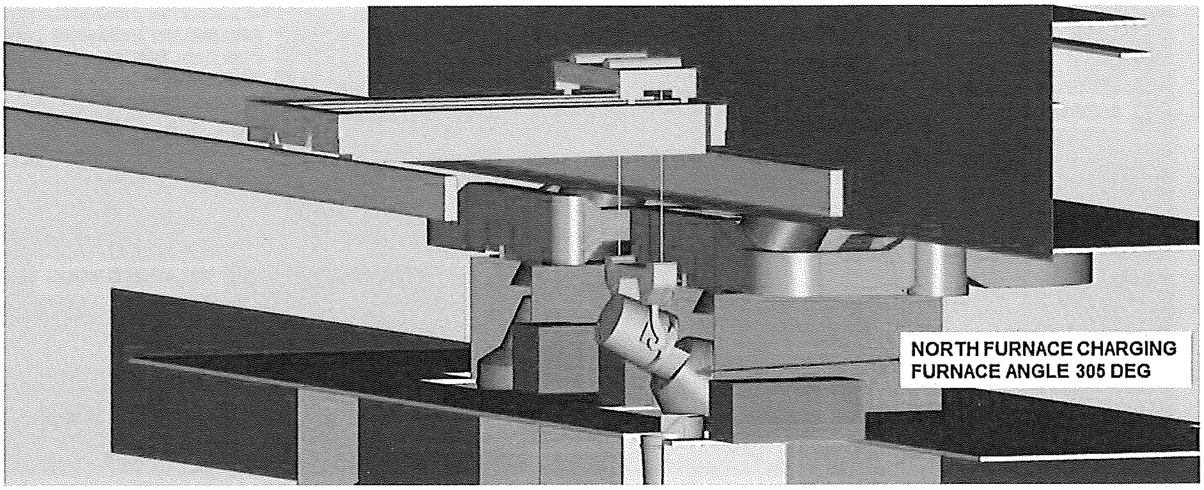


Figure 2-6 – Basic Oxygen Furnace Shop Interior

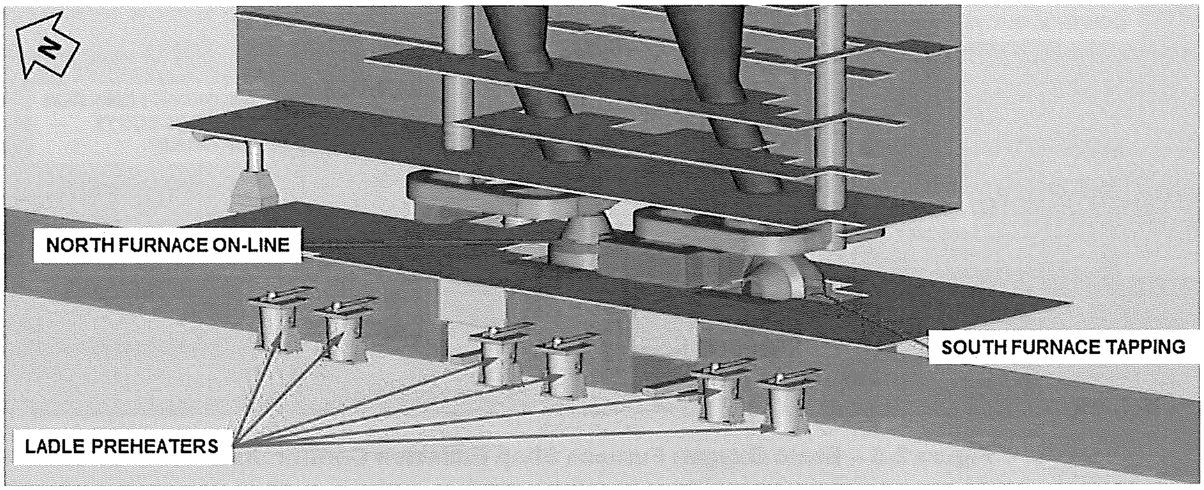


Figure 2-7 – Basic Oxygen Furnace Shop Interior

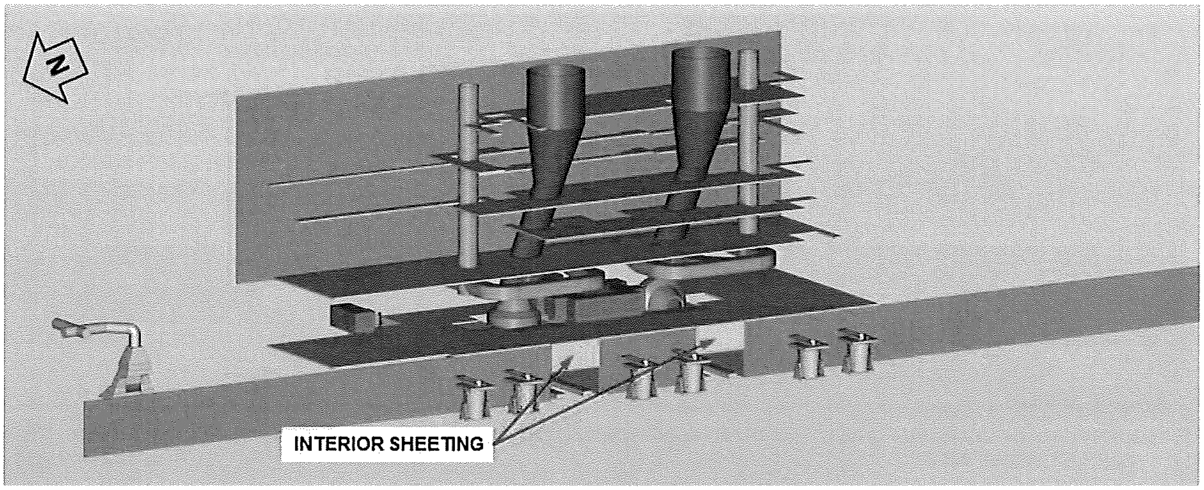


Figure 2-8 – Basic Oxygen Furnace Shop Interior

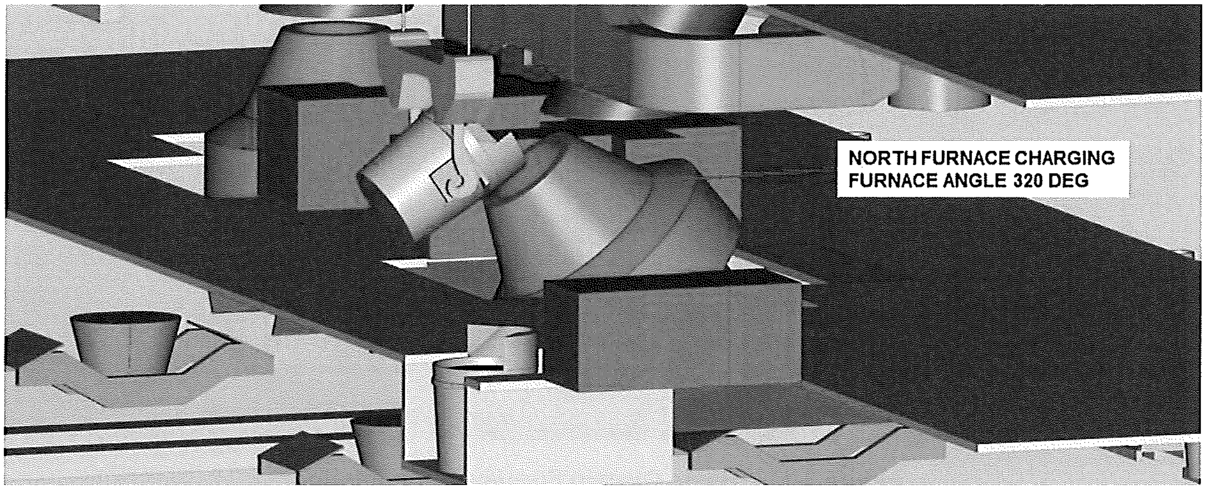


Figure 2-9 – Basic Oxygen Furnace Shop Interior

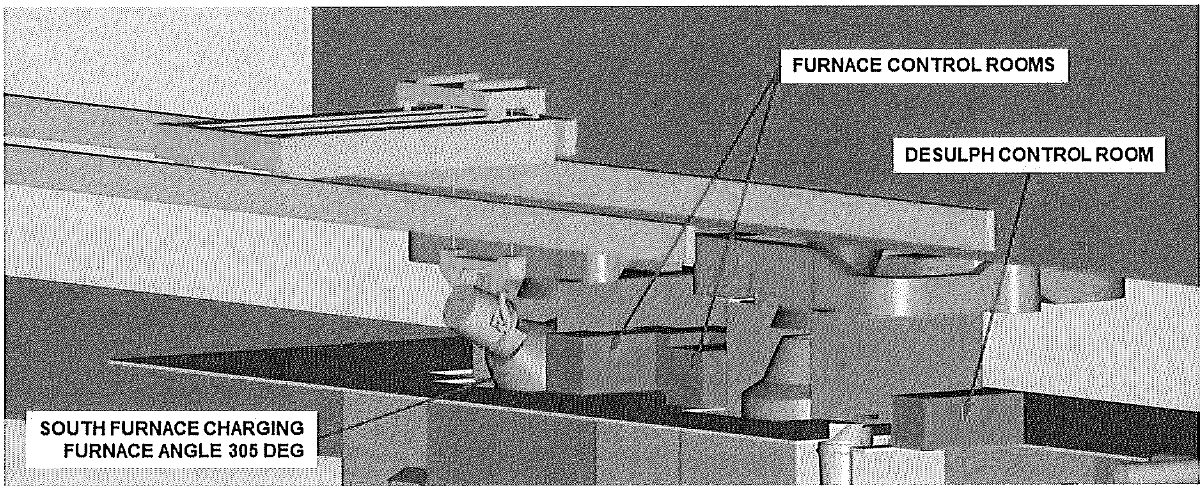


Figure 2-10 – Basic Oxygen Furnace Shop Interior

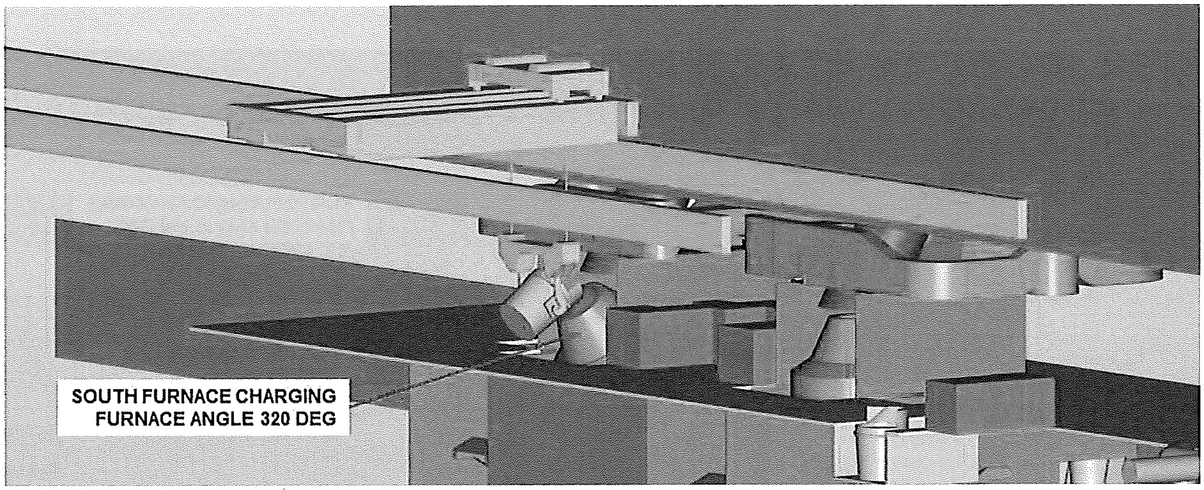


Figure 2-11 – Basic Oxygen Furnace Shop Interior

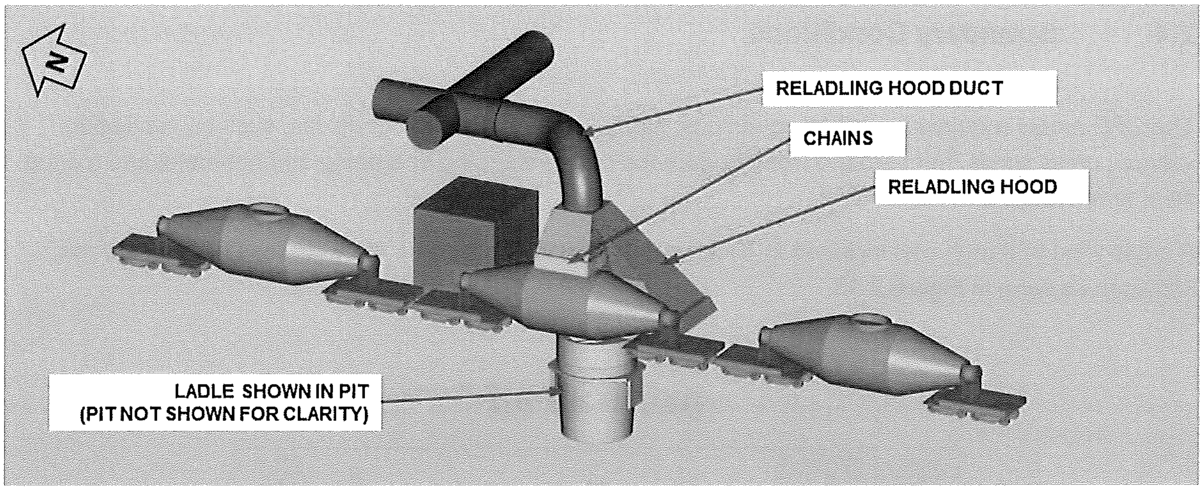


Figure 2-12 – Basic Oxygen Furnace Shop – Hot Metal Reladling

2.3 Modeling Method

The current charging and tapping operations were modeled using the existing conditions to determine the capture efficiency. The models were modeled as steady state, that is, the variables do not change during the course of the model. The corresponding capture efficiency is then calculated for the worst case condition rather than average conditions.

2.4 Boundary Conditions

The CFD model requires boundary conditions, that is, a starting set of conditions, such as ventilation volume, cross winds, temperature from the furnace during charging or tapping and hot metal and molten steel temperatures.

A cross wind of 8 mph was included in each model run and is based on the wind rose data for Detroit, Michigan as seen in Figure 2-13.

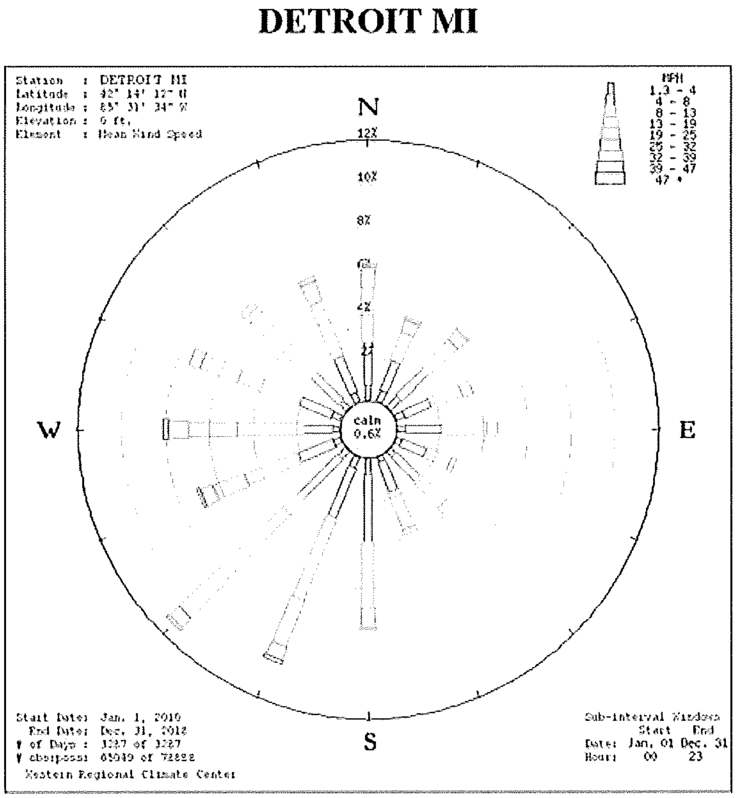


Figure 2-13 – Wind Rose – Detroit, Michigan

The ventilation volume varied based on operation and was measured the week of November 11, 2019. For the purpose of the modeling, the lowest measured volume for a particular activity was used in the model. Table 2-1 presents the ventilation volume used in the CFD models.

Table 2-1 – Summary of Flow Test Results

Vessel "A" North Furnace		Vessel "B" South Furnace	
Status	**Uptake Volume (acfm)**	**Status**	**Uptake Volume (acfm)**
Charging	566,164	On-Line	N/A
Tapping	538,746	Off-Line	N/A
On-Line	N/A	Charging	590,983
Off-Line	N/A	Tapping	635,365
Charging	534,595	Tapping	324,121
Tapping	318,218	Charging	553,326

The flow was measured in the uptake, as seen in Figure 2-5, and not at the local hoods for obvious safety concerns. Measuring the flow in the uptake satisfied both the safety concerns and the EPA Method 1 criteria. In order to allocate the proper volume to the hood, dampers were placed in the duct and adjusted to match the operational position. Damper positions with respect to shop operation are presented in Table 2-2.

Table 2-2 – Furnace Status and Damper Position

Vessel "A" North Furnace				Vessel "B" South Furnace			
Status	**Charge Damper North**	**Charge Damper South**	**Tap Damper**	**Status**	**Charge Damper North**	**Charge Damper South**	**Tap Damper**
Charging	100%	100%	0%	Off-Line	0%	0%	0%
Charging	100%	100%	0%	On-Line	20%	20%	0%
Tapping	75%	0%	100%	Off-Line	0%	0%	0%
Tapping	75%	0%	100%	On-Line	20%	20%	0%
Off-Line	0%	0%	0%	Charging	100%	100%	0%
On-Line	20%	20%	0%	Charging	100%	100%	0%
Off-Line	0%	0%	0%	Tapping	75%	0%	100%
On-Line	20%	20%	0%	Tapping	75%	0%	100%
Charging	100%	100%	0%	Tapping	0%	0%	75%
Tapping	0%	0%	75%	Charging	100%	100%	0%

Notes – Damper percentage expressed as percent open

As with the furnace ventilation volumes, the ladle reladling hood was also tested. The test location was outside, away from the process, but provided good results in accordance with the EPA test criteria. The lowest value measured during the flow testing is presented in Table 2-3.

Table 2-3 – Hot Metal Reladling Hood Volume

Vessel "A" North Furnace	Vessel "B" South Furnace	Hot Metal Reladling Hood Volume (acfm)
Off-Line	On-Line	101,711

Note that the lowest measured value was used as the boundary condition for the CFD model for charging, tapping and hot metal reladling. The lowest value was used to demonstrate that the emission control system achieves 98% capture under all operating scenarios. Obviously, when the ventilation volume is larger, the capture efficiency would be higher.

Simulating a hot metal charge required several boundary conditions and two unique sets of geometry. When the hot metal charge begins, the furnace is at an angle of 320 deg, as seen in Figure 2-14. As the pour continues, the furnace is gradually rotated and finishes at an angle of 305 deg. The two hot metal charge models simulate the angle at 320 deg and 305 degrees and demonstrates 98% capture at all times.

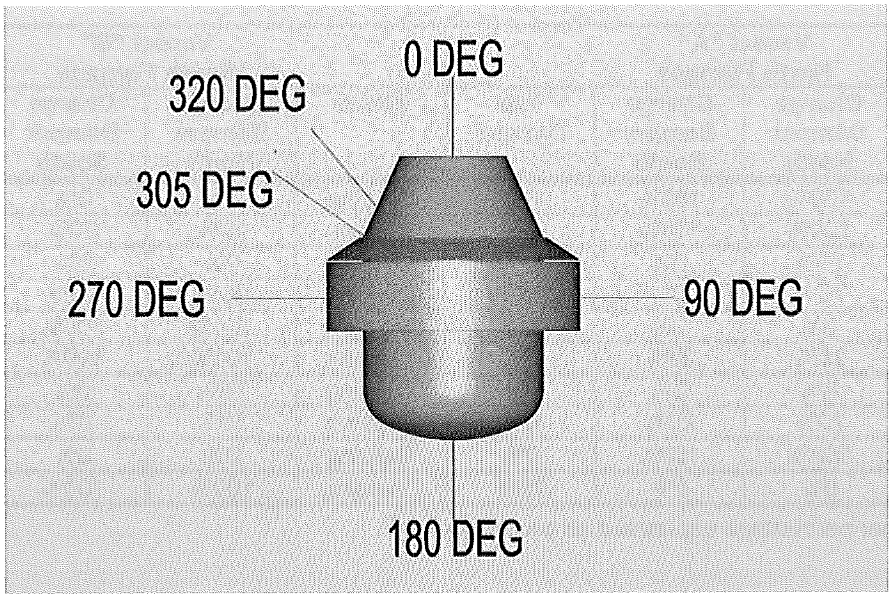


Figure 2-14 – Vessel Angle

Several key boundary conditions must be included and need to be as accurate as possible to ensure quality results. The temperature of the molten iron is 2500 deg F and is based on past experience and discussions with AK Steel and is assigned to both the iron inside the ladle and inside the furnace. The fume exit rate from the furnace was assigned a value of 145,000 acfm. This is based on observations of this furnace and other, similar furnaces without a secondary emission control system.

As with the charging of hot metal, key variables must be assigned when simulating tapping. The molten steel temperature was assigned a value of 2900 deg F, AK's target tap temperature.

The same was done for the hot metal reladling. A temperature of 2500 deg F was assigned to the molten iron in both the ladle and torpedo cars.

Additionally, the miscellaneous heat sources were also included in the model. A ladle at the desulphurization station was included and a temperature of 2500 deg F was assigned to the molten iron. The model assumes that the hood is retracted and the ladle is sitting at the station. The six ladle preheaters located in the teeming aisle were also included and assigned an internal temperature of 2000 deg F.

The primary emission control system was also included in the models and assigned a ventilation rate of 250,000 acfm during charging and tapping.

2.5 Mesh

The CFD modelling software breaks down the complex geometry of the BOF shop into smaller pieces, typically referred to as the mesh or grid. Here, the calculations are performed to solve the equations for velocity, temperature, pressure, etc. Figure 2-15 illustrates the typical mesh for hot metal charging.

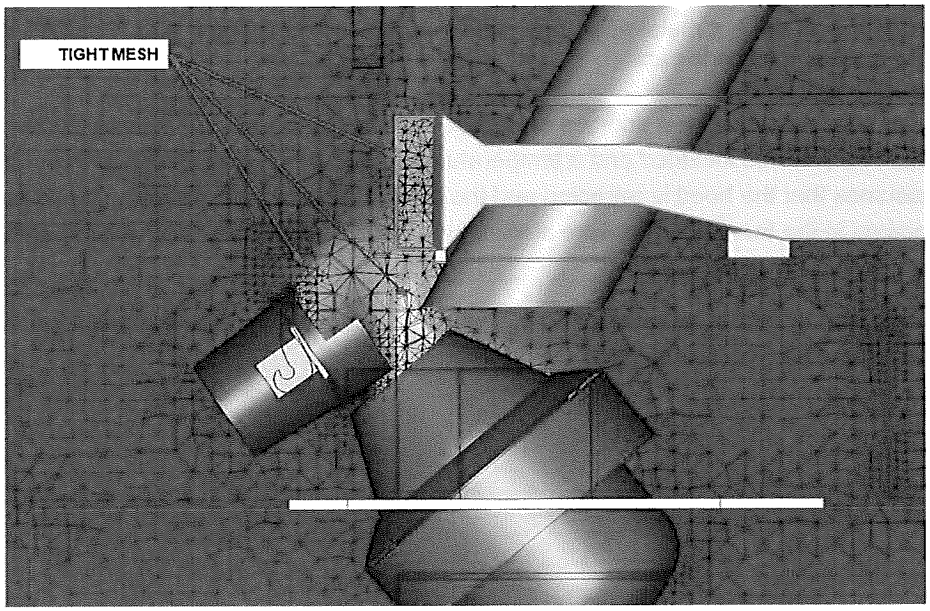


Figure 2-15 – Typical Mesh (Some items not shown for clarity)

2.6 Turbulence

The turbulence model used for all AK Dearborn models is k-epsilon. The k-epsilon model is one of the most common models used in CFD analysis to represent mean flow characteristics for turbulent flow. This model is a two equation model which accounts for turbulent kinetic energy and dissipation of turbulent kinetic energy. The k-epsilon model was developed and used to better predict the turbulence in a mathematical model and is often considered the "workhorse" of the CFD models.

2.7 Capture Efficiency

The capture efficiency is calculated by inserting particles of various sizes ranging from 0.5 microns up to 100 microns into the model just above the source of interest. For example, when calculating the capture efficiency during charging, particles are placed just inside the furnace and then assigned size and density. The model will then calculate their trajectory based on their properties and other various conditions such as the thermal properties from the furnace, cross winds entering the shop and influence from the emission control system. Figure 2-16 represents an abbreviated particle trace during a hot metal charge. The furnace is shown transparent to show the particles generated inside the furnace and leaving through the mouth of the furnace.

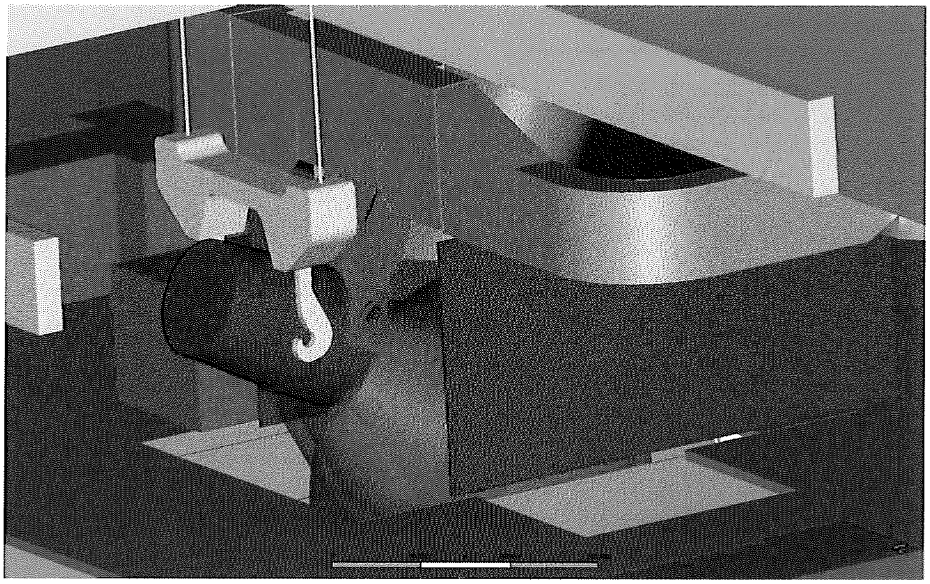


Figure 2-16 – Abbreviated Particle Trace

A particle trace whose trajectory ends inside the duct is considered captured by the baghouse. Any other particles not counted in the duct are then assumed to have either exited the building or settled within the shop. The particle size distribution (the percent of each particle size that makes up the off-gas sample) is based on data supplied by the US EPA for an uncontrolled BOF shops. This distribution is used in the determination of the capture efficiency. Figure 2-17 represents the particle distribution as published by the US EPA.

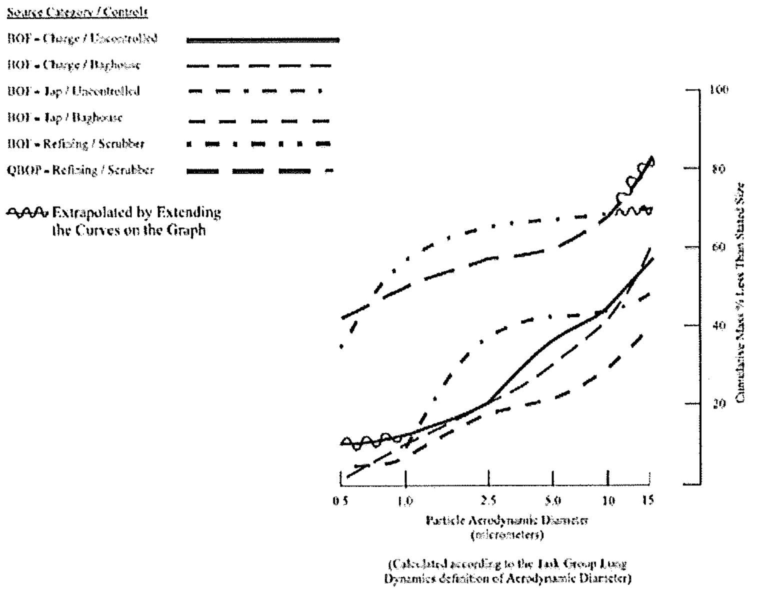


Figure 2-17 – Particle Size Distribution

3. Computational Fluid Dynamic Modeling Results

This section provides general commentary about the CFD model results. The CFD models simulated hot metal charging, tapping and hot metal reladling. The hot metal charge and tapping models were run under different ventilation rates as presented in Table 2-1 while the hot metal reladling was run with one volume as presented in Table 2-3.

3.1 Charging (Vessel Angle 320 deg)

Figure 3-1 illustrates the vessel at an angle of 320 deg, which is the angle of the vessel at the start of the pour. A section was inserted at the centerline of the furnace and the velocity vectors are displayed. As seen, the vectors are pointing towards the secondary emission capture hood which is an indication of good capture efficiency.

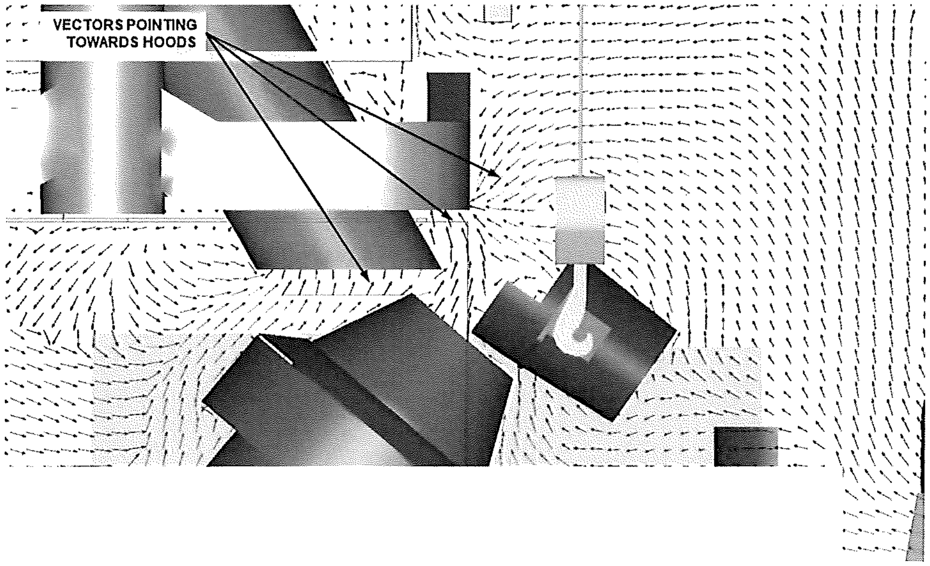


Figure 3-1 – "B" Furnace (South Furnace) Charging – Vessel Angle 320 deg – Looking North (some items not shown for clarity)

Photo 3-1 is a photo of "B" Furnace looking north just as the charge begins. The vessel angle is at 320 deg and the emissions are ventilated by the emission control system.

Photo 3-1 – "B" Furnace (South Furnace) Charging – Looking North

Figure 3-2 is the same section as seen in Figure 3-1 with the vectors turned off and the static pressure displayed. As seen, the pressure is negative not only at the hood inlet but extending down towards the furnace and ladle. This negative pressure influences the emissions towards and into the secondary emission hood resulting in a high capture efficiency.

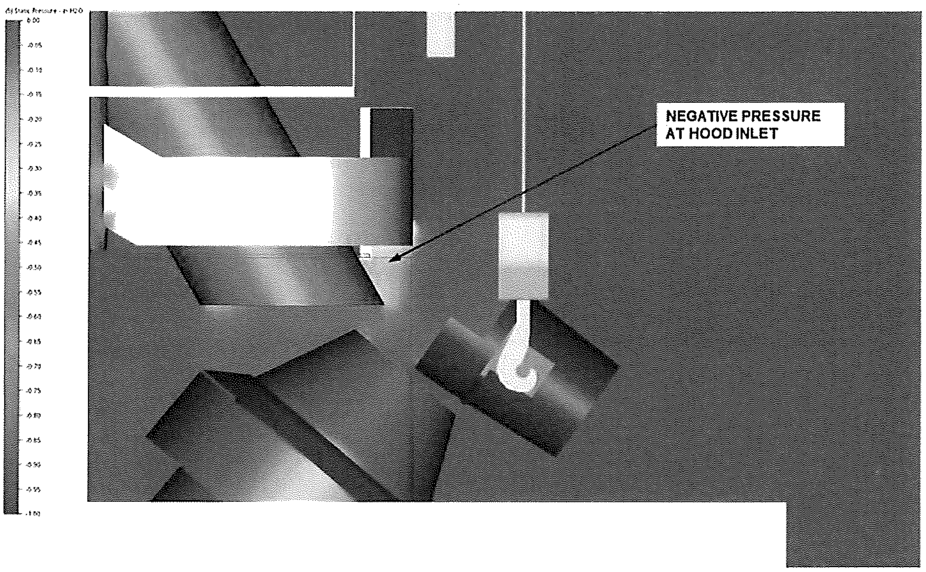


Figure 3-2 – "B" Furnace (South Furnace) Charging – Vessel Angle 320 deg – Looking North (some items not shown for clarity)

Figure 3-3 is a 3D representation of the plume. As seen, the emissions are drawn directly into the secondary emission control hood, confirming the vectors and static pressure results shown in the figures above. As seen, the results qualitatively agree with Photo 3-1.

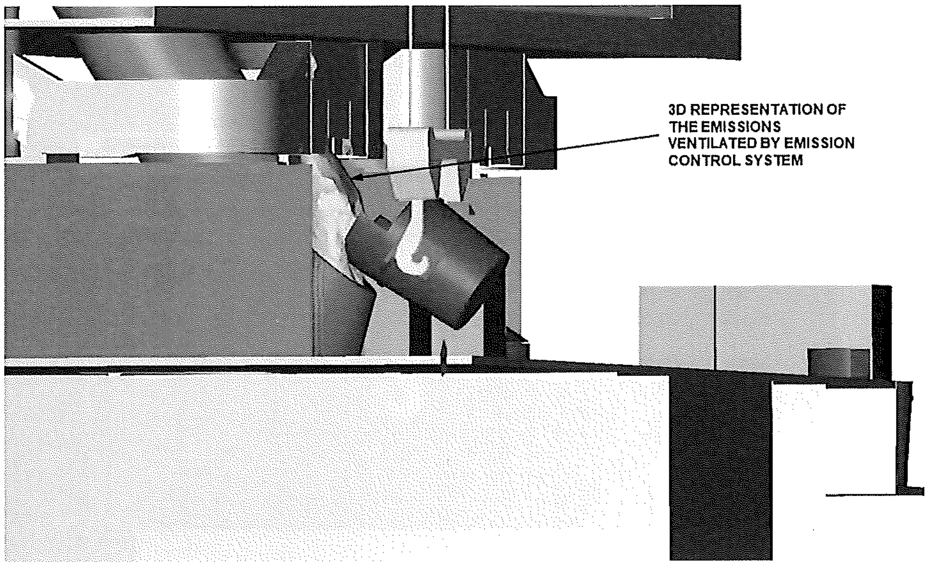


Figure 3-3 – "B" Furnace (South Furnace) Charging – Vessel Angle 320 deg – Looking North (some items not shown for clarity)

Figure 3-4 illustrates a particle trace for a 10 micron particle. As seen, the particle trace agrees with the 3D representation of the emission plume shown above.

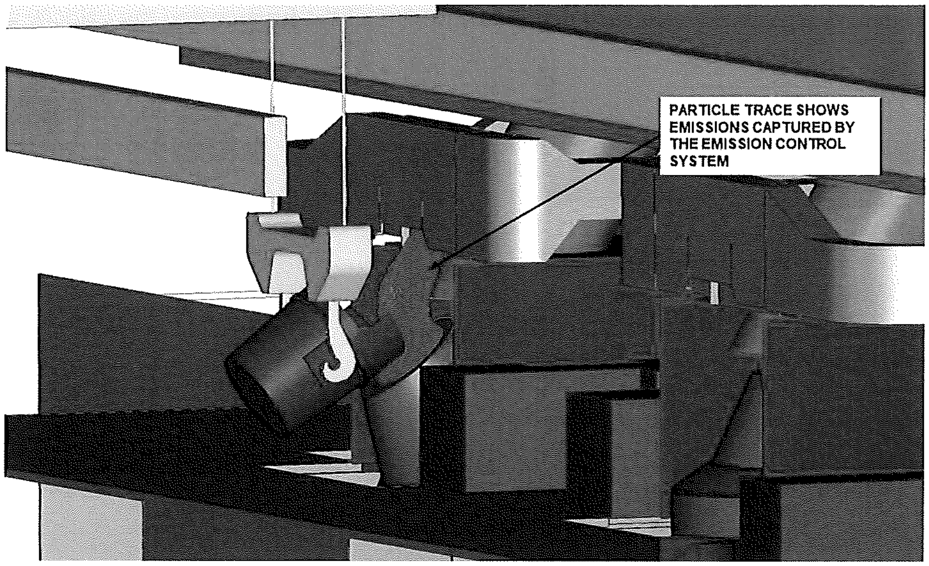


Figure 3-4 – "B" Furnace (South Furnace) Charging – Vessel Angle 320 deg – Looking South (some items not shown for clarity)

3.2 Charging (Vessel Angle 305 deg)

Figure 3-5 illustrates the vessel at an angle of 305 deg, which is the angle of the vessel at the end of the pour. As with above, a section was inserted at the centerline of the furnace and the velocity vectors are displayed.

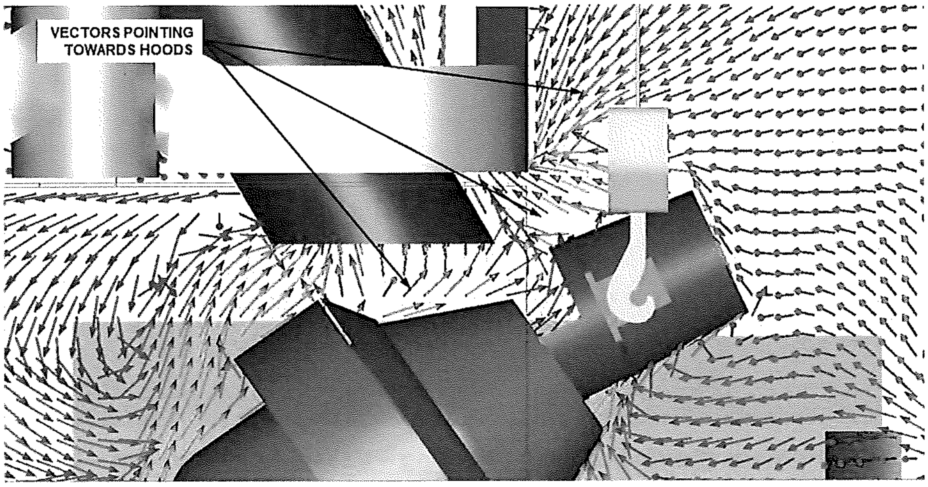


Figure 3-5 – "B" Furnace (South Furnace) Charging – Vessel Angle 305 deg – Looking North (some items not shown for clarity)

As seen in Figure 3-5, the vectors are pointing towards the secondary emission control hood, indicating a high capture efficiency.

Photo 3-2 was taken as the charge ended and the ladle was moving away from the furnace. As seen, the emissions generated inside the ladle and furnace are influenced and captured by the secondary emission system resulting in a very high capture efficiency.

Photo 3-2 – "B" Furnace (South Furnace) End of Charge – Looking North

Figure 3-6 illustrates the static pressure at the hood inlet and the area immediately surrounding the secondary emission control hood.

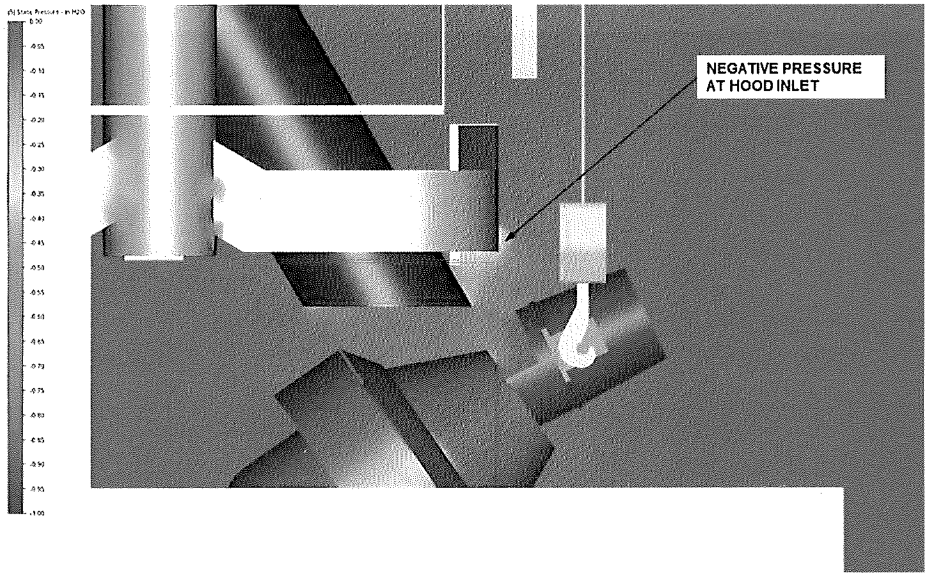


Figure 3-6 – "B" Furnace (South Furnace) Charging – Vessel Angle 305 deg – Looking North (some items not shown for clarity)

As seen, there is a slight negative pressure in the area immediately around the hood which indicates that the emissions will be drawn towards the secondary hood.

Figure 3-7 illustrates a 3D representation of the emission plume. As seen, the emissions are drawn towards the secondary hood, confirming what was presented in Figures 3-5 and 3-6.

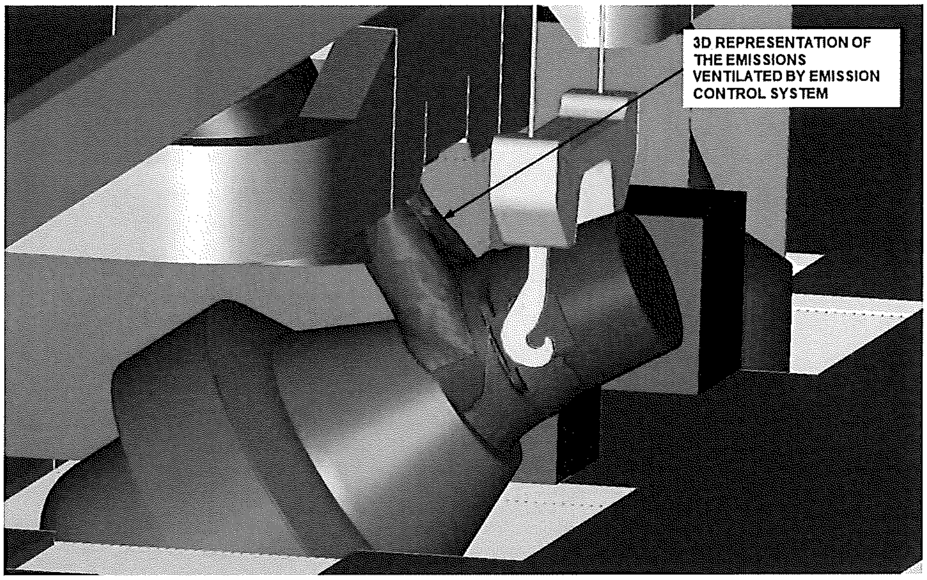


Figure 3-7 – "B" Furnace (South Furnace) Charging – Vessel Angle 305 deg – Looking North (some items not shown for clarity)

Figure 3-8 confirms the results by placing a 10 micron particle inside the furnace. As seen, the particles are drafted into the secondary emission hood.

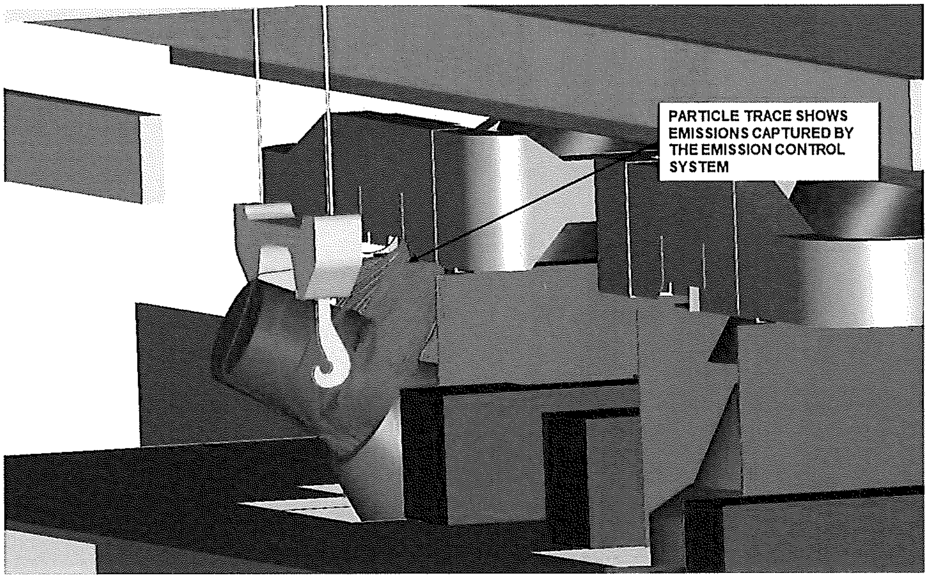


Figure 3-8 – "B" Furnace (South Furnace) Charging – Vessel Angle 305 deg – Looking South (some items not shown for clarity)

3.3 Tapping

When the steel making cycle is complete, the furnace is rotated to approximately 90 deg and the molten steel is poured from the furnace to an awaiting ladle. Figure 3-9 illustrates the velocity vectors taken at the centerline of the furnace and ladle. As seen, even though the hood is a large distance above the ladle, the vectors are pointing towards the hood indicating a high capture efficiency.

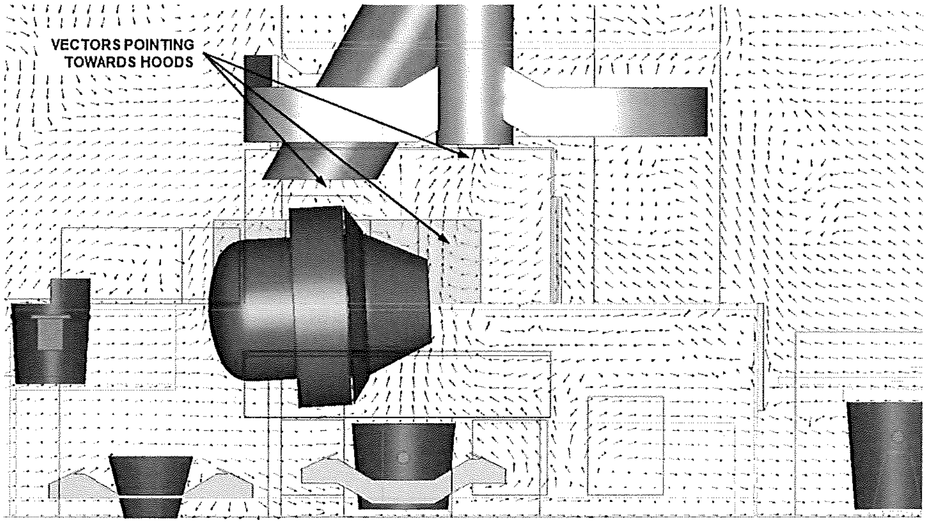


Figure 3-9 – "A" Furnace (North Furnace) Tapping – Looking South (some items not shown for clarity)

Figure 3-10 is the same section with the vectors turned off and the static pressure displayed. As seen, there is a slight negative pressure at the hood inlet and inside the enclosure indicating a high capture efficiency.

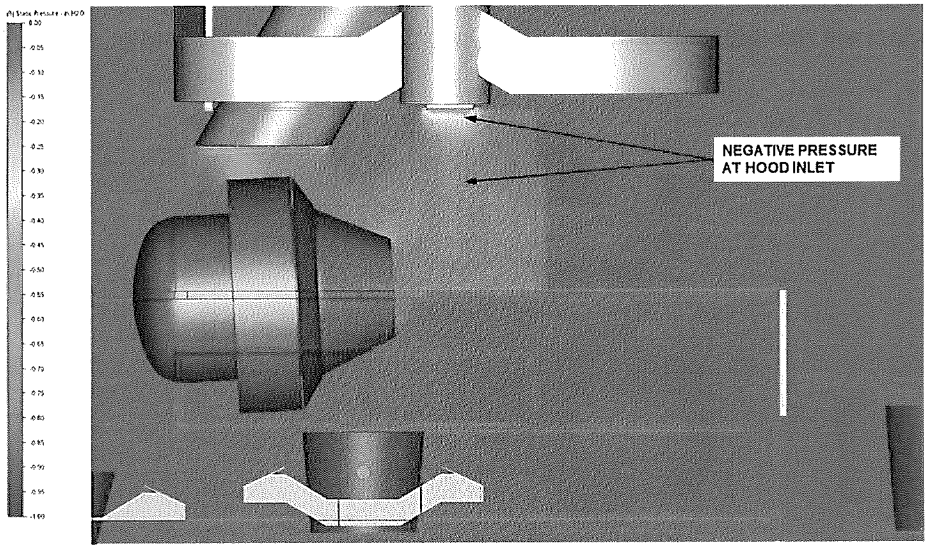


Figure 3-10 – "A" Furnace (North Furnace) Tapping – Looking South (some items not shown for clarity)

Figure 3-11 illustrates a 3D emission plume. As seen, the emissions are initially contained by the enclosure and eventually drawn into either the primary hood or the secondary hood.

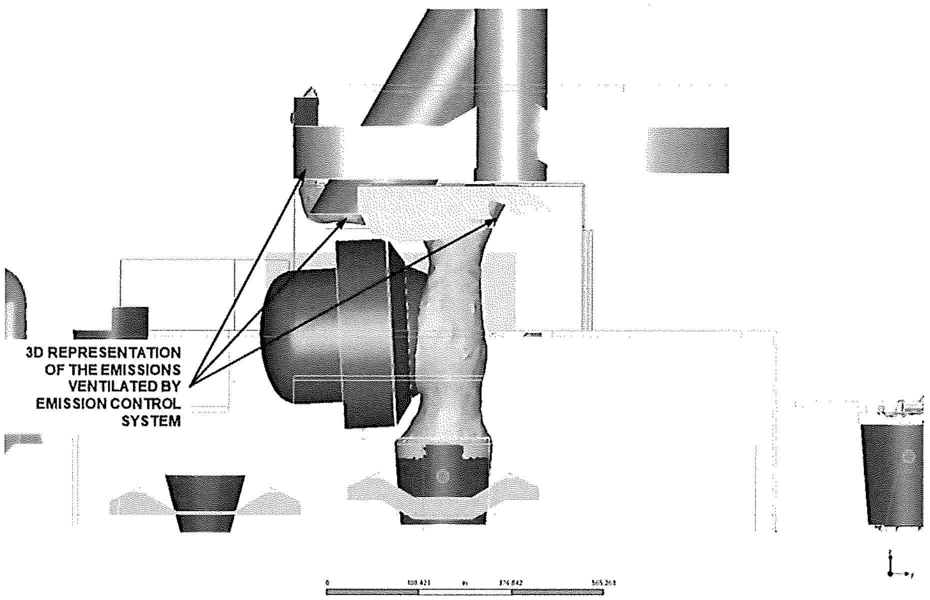
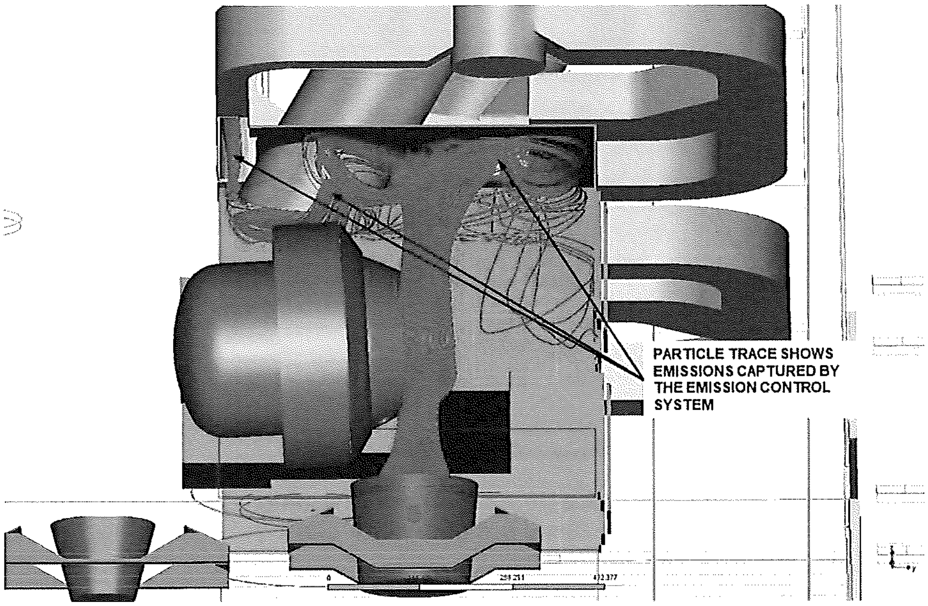


Figure 3-11 – "A" Furnace (North Furnace) Tapping – Looking South (some items not shown for clarity)

Figure 3-12 illustrates an abbreviated 10 micron particle trace. The particle trace confirms the results seen in Figures 3-9, 3-10 and 3-11. The enclosure contains the emissions allowing the primary hood and secondary tapping hood to evacuate the emissions. In some instances where the charge damper is open, the emissions are drawn into the charge hood.



PARTICLE TRACE SHOWS EMISSIONS CAPTURED BY THE EMISSION CONTROL SYSTEM

Figure 3-12 – "A" Furnace (North Furnace) Tapping – Looking South
(some items not shown for clarity)

3.4 Hot Metal Reladling

When the hot metal is brought to the basic oxygen furnace shop, it is transferred from the torpedo car to an awaiting ladle. The ladle is placed in a pit and then the emission control hood is moved in place. Once the hood is ready, the torpedo car rotates pouring the hot metal into the awaiting ladle.

Figure 3-13 illustrates a section taken at the centerline of the torpedo car. As seen, a portion of the vectors point towards the hood while another portion pointing out through the chains. The chains were modeled as a resistance element with a free area ratio of 0.5 (50% open area) as opposed to modeling each individual chain hanging around the hood. This is an indication of some emissions possibly escaping the hood.

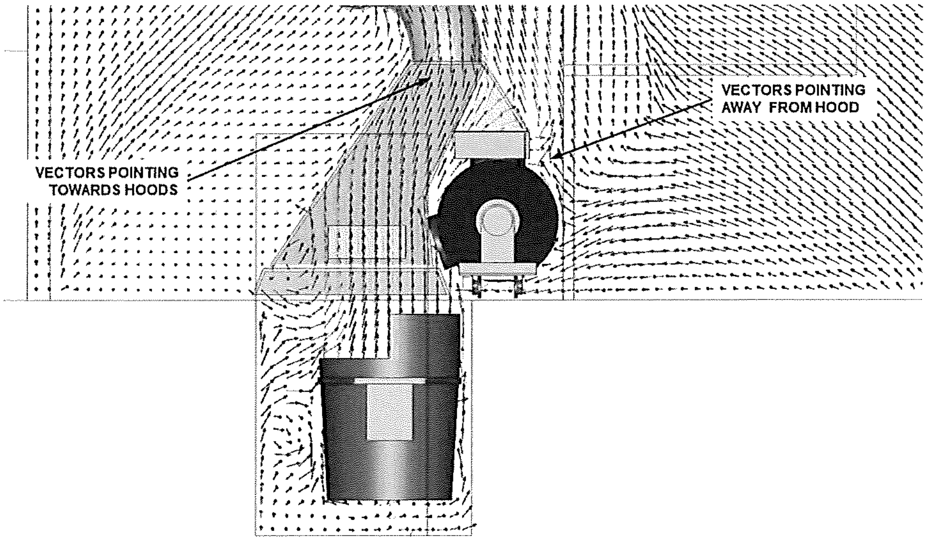


Figure 3-13 – Hot Metal Reladling – Looking South (some items not shown for clarity)

Figure 3-14 is a section showing the static pressure inside the hot metal reladling hood. As seen, there is a slight negative pressure at the hood inlet but does not extend much beyond the hood inlet as seen with charging and tapping of the furnace.

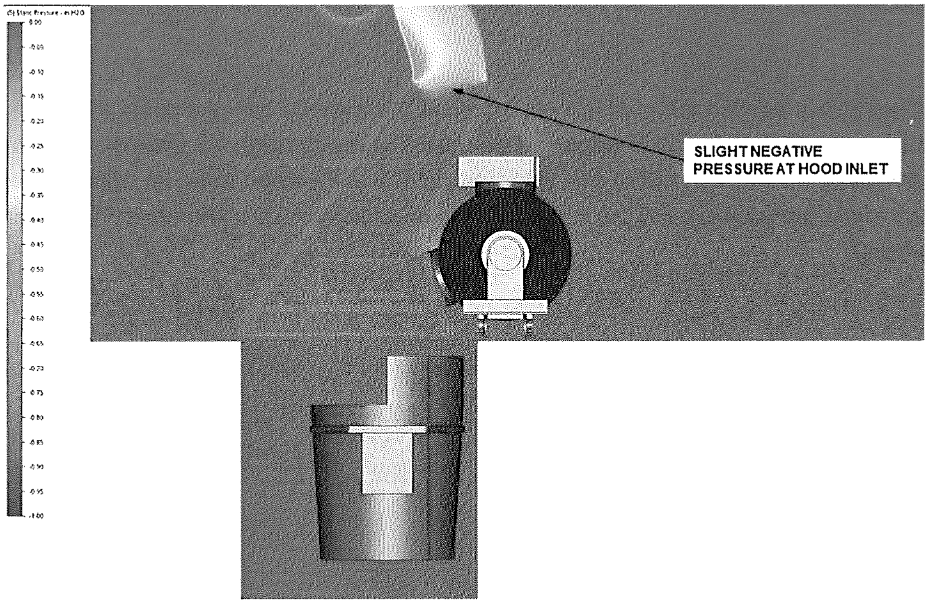


Figure 3-14 – Hot Metal Reladling – Looking South (some items not shown for clarity)

Figure 3-15 illustrates a 3D representation of the emission plume. As seen, a portion of the emissions are escaping the hood and migrating in the shop. This was confirmed by observations. However, the CFD model confirms that 98% capture is being achieved during the transfer of hot metal.

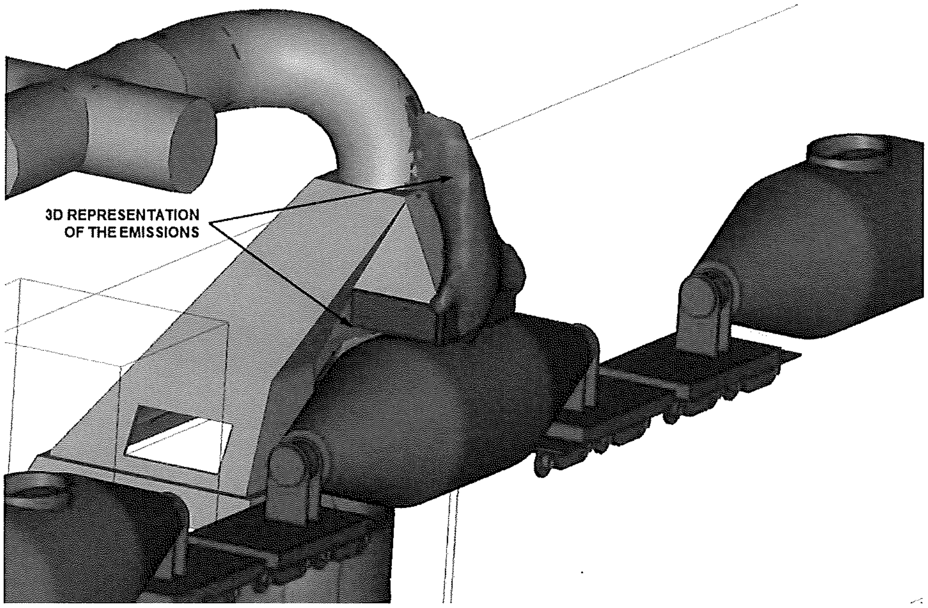


Figure 3-15 – Hot Metal Reladling – Looking South (some items not shown for clarity)

Figure 3-16 illustrates an abbreviated 10 micron particle trace. As seen, and confirmed by the figures above, the ventilation is such that emissions are escaping the emission control hood.

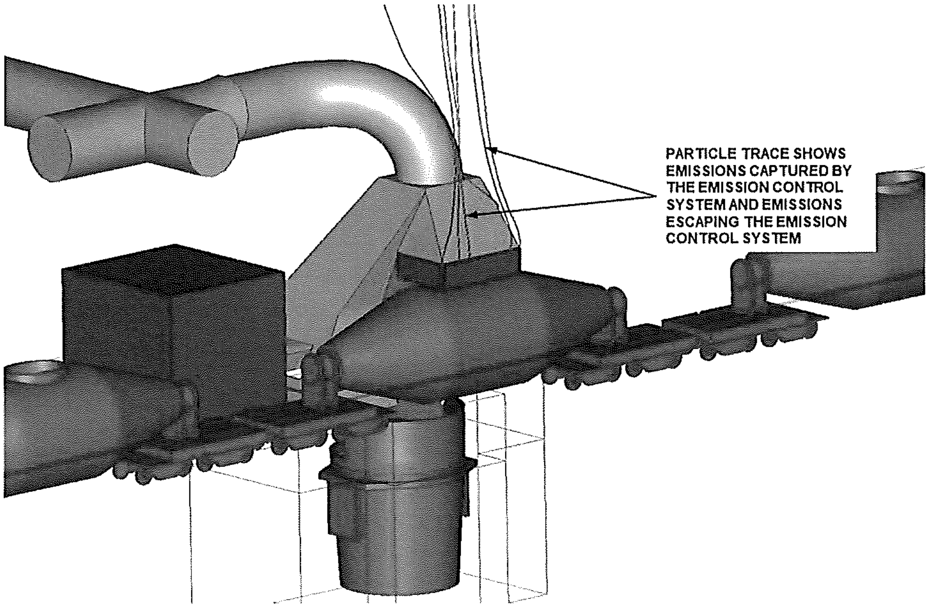


Figure 3-16 – Hot Metal Reladling – Looking South (some items not shown for clarity)

4. Summary of Model Results

Table 4-1 – BOF Capture Efficiency

Vessel "A" North Furnace	Vessel "B" South Furnace	Capture Efficiency
Charge (Vessel at 320 deg)	Online	99.6%
Charge (Vessel at 305 deg)	Online	99.5%
Tapping	Online	98.3%
Online	Charge (Vessel at 320 deg)	99.7%
Online	Charge (Vessel at 305 deg)	99.5%
Online	Tapping	99.1%
Charge (Vessel at 305 deg)	Tapping	98.4%/ 98.0%
Tapping	Charge (Vessel at 305 deg)	98.0% / 98.9%

Table 4-2 – Hot Metal Reladling Capture Efficiency

Activity	Capture Efficiency
Hot Metal Reladling	98.0%

5. Minimum Volume Requirements

Several iterations of the charge, tap and hot metal reladling models were run to determine at what volume the capture efficiency drops below 98%. Hatch assumes that the furnaces are a mirror image of each other, and the emission control system hoods are identical therefore the minimum volume calculated during a certain activity will be the same for both furnaces.

5.1 Hot Metal Charge / Online or Offline

In this scenario, one furnace is charging and the other furnace is either online or offline. The position of the charging furnace is 305 deg, the furthest position away from the hood. The data above shows that the capture efficiency dips slightly as the vessel is rotated during the charge making this position the worst case scenario. The assumption is then made that the minimum volume must be capable of achieving 98% when the furnace is at the end of the hot metal charge. This scenario assumes that both charge dampers are 100% open and that the tap damper is closed. The ventilation volume at the primary hood remains at 250,000 acfm.

Under these conditions, the minimum volume required at the uptake during a hot metal charge with one furnace either online or offline to achieve 98% capture is 475,000 acfm.

5.2 Tapping / Online or Offline

In this scenario, one furnace is tapping and the other furnace is online of offline. The tap damper is 100% open and the north charge damper is 75% open and the south charge damper is closed. The ventilation volume of the primary system is 250,000 acfm.

Under these conditions, the minimum volume required at the uptake during tapping with one furnace either online or offline to achieve 98% capture is 450,000 acfm.

5.3 Charging / Tapping

In this scenario, one furnace is charging and the other is tapping. The charging vessel is again at an angle of 305 deg. The charging furnace's charge dampers are 100% open and its tap damper is closed. The tapping furnace's tap damper is 75% open while its charge dampers are closed. The primary system is set to 250,000 acfm for each furnace.

Under these conditions, the minimum volume required at the charging furnace's uptake with the other furnace tapping to achieve 98% capture is 475,000 acfm.

The minimum volume required at the tapping furnace's uptake with the other furnace charging to achieve 98% capture is 300,000 acfm.

It is important to point out the difference between this scenario and the tapping scenario above. In this scenario, with one furnace charging and one furnace taping, the minimum volume required in the tapping furnace's uptake is 300,000 acfm while the minimum volume required for one furnace tapping is 450,000 acfm. In this scenario, the tapping furnace's charge damper is closed allocating the full 300,000 acfm plus the 250,000 acfm to the tap enclosure. In the scenario with a single furnace tapping, one charge damper is 75% open which allocates approximately 30% of the total volume to the charge hood leaving approximately 300,000 acfm at the tap hood. While the charge damper does evacuate a small portion of the emissions, the bulk of the emissions are evacuated by the primary hood and tap hood.

5.4 Hot Metal Reladling

As seen in Table 4-2, the capture efficiency is 98.0% at a volume of 101,700 acfm. A model was run with the ventilation volume at 100,000 acfm and the capture efficiency remained at 98.0% indicating that the ventilation rate at the hot metal reladling station should be at least 100,000 acfm.

6. Timeline of Modeling

Key Dates	Description
September 10, 2019	Submitted Notification to State
November 11, 2019	Site Visit and Observation
December 16, 2019	Start of CFD Model Runs
February 7, 2020	End of CFD Model Runs
March 10, 2020	Report Provided to AK Steel

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