323081

Utilizing Advancements in Simulation to Improve Occupational Health and Safety

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Learning Objectives

- Learn how to identify certain types of environmental hazards
- Learn how to predict thermal stress on workers
- Learn how to compare various solutions
- Learn how to plan environments to reduce indoor environmental concerns

Description

Health and safety are now front and center as industrial facilities take aim to help protect employees and provide safe work environments. Typical industrial hazards include temperature extremes and inhalable particulate. Utilizing advancements in computer simulation, engineers can predict conditions within the work environment by identifying all the potential hazards workers may face. Simulations of the facility can be generated to model hazards such as temperature extremes and particulate dispersion patterns. The results can then be analyzed to determine the thermal stress on employees and the capture efficiency of the emission control system. By studying these results, engineers can run additional "what if" scenarios and compare the results to determine the best course of action. Utilizing this technology, engineers can design practical yet cost-effective "right-sized" solutions to satisfy both industrial hygiene and regulatory issues.

Speaker(s)

Brian Bakowski is a degreed engineer with over 20 years of experience with CFD technology as a design and analysis tool in heavy industry, primarily in the steel and aluminum sectors. Brian has performed analyses for coke oven batteries, blast furnace casthouses, electric arc furnace melt shops, basic oxygen furnace melt shops and continuous casters. Brian has performed many analyses to assist steel manufacturers with troubleshooting existing equipment and up to the design and construction of new emission control systems. Brian has presented CFD technology at various conferences, included Association of Iron and Steel Technology and the Air and Waste Management Association. Brian has been published in several trade magazines including *Foundry Management and Technology*, *Digital Engineering* and *Steel Times International*.

Introduction

Health and safety are now front and center as industrial facilities take aim to protect employees and provide a safe work environment. As one would imagine, the cost of programs to prevent injury is far less than the cost of an injury. A safe and healthy workplace attracts and retains quality employees and is an asset to a community and operates more efficiently. Additionally, a safe workplace can also lower injury/illness costs, reduce absenteeism and turnover, increase productivity and quality, and raise employee morale. In other words, safety is good for business. Providing the proper personal protection equipment and training are just two of the ways this is accomplished. Another method, which uses the latest advancements in computer simulation, is to predict the conditions within the work environment and identify all the potential hazards workers may face. By utilizing this technology, engineers can predict conditions which affect health and safety and make changes as required to provide a safer environment for the workforce. This paper examines advancements in computer simulation and how this technology can be applied to provide a safer workplace.

Early Work in Industrial Hygiene

The steel industry, as well as other heavy industries, once had a poor reputation regarding employee health and safety. Looking back at the beginning of the industrial revolution in this country, there are countless accounts of unsafe working conditions, which led to accidents and even fatalities. In fact, in the early 1900's, Allegheny County in Pennsylvania lost over 500 workers in one calendar year to industrial accidents. Employers estimated that 95% of all accidents were the result of employee carelessness while research by Crystal Eastman titled *Work Accidents and the Law* in 1910 provided data that suggested otherwise.[(1)] Crystal Eastman and her team of researchers investigated all industrial accidents in the Pittsburgh, Pennsylvania area for a period of one year. The nature of the accident was investigated as well as who was at fault and the economic effect on families. The three main industrial categories investigated were railroads, mines and steel mills with steel mills as the largest manufacturing sector in the research. Ms. Eastman showed that of all the accidents investigated, approximately 30% were the fault of the employer. Furthering her investigation, she showed that approximately 44% of the accidents could be blamed on the employee or a co-worker. In the cases where fault could be blamed on the employee, research showed that the conditions in which they worked led to the accident citing long work hours, temperature extremes, noise and machines operating at high speeds.

Ms. Eastman was not the only person studying the effects of unsafe conditions in an industrial environment. In fact, many other researchers were performing research of their own with documented cases dating back as early as 1556. In 1910, Dr. Alice Hamilton began to study the relationship between exposure to toxins and ill health and provided solutions to the problems she encountered. Dr. Hamilton, as some suggest, should be considered the founder of modern day industrial hygiene.

Years prior to Ms. Eastman's and Dr. Hamilton's research, Mr. Benjamin McCready published *On the Influence of Trades, Professions, and Occupations in the United States, in the Production of Disease*, which is considered the first work on occupational medicine published in the United States. All of the work by these early pioneers of industrial hygiene led to the creation of the United States Department of Labor in 1913 and the creation of the Occupational Safety and Health Administration (OSHA) in 1970. Furthering the work of these leaders, and using modern technology, we can begin to evaluate employee safety in ways never thought possible and help employers accomplish their health and safety goals.

Computational Fluid Dynamic 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 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).

One of the advanced uses of CFD modeling is in the design of emission capture hoods. Prior to using CFD models, several other methods were used. One particular set of calculations, often referred to as the Hemeon Method, considers the diameter of the hot source, the temperature of the source and the distance from the source to the hood to calculate a hood size and ventilation volume.[(2)] The advantage to this method is that an approximate hood volume could be found within a few hours. The disadvantage is that the method does not account for outside forces such as crosswinds or the effect of thermal currents inside the building nor can it quantify the capture efficiency of the hood. Another traditional method is the use of water models. The water models require a scaled down version of the facility, such as a melt shop, to be built from Plexiglas® or some other similar material. These models include all physical boundaries required to simulate the deflection of the plume as it moves from the source. The model is then filled with water to represent ambient air and a dye is inserted to simulate a plume rising from a source and either being captured by the emission control system or migrating through the shop. These models are useful for approximating the size of a canopy hood as the plume surge is visible inside the model. Computational Fluid Dynamic modeling has several advantages over these traditional methods. The first is that the time and money required to create a CFD model is far less than the time and money required to build a physical model. The second advantage is the ability to create a computer model to scale as opposed to scaling features down as with a physical model. Thirdly, various options can be run rather quickly as the time required to modify a CADD file is far less than the time required to modify a physical model. Fourthly, the output from the CFD model can be used to quantify capture efficiency as well as temperature, pressure and velocity gradients within the facility. CFD modeling can also depict how particles are moving and settling within the shop based on their size and density.

Identify Environmental Hazards

Particulate Matter

Particulate matter is typically classified one of three ways. The first, PM, groups all particulate matter into this one, generic category. Particulate matter less than 10 microns is classified as PM_{10} and particulate matter smaller than 2.5 microns is classified as $PM_{2.5}$. These smaller particles pose serious threats to humans because these are easily inhaled and will become trapped in the lungs and may even enter the bloodstream.

Particulate matter can be formed one of two ways. Large, coarse particles are formed during the mechanical break up of larger particles. These particles can come from mining operations, roads and mechanical fabrication. These large particles can be seen by the human eye. Other particles are formed during a chemical reaction, such as kish. Kish is produced in the iron and steel making industries when iron oxides are released and some of the carbon is precipitated. These particles are very small and cannot be seen by the human eye. Most, if not all manufacturing processes emit some sort of particulate matter.

Because of health concerns, OSHA has implemented exposure limits for particulate matter released internally (within a shop) during various manufacturing processes. A select list is shown in Table 1.(3)

Table 1 – Particulate Exposure Limits

Contaminant	Exposure Limit
Iron Oxides (fume)	10 mg/m^3
Lead	50 $\mu g/m^3$
Manganese Fume	15 mg/m^3
Kish	5 mg/m^3
Chromium IV Compounds	5 $\mu g/m^3$

Iron oxides, lead and manganese fume are released during various stages of the steel making cycle. The amount of lead and manganese released is highly dependent on the quality of scrap. Kish is formed during the casting of the blast furnace when the released iron oxide precipitates and forms graphite flakes. Chromium is present in stainless steel and different alloys and is converted to its hexavalent state, Cr(VI), during the welding process. This fume is highly toxic and can damage the eyes, nose and throat as well as cause cancer. The size of the particulate generated is of special concern. The size of the particle affects both their movement within a shop and their behavior in our respiratory system.(4)

Thermal Stress

Although a specific heat standard has not been adopted by OSHA, the National Institute for Occupational Safety and Health (NIOSH) has been providing recommendations to OSHA over the last 40 years. Heat stress occurs when the body's means of controlling internal temperature begins to fail. Three major factors influence the degree of thermal stress workers must endure with the most obvious being the climate in which the worker is performing their duties. The other two are work demands and clothing. The tradition for more than 40 years has been to describe thermal balance with an equation describing the heat exchange between the body and environment [4]. This equation is:

$$S = (M + W) + R + C + K + (C_{RESP} + E_{RESP}) + E \quad \textbf{(Equation 1)}$$

Where:

- S = heat storage rate
- M = metabolic rate (W/m^2)
- W = external work rate (W/m^2)
- R = radiant heat exchange (W/m^2)
- C = convective heat exchange rate (W/m^2)
- K = conductive heat exchange rate (W/m^2)
- C_{RESP} = rate of convective heat exchange by respiration (W/m^2)
- E_{RESP} = rate of evaporative heat loss by respiration (W/m^2)
- E = rate of evaporative heat loss (W/m^2)

As stated above, metabolic rate and clothing are major variables to consider when calculating thermal comfort of employees. Table 2 below lists metabolic rates for various activities.[5]

Table 2 – Metabolic Rates for Select Activities

Activity	Metabolic Rate (W/m^2)
Standing	70
Walking slowly	115
Walking moderately	150
Walking briskly	220
Lifting/packing	120
Pick and shovel work	235-280
Light machine work	115-140
Heavy machine work	235

Clothing is a very important factor to consider when calculating thermal comfort of employees. Typical work clothing in a melt shop requires long pants with a long sleeve shirt with potentially an aluminized (aka "silvers") hood, and jacket. Table 3 below represents the differences in clothing insulation values and is represented by the symbol "clo". [5]

Table 3 – Typical Clothing Insulation Values

Clothing	I_{cl} (clo)
Trousers w/short sleeve shirt	0.57
Trousers w/long sleeve shirt	0.61
Overalls, long pants, flannel shirt	1.37

As seen in Equation 1 above, many other factors along with climate, clothes and metabolic rate must be considered. Air movement within an area also plays an important factor when determining thermal stress. Using CFD simulation software, we can not only account for the climate in which the worker performs their duties, but also their metabolic rate and clothing factors.

Carbon Monoxide

Carbon monoxide (CO) is an odorless and colorless gas. Carbon monoxide cannot be seen and does not irritate any of the senses. The only way to detect carbon monoxide is by using detectors specifically designed to detect the gas. These are either seen as a small device worn by employees or as an area monitor located in an area known to release carbon monoxide. Carbon monoxide is produced by the incomplete combustion of carbon containing fuels, such as gas, coal, coke and oil. Any process using any of these fuels are potential sources of carbon monoxide.
Symptoms of carbon monoxide exposure include fatigue, dizziness and a headache. Table 4 illustrates the affects of carbon monoxide exposure.

Table 4 – Carbon Monoxide Exposure

35 ppm	Headache and dizziness after 6-8 hours of exposure
100 ppm	Slight headache within 2-3 hours of exposure
200 ppm	Headache within 2-3 hours of exposure
400 ppm	Frontal headache within 1-2 hours of exposure
800 ppm	Dizziness, nausea, and convulsions within 45 minutes. Insensible within two hours
1600 ppm	Headache, dizziness, and nausea within 20 minutes. Death in less than two hours
3200 ppm	Headache, dizziness and nausea in five to ten minutes. Death within 30 minutes
6400 ppm	Headache and dizziness in one to two minutes. Death in less than 20 minutes
12800 ppm	Death in less than three minutes

Predicting Environmental Hazards

Particulate Matter

Using simulation software, we can accurately predict the capture efficiency of the emission control system during all aspects of the iron producing/steel making cycle. Figure 1 below represents the model geometry for a typical dual electric arc furnace shop with one furnace charging and the other tapping.

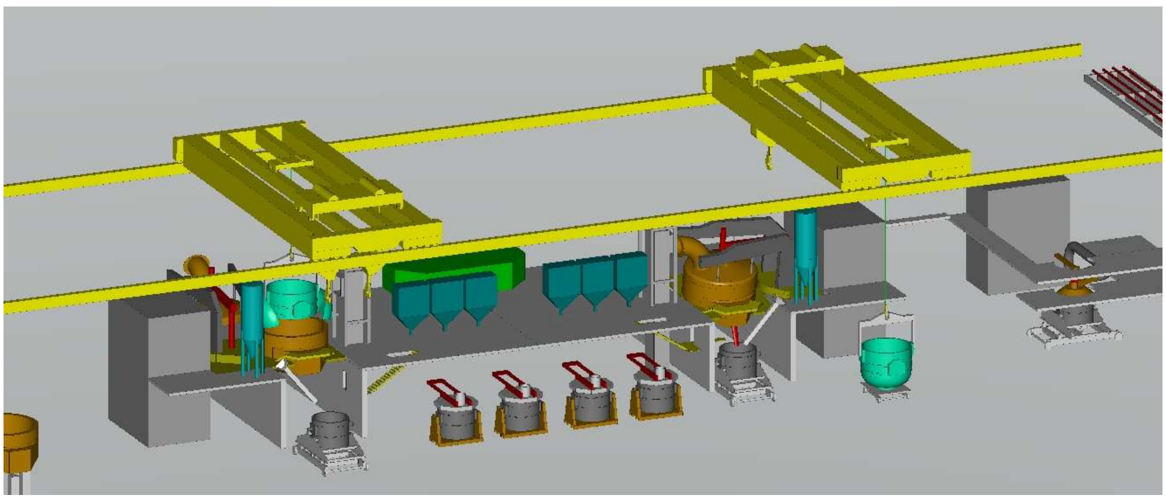

Figure 1 – Typical Dual Electric Arc Furnace Shop

For accurate results, the geometry should include all interior boundaries. This includes the physical boundary of the shop, furnace(s), interior sheeting, cranes and ventilation hoods. Special consideration must be given to ancillary equipment/processes such as ladle preheaters and casters. Ladle preheaters and casters are capable of generating large quantities of heat which may influence the movement of the plume and the total capture efficiency.

Once the geometry is created, boundary conditions are added to represent various process conditions. For example, the ventilation volume of the emission control system, the temperatures generated by miscellaneous equipment, cross winds and any openings to the atmosphere such as roof vents are conditions which must be considered. When the model is completed, the user can then accurately predict the capture efficiency of the emission control system and, with a large degree of certainty, predict the zone where other constituents such as lead, manganese and particulate will drop out within the shop.

Figure 2 below represents a 20 micron particle trace of metal dust generated during a scrap charge.

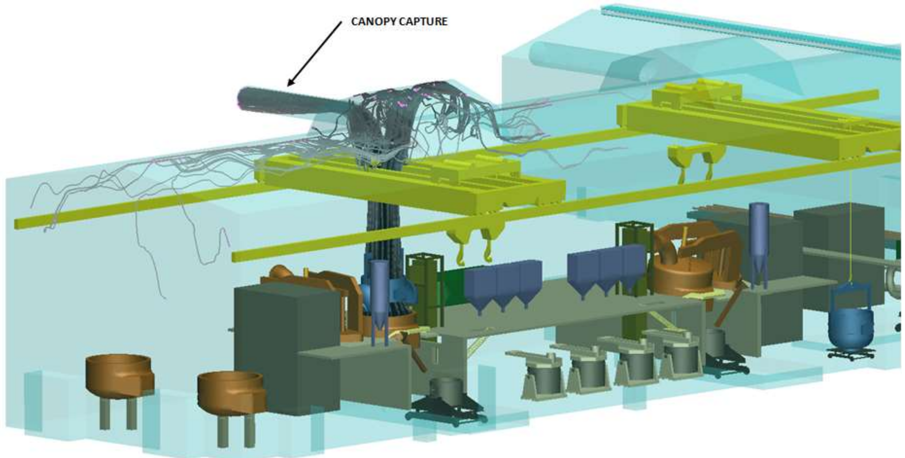

Figure 2 – 20 Micron Metal Dust Particle Trace – Looking East

In Figure 2 above, we see a large portion of the dust drafted by the emission control system. Using the software, we calculate a canopy hood capture efficiency of 78%. We also see particulate migrating away from the canopy and drifting in either direction in the shop. This particulate is out of the influence of the canopy and will from a haze at either end of the shop. It will eventually settle to the floor as the air cools.

Figures 3 and 4 below represent the same particle trace with the properties of lead assigned to the particle.

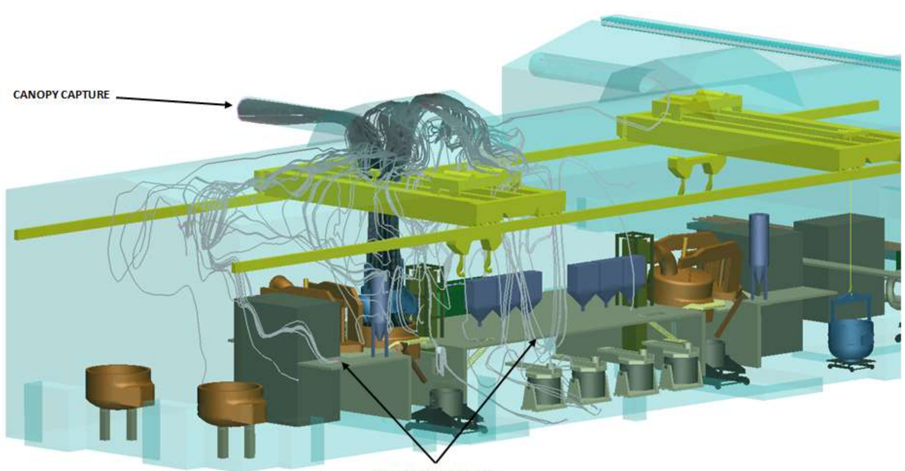

Figure 3 – 20 Micron Lead Particle Trace – Looking East

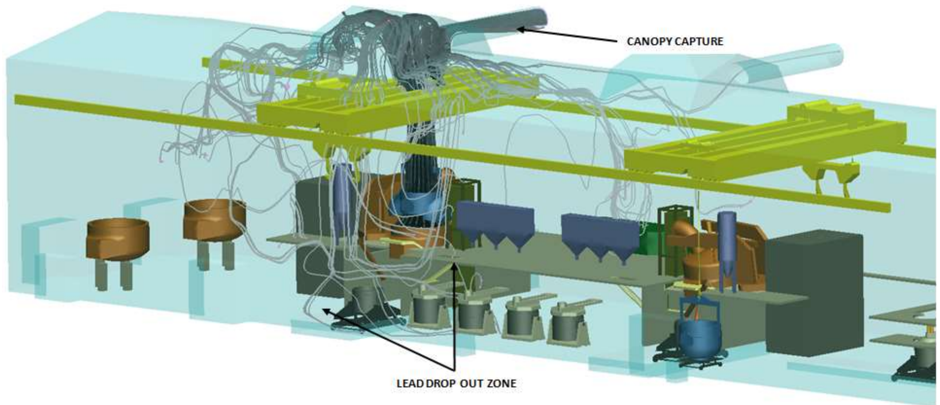

Figure 4 – 20 Micron Lead Particle Trace – Looking West

Comparing Figure 2 with Figures 3 and 4, we see that the metal dust remains suspended for a much longer period whereas the lead drops out around the furnace deck. This is due to the difference in density between the two materials. Using the simulation software, we can use this data to ensure that the workers in the lead drop out zone have the proper personal protection equipment. Secondly, we can use the model to develop methods to increase the capture efficiency to reduce the amount of lead and other particulate which migrate and settle within the shop.

One of the methods to increase capture efficiency is to add additional volume to the main canopy. Often, additional volume can be made available by evaluating the current damper configurations and setpoints. Another method is to remove heat sources from the shop. As stated above, ladle preheaters are a significant source of heat and may influence particulate away from the canopy. Venting these sources (if possible) may increase capture efficiency.

Figure 5 illustrates capture efficiency with an increased canopy volume of 15% and assumes that the ladle preheaters are vented to the outside. The model calculates an increased capture efficiency of 85%. We also see that with the ladle preheaters vented to the outside, the particulate does not migrate as far away from the canopy as in Figure 2 above.

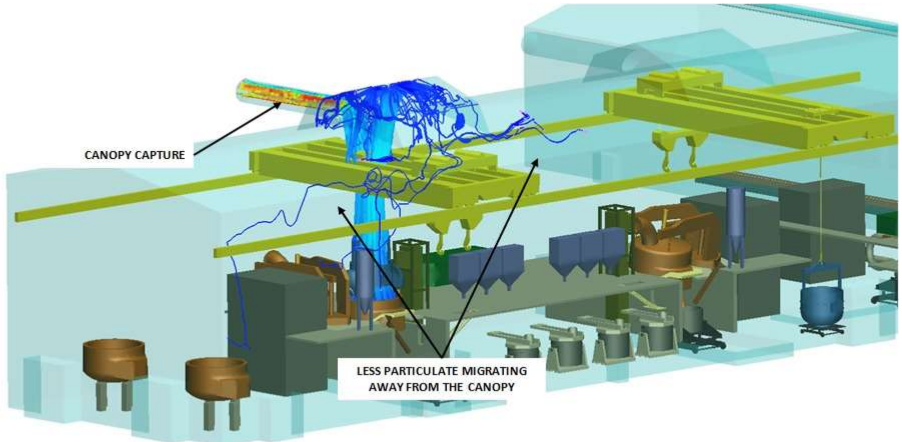

Figure 5 – Revised 20 Micron Metal Dust Particle Trace – Looking East

Figure 6 below shows the same particle trace as in Figure 5 but with the properties of lead assigned to the particles.

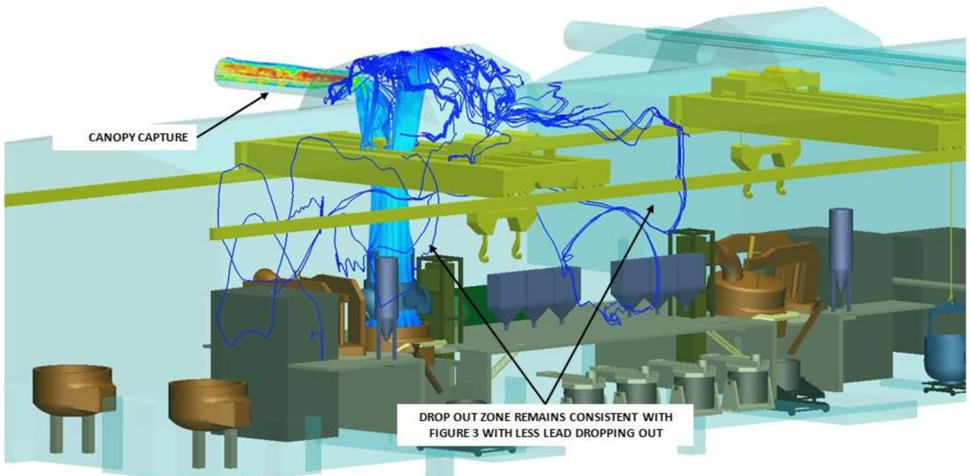

Figure 6 – Revised 20 Micron Lead Particle Trace – Looking East

Comparing these two scenarios, we see that increasing the volume by 15% increases the canopy capture efficiency from 78% to 85%.

Using CFD simulation software, we can predict the current capture efficiency of the emission control system. Alternate scenarios can also be run to make the most effective use of the existing system. Should additional controls be required, CFD can "right size" the volume and controls providing cost savings to the project. The above examples demonstrate these capabilities and are one of the many strengths of CFD simulation.

Thermal Stress

Looking at the model created for the electric arc furnace shop, we can place “workers” at various locations, in this case near the caster, to determine the amount of thermal stress on the workers as shown in Figures 7 and 8 below.

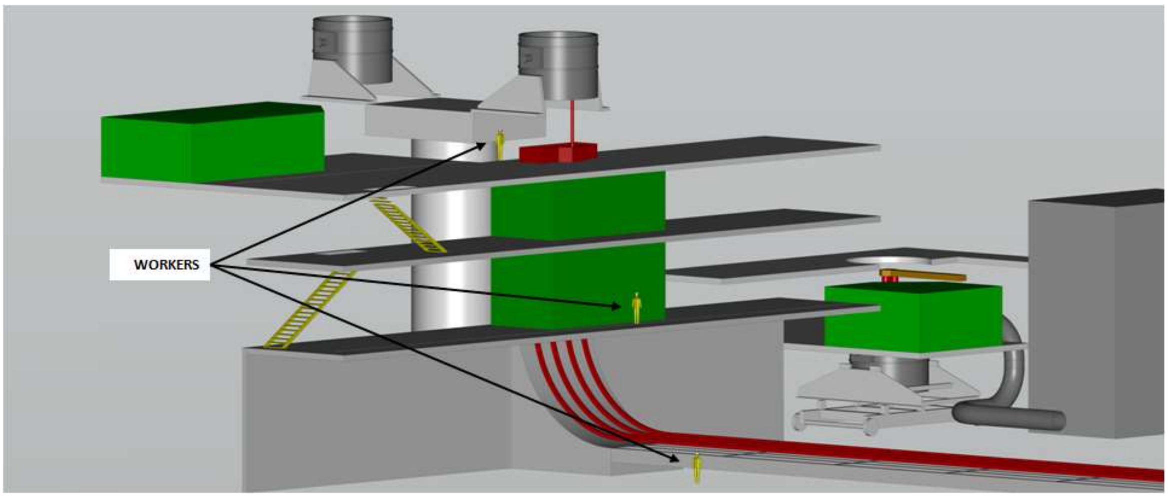

Figure 7 – Workers at the Caster

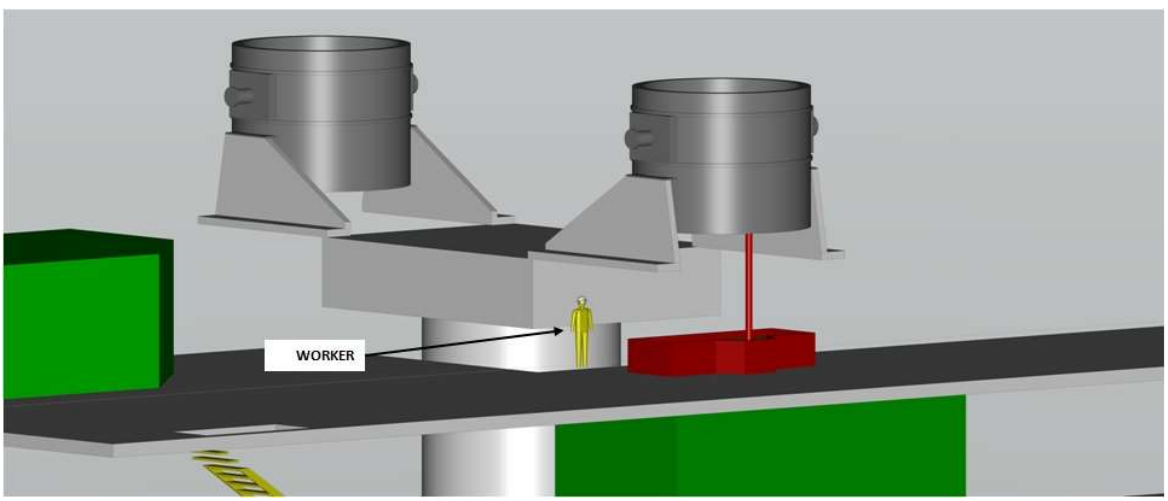

Figure 8 – Worker on the Tundish Deck

The model boundary conditions are set including the worker’s metabolic rate and clothing insulation factor. In this example, a metabolic rate of 120 is assigned to represent typical duties at the caster. A clothing factor of 1.37 has been assigned to represent the worker in full fire retardant clothing.

The heat stress of the worker is evaluated using the Predictive Mean Vote (PMV). The PMV refers to a thermal scale running from cold (-3) to hot (+3) originally developed by Ole Fanger. [(5)] This scale is shown in Table 4 below.

Table 5 – Thermal Scale

PMV Value	Sensation
-3	Cold
-2	Cool
-1	Slightly Cool
0	Neutral
1	Slightly Warm
2	Warm
3	Hot

It is important to note that the PMV is very subjective and is an average response from a large group of people. Because the PMV is subjective, there will be a distribution of satisfaction among the sample group. Figure 9 below represents this distribution[5].

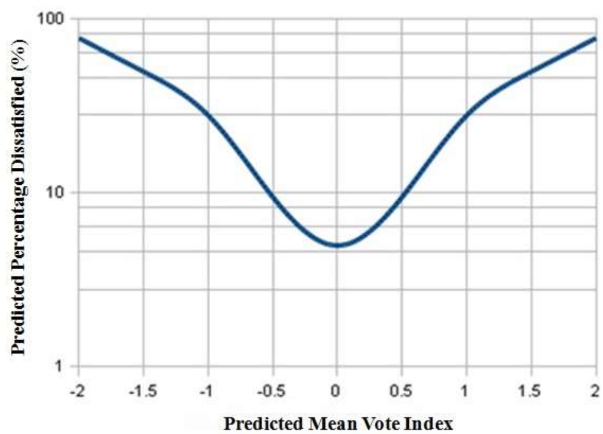

Figure 9 – Predicted Percentage Dissatisfied (PPD)

No single environment is judged satisfactory by everybody, even if they are wearing identical clothing and performing identical functions.

Evaluating the heat stress in the workers with red indicating “hot” (+3), we see that the worker nearest to the tundish is under the most thermal stress (completely “red”) as seen in Figure 10 below. The worker at grade level, as seen in Figure 11, shows the front of the worker (the side facing the product) as “red” indicating the front portion of the body is hot while the legs and the back are “orange” representing a warm sensation.

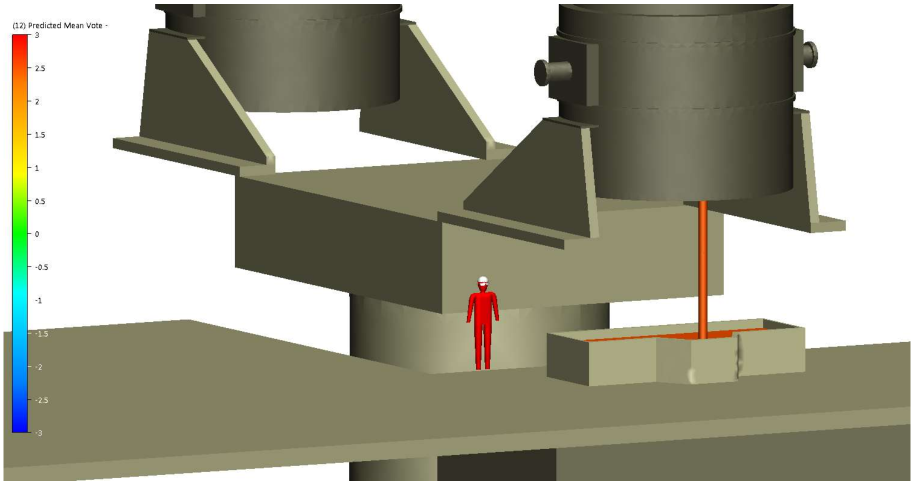

Figure 10 – Tundish Worker Thermal Stress

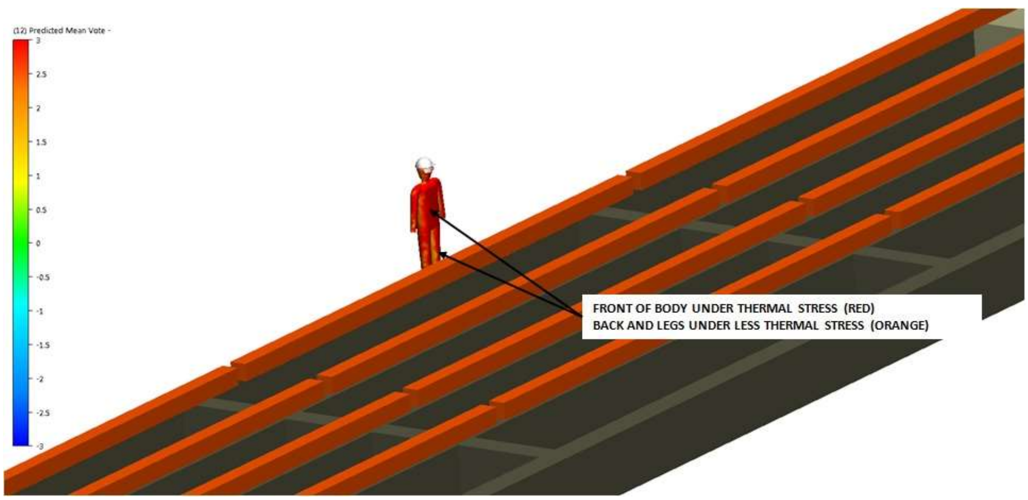

Figure 11 – Worker Thermal Stress

As demonstrated with the capture efficiency above, we can use CFD simulation software to develop a strategy to alleviate the thermal stress on the workers. As anyone who has worked near a caster knows, the environment is extremely hot and humid and maintaining even slightly comfortable conditions can be difficult at best. Examining the model results, we can look for ways to reduce the temperature at the caster.

Figure 12 below is a temperature profile at the caster centerline. In this profile, we see elevated temperatures above the tundish, turning zone and the straightener. The temperature begins to decrease as the product moves towards the storage yard.

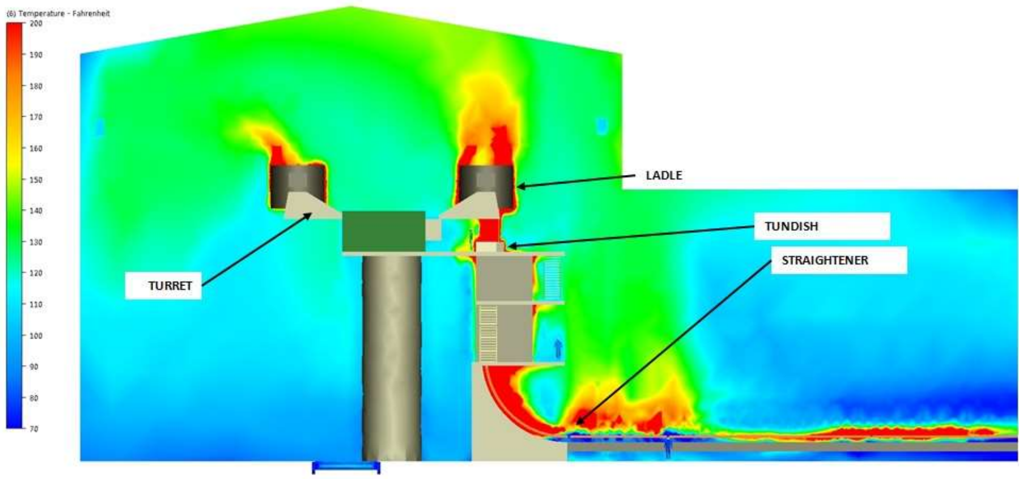

Figure 12 – Temperature Profile

As stated above, air movement plays an important role in worker comfort. In this example, a floor fan was added to the tundish deck. The fan was positioned so that it can remain stationary and out of the way of normal activities at the caster, such as changing the tundish. Figure 13 below illustrates the addition of the floor fan along with the thermal stress on the worker (some details removed for clarity).

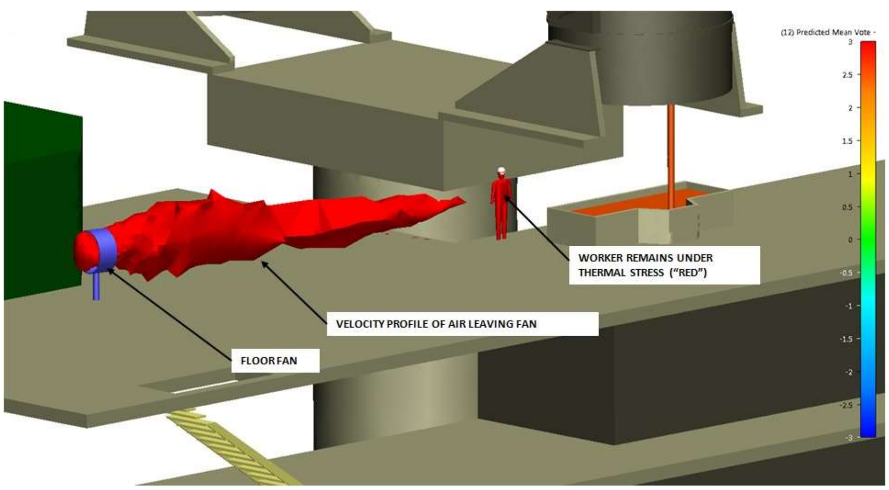

Figure 13 – Floor Fan

We see that the worker is still red (+3) indicating that they are still under thermal stress. This is because the fan is not cooling the air as it exits towards the worker. The fan is merely forcing already hot air towards the worker and, considering the workers clothing insulation, provides minimal thermal comfort.

In this case, to lessen the temperature at the caster, the entire building needs to be evaluated. The temperature profile in Figure 12 above shows that the heat is accumulating above the tundish deck and needs additional means to exit the building. We also learned that a floor fan would not provide relief and need to consider another method. The following example adds gravity vents above the caster turning zone, straightener and run out, cooling air duct on the tundish deck and a ventilation hood above the turret. Figure 14 below illustrates the results of incorporating these changes.

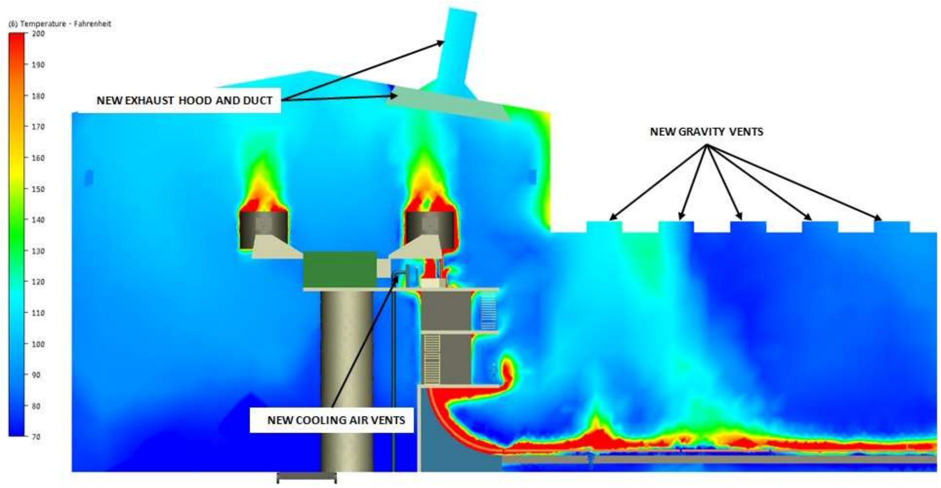

Figure 14 – Revised Temperature Profile

Comparing Figure 14 to Figure 12, we can see a change in the temperature profile along the caster. In Figure 12, we see that the air temperature above the straightener and turret reaches approximately 140 deg F. In Figure 14, we see that the temperature in the same areas reaches approximately 120 deg F. Taking a closer look at the worker on the tundish deck, we see that the cooling air vents are providing some comfort as seen in Figure 15 below. The front of the worker is still red while the worker's back is green indicating a neutral sensation.

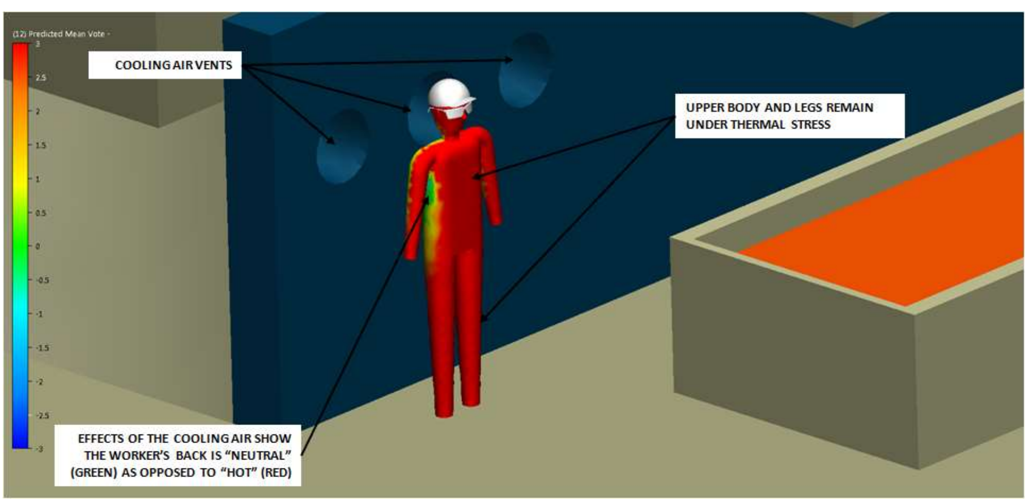

Figure 15 – Revised Tundish Worker Thermal Stress

Comparing Figure 16 below to Figure 11 above, we see that the worker at grade level has also experienced relief from thermal stress. The worker's upper body is still red indicating this section of the body is hot while the legs and back are orange indicating the worker is warm in these areas.

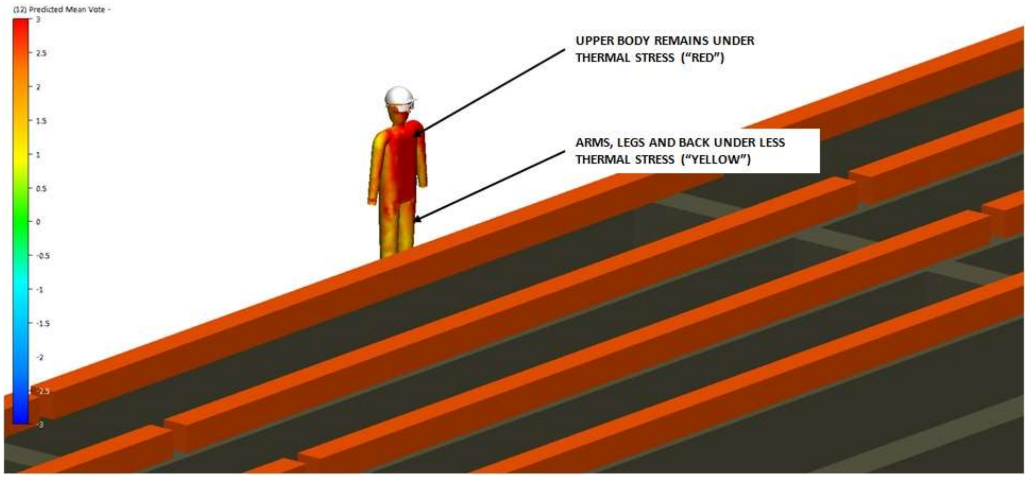

Figure 16 – Revised Worker Thermal Stress

Although OSHA does not have a specific standard that covers working in hot environments, under the OSH Act, employers have a duty to protect workers from recognized serious hazards in the workplace, including heat related hazards. (6) Using the simulation software, we can determine the level of thermal stress on workers and design ways to reduce the temperature in the workplace.

Carbon Monoxide

As stated above, carbon monoxide is formed from the incomplete combustion of carbon fuels. In an electric arc furnace melt shop, the carbon monoxide is formed when oxygen is injected into the molten metal bath. Oxygen injection rates vary but start at approximately 300 scfm. The carbon in the molten bath reacts with the oxygen and forms carbon monoxide and carbon dioxide. If these gases are not properly evacuated, excess carbon monoxide will either escape the furnace into the surrounding atmosphere or, if the concentration is high enough, cause an explosion.

Setting up the model, we assign a scaler of 0 at the inlets to represent the air entering the building. Inside the furnace, we assign a scaler of 1 to represent the carbon monoxide entering the melt shop from the furnace. One must understand that the diffusion will vary with temperature and pressure and therefore this should be considered when setting the boundary conditions. The standard density of air is 0.075 lb/cf and the standard density of carbon monoxide is 0.071 lb/cf. The approximate gas temperature from the furnace is approximately 1500 deg F, therefore the density of carbon monoxide is 0.019 lb/cf. The easiest way to handle this is to assign variable air to the domain and modify the density as a function of scaler. This is shown in Figure 17.

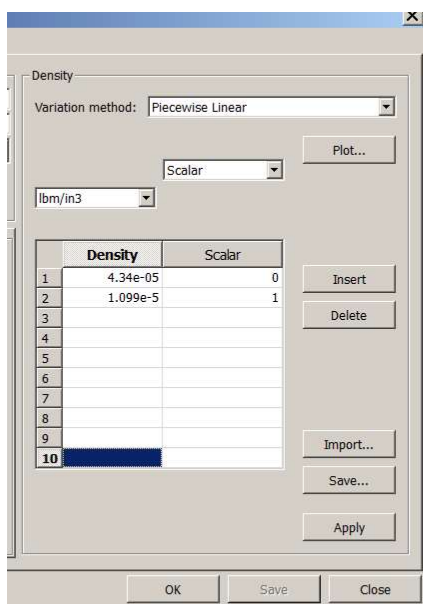

Figure 17 – Density Variation

Furthermore, the correct diffusion coefficient must also be entered with the scaler boundary condition. Little information was found pertaining to diffusion coefficients at this elevated temperature therefore known diffusion coefficients at known temperatures were plotted and extrapolated out to 1500 deg F.

As seen in Figure 18, a large portion of the carbon monoxide is evacuated by the emission control system. However, as seen in Figure 19 and changing the legend, we can see that some carbon monoxide has escaped and is now in the upper levels of the melt shop. Performing a mass and energy balance, we can calculate a concentration of approximately 6000 ppm inside the furnace. Looking at the results in Figure 19, we see that the concentration near the furnace will be upwards of 100 ppm. At these concentrations, any employee working in the upper levels of the melt shop, such as performing maintenance on the overhead crane, should take the necessary precautions to avoid over exposure to carbon monoxide.

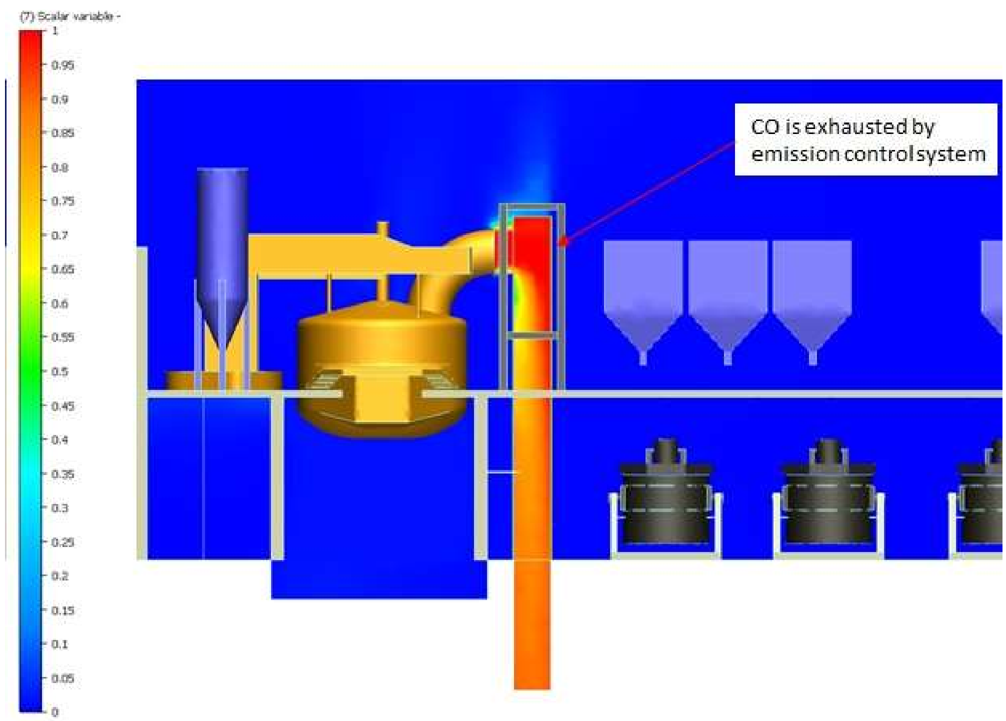

Figure 18 – Carbon Monoxide Evacuated by Emission Control System

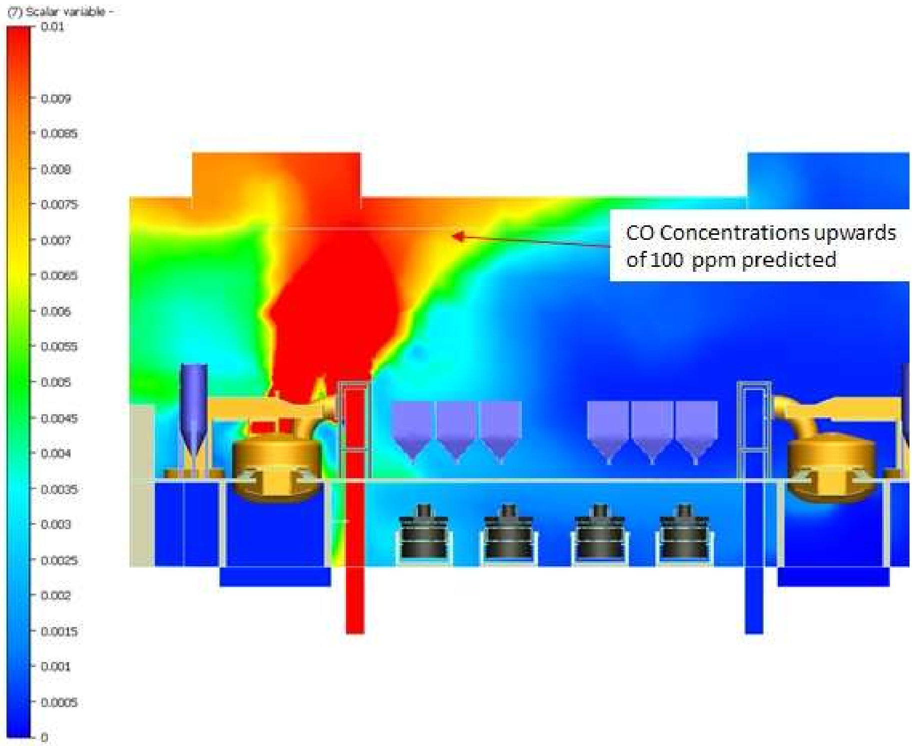

Figure 19 – Carbon Monoxide Accumulating Inside Melt Shop

Additionally, as seen in Figure 19, we see the influence of the ladle preheaters and how the temperature of these preheaters can influence gas and particulate inside the melt shop. The internal temperature of a ladle preheater is upwards of 1800 deg F. These and other high temperature sources must be considered when performing an analysis of this type.

Conclusion

Computational Fluid Dynamic (CFD) Modeling has been an effective tool to assist in the design of emission control systems for well over a decade. As seen in the examples presented above, CFD modeling was used to predict the capture efficiency of the emission control system, drop out zones for hazardous pollutants, thermal stress on workers and the concentration of carbon monoxide within the melt shop. CFD was also used to run "what if' scenarios to determine the best achievable results within the confines of the existing system parameters.

CFD was also used to predict the carbon monoxide concentration and thermal comfort of the workers. Ms. Eastman showed in her research that the environment in which employees performed their duties contributed to the frequency of accidents. Among the several environments studied, temperature extremes and exposure to gases were among the pre-conditions for accidents. The case cited in this paper showed that all workers were under thermal stress while performing their duties. CFD was used to run "what if" scenarios to determine the best way to relieve the thermal stress of the workers. The simulations showed that adding fans to the tundish deck would not by themselves provide the necessary cooling for the worker. CFD showed that adding cooling air near the tundish and providing additional ventilation above both the tundish and the caster run out would alleviate thermal stress for the workers.

Coupling CFD with experienced process engineers can be used to provide better indoor air quality and a safer work environment.

Thank you for attending my class. I trust that everyone has met their objectives and understands how to identify certain hazards and how to mitigate these hazards.

My contact information is as follows:

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