CFD AS A TOOL TO DESIGN EFFICIENT DEDUSTING SYSTEMS FOR STEEL-MAKING PLANTS

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ABSTRACT
The capital and operation cost for dedusting systems in steel industry is quite high and simple empirical formulas commonly used for the design of dedusting system give poor agreement with measurements. Some examples of deducting system design with CFD and the effectiveness of the method are examined.

The behaviour of gas and dust emitted from converter is numerically analysed to predict the dust particle trajectory and the capture efficiency of hoods. The numerical calculation shows that the modification of present hoods, addition of two side hoods or increases in air flow rate make the dust capture performance better.

It is confirmed that CFD is an excellent alternative for the design and improvement of large deducting systems and the implementation of new design for a deducting system at Kwangyang Works drastically reduces the number of visible dust emission from the plant roof.

NOMENCLATURE

$A_c$ area of rising column of air at the hood face
$A_f$ total area of hood face
$A_s$ area of hot surface source
$C$ constants
$D_c$ diameter of hot column of air
$D_h$ diameter of hood
$D_s$ diameter of hot surface source
$E$ total energy
$F_t$ external body force
$G_b$ generation of turbulent kinetic energy due to buoyancy
$G_k$ generation of turbulent kinetic energy due to the mean velocity gradient
$g_i$ gravitational acceleration
$k$ turbulent kinetic energy
$k_{eff}$ effective conductivity
$p$ pressure
$S_h$ volumetric heat source
$S_m$ mass source
$t$ time
$T$ temperature
$u_i$ velocity
$u_p$ particle velocity
$V_t$ volume flow rate of air through the hood
$v_j$ velocity of the hot air jet at the level of hood face
$v_r$ required velocity through the remaining area of the hood
$x_f$ distance from the point source to the hood face
$x_i$ independent variable in Cartesian coordinate system
$y$ distance from the hot surface source to the hood face
$z$ distance from the hypothetical point source to the hot surface source

$\Delta T$ temperature difference between hot surface source and ambient air
$\epsilon$ turbulent rate of dissipation
$\rho$ density
$\mu$ dynamic viscosity
$\mu_t$ turbulent viscosity
$\sigma$ turbulent Prandtl numbers
$\tau_{ij}$ shear stress

INTRODUCTION
It is essential to install dedusting facilities in iron and steel making process where variety of and lots of dust are generated. Installation of dedusting system makes the working environment clean and improves productivity.

Steel making process with converter is done by the following order, scrap charging, pig iron charging, oxygen blowing, steel discharging, and slag discharging. The amount of dust emitted from converter is maximized during pig iron charging. Common dedusting system is composed of hoods, ducts, fan, dedustor, and a stack.

Most of dust generated from source are captured into hoods, transported by air to dedustor through ducts, and separated from air and stored in storage silo. The rest of the dust not captured into hoods moves up to monitor at the top of the plant building, and finally it causes visible dust emission to environment. Dust emission from ladle after charging and slopping are two additional reasons of visible dust emission.

It has been common to use simple empirical formulas introduced by considering natural convection on heated plate for the design of dust removal system at steel-making plants with electric arc furnace or converter (Hemeon, 1955 and Sutton, 1950) and the method is well summarized in a handbook (Fogiel, 1978) but it gives poor agreement with measurements. Most of the errors are due to the neglect of characteristics of dust, geometry and flow condition around dust source. Use of Computational Fluid Dynamics for the design of deducting system covers this weakness of conventional hood design method so that it improves accuracy of design. The behaviour of fluid in plant building and gas emitted from converter is numerically analysed to obtain velocity, pressure, and temperature distribution. It also makes the visualization of gas and dust behaviour and quantitative prediction of capture efficiency of dust particles possible. The capture efficiency of dust to hoods depends on the configuration of hoods and airflow rates. The capture efficiency is generally higher at higher airflow rate and at shorter distance of hood from dust source. Optimization of deducting system can be accomplished by making the capture efficiency maximum at lowest airflow rate. The
capital cost as well as the operation cost for dedusting systems in steel industry is so high that proper design and economical operation of dedusting system are very important.

Two examples of dedusting system remodelling with CFD for steel making plants in Pohang and Kwangyang Works of POSCO and the effectiveness of optimum design with CFD are discussed.

**THEORY**

Design method and differences between conventional hood design and hood design with CFD are briefly explained and compared in this section. In conventional hood design, several simple empirical formulas introduced by considering natural convection on heated plate are used so that it takes little time but conventional hood design gives less accurate result. On the other hand, in hood design with CFD, velocity, pressure, temperature distributions in the plant building including characteristics of dust, geometry and flow condition around dust source are considered so that it takes much time and it gives quite accurate result. CFD result visualizes the behaviour of gas and dust particles and quantifies the capture efficiency of dust particle.

**Conventional Hood Design**

As the heated air stream rising from a hot surface moves upward, it mixes turbulently with the surrounding air. The geometry of hot source and hood are shown in Figure 1 (Fogiel, 1978).

![Figure 1: Geometry of hot source and hood.](image)

The higher the air column rises, the larger the area of hot air becomes and the more diluted with ambient air. Sutton (1950) investigated the turbulent mixing of a rising column of hot air above a heat source. Hemeon (1955) applied Sutton’s result to the design of hood and suggested the following four equations to calculate the diameter of air column at the level of hood face, the diameter of hood, the velocity of air column at the level of hood face, the total volume flow rate of air entering the hood.

\[
D_c = 0.434y^{0.08}
\]

\[
D_f = D_c + 0.8y
\]

\[
\nu_c = 0.08 \frac{A_{12} \Delta T y^{12}}{x_c^{14}}
\]

\[
V_c = \nu_c A_f + \nu_c (A_f - A_p)
\]

, where the distance between hot source and hypothetical point source is given by a following equation.

\[
z = 2.356D_c^{1.136}
\]

**Hood Design with CFD**

Use of CFD for the design of dedusting system covers weakness of conventional hood design method by considering the velocity, pressure, temperature distribution of gas and the motion of dust particle in the plant building. The behaviour of gas and dust particle can be visualized and the performance of dedusting system can also be estimated quantitatively by capture efficiency. Figure 2 shows the general procedure of dedusting system design with CFD. Upper half of the figure shows how to decide optimum hood geometry and air flow rate and lower half shows how to decide the shape and size of the duct network of the dedusting system. This study is confined to the decision of hood location, hood size, and flow rate of air entering hoods.

![Figure 2: Procedure of dedusting system design with CFD.](image)

The distributions of velocity, pressure, temperature, and the trajectory of dust particles at a set of given geometry and conditions can be calculated by CFD. Typical governing equations are a continuity equation, Navier-Stoke equations, turbulence equations, an energy equation, and an equation of motion for particles and are listed below. (Fluent Manual, 1998) These governing equations and boundary conditions are discretized into several simultaneous linear equations and solved iteratively to finally find the distributions of flow variables. The vector field of velocity, distributions of pressure and temperature, and trajectory of particles can be visualized with calculated flow variables. The capture efficiency for a given hood configuration and a given air flow rate can be calculated with the quantitative fate of dust particles.
\[ \frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) + \frac{G_i}{\rho} - \rho \varepsilon \]

\[ \frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu}{\sigma_f} \right) \frac{\partial k}{\partial x_j} + \frac{G_k}{\rho} + G_{\rho} - \rho \varepsilon \frac{\varepsilon}{k} \]

\[ \frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = - \frac{\partial}{\partial x_j} \left( k_{\varepsilon} \frac{\partial \varepsilon}{\partial x_j} + \frac{\varepsilon}{c_{\rho}} (\rho_{\rho} - \rho) \right) + S_{\varepsilon} \]

\[ \frac{dt}{dt} = F_{\rho}(u - u_{\rho}) + g_{\rho}(\rho_{\rho} - \rho) / \rho_{\rho} + F_i \]

A commercial CFD code, called Fluent, has been used to get a series of solutions and post-processing of the solutions.

**MODEL DESCRIPTION**

In the beginning stage of this study, the general behaviour of gas dust in plant buildings and current problems of the plant are broadly examined. Before stepping into numerical simulation, several input parameters and boundary conditions are collected by direct measurement and sampling at the field and from property tables. Capture efficiency at a given hood configuration and airflow rate can be calculated with the result of numerical simulation. Comparisons of capture efficiencies calculated at several different hood configurations and airflow rates by trial and error lead to the optimization of dedusting system.

**General Behaviour of Gas and Dust in Plant Buildings**

The amount of dust emitted from converter is maximized during pig iron charging so that the hood system is designed on the basis of this pig iron charging. The behaviour of hot air column and dust emitted from converter before improvement is schematically described in the Figure 3.

**RESULTS**

By comparison between the trajectory of dust particles and capture efficiencies before and after improvement, the optimum geometry of hoods and airflow rates of each hood is suggested for improvement of dedusting system and the effectiveness of this improvement after installation is examined.

**Input Parameters for CFD**

The geometry of real plant building is so complex that it is impossible to analyze as it is. The geometry used in this analysis is simplified as much as possible until it does not give distinctive difference. The following two figures show three-dimensional geometry of steel making plants created by CAD program.

![Figure 3: Behaviour of hot air and dust during pig iron charging before improvement.](image)

![Figure 4: Geometry of plant created by CAD program.](image)
The number of volume elements in the domain is about 2 million or less. It takes less than 5 day to get a converged steady state solution using 1 CPU in Compaq ES45 server. The size distribution and density of dust particles give quite influence to the trajectory of dust particles so that the dust captured through canopy hood to a bag filter is sampled and analysed with particle size analyser and pycnometer. The size distribution and SEM photo of the dust are shown in Figure 5.

![Size分布图](image1)

**Figure 5**: Size distributions and SEM photos of dust captured through canopy hoods to bag filters.

The size of the dust is relatively fine and the shape of the dust is mostly spherical. The true density and average diameter of dust captured at canopy hood are 3.33 g/cm$^3$ and 15.5 µm for No.2 steel making plant at Kwangyang Works and 2.6 g/cm$^3$ and 15.6 µm for No.2 steel making plant at Pohang Works. A Rosin–Rammler form of equations for the size distribution of dust is used for the simulation. The temperature of air in thermal plume ranges from about 10 °C to over 1,000°C so that the density difference is too high to neglect the effect of temperature. Piecewise linear properties of air, such as, density, specific heat, viscosity, and thermal conductivity for the range from 0 °C to 2,500°C are used to consider the temperature dependency of the flow. (Lindon, 1992)

**Governing Equations and Boundary Conditions**

Equations used to study the behaviour of thermal plume and dust are continuity equation for mass conservation of air, Navier-Stokes equation for momentum conservation of air, energy equation for energy conservation of air, and equation of motion for momentum conservation of dust particles. Two more equations for the turbulence of air flow are $k$ equation and $\varepsilon$ equation because the size of plant building is quite large but the flow pattern is relative simple and this standard $k$-$\varepsilon$ turbulence model is relatively simple, gives reasonable solution for this kind of flow, and has good convergence characteristics.

Boundary conditions for Navier-Stokes equations are no slip condition at walls, pressure inlet or pressure outlet condition at windows, doors, and monitors, velocity inlets at the entrance of hoods. Boundary conditions for energy equation are zero heat flux at building walls, constant temperature at some heated surface, for example, the external surface of ladle and converter. A stream of molten pig iron flowed out of the ladle collides to the surface of molten pig iron in the converter. Agitation and wave on the surface of molten iron cause not only violent heat exchange between air and molten iron and slag but also chemical reaction between air and molten iron and slag. The phenomenon above the converter is too complex to include in this engineering analysis and the major parameters to decide the geometry of hood and suction flow rate are velocity and temperature of thermal plume above converter. It is also very difficult to measure the condition on surface of molten iron and slag. As an alternative way, the boundary conditions on the surface of molten iron and slag in the converter is simplified by using direct measurement of temperature and velocity at a reference point above converter and determination of boundary conditions by numerical trial and error method. The first step is to measure the temperature and velocity of thermal plume at a specified location above converter. The second step is to calculate the temperature and velocity of thermal plume at an above specified location by numerical simulation with a trial thermal boundary condition on the surface. Third step is to compare the measured and calculated temperature and velocity of thermal plume at a specified location. The last step is to decide the thermal boundary condition on the surface of molten iron and converter by trial and error until the measured and calculated value at a specified location shows negligible difference.

The thermal boundary condition of No.2 steel-making plant in Kwangyang Works decided by above method is that the temperature and velocity at the elliptic surface of molten iron in the converter is 827°C and 4.3 m/s. The
The total airflow rate at the duct of canopy hoods is measured to be 11,880 m$^3$/min and is 11% lower than the design flow rate 13,340 m$^3$/min.

The thermal boundary condition of No.2 steel-making plant in Pohang Works decided by the same method is that the temperature and velocity at the bottom circle of the converter is 2,227°C and 7.5 m/s. The total airflow rate at the duct of canopy hoods is measured to be 13,912 m$^3$/min and is about 7% lower than the design flow rate 15,000 m$^3$/min.

**Solutions for Present State of No.2 Steel-Making Plant in Kwangyang Works**

The velocity distribution of hot air and trajectory of dust particles for the present state before improvement are shown in Figure 6. Hot air discharged from converter #1 moves upward and part of the hot air is captured to the charging and canopy hood. The hot air not captured to the hood rises up to the roof and finally passes through the monitor at the top of the plant building. The figure also shows that many of dust particles carried by hot air also pass through both left and right part of the monitor. The capture efficiency of this case is 68.5% that is relatively low and this causes frequent visible dust emission.

**Numerical Simulation for Improved States of No.2 Steel-Making Plant in Kwangyang Works**

Seven cases with different hood configurations and at different airflow rates are examined for improvement and are summarized in the following Figure 7.

When the airflow rate is increased up to design airflow rate 30,000 m$^3$/min for the present hood configuration (light blue square in the figure), the capture efficiency is increased to 80.2% that is higher than that of present state. When some colour sheets are installed to prevent dust penetration to the monitor, interception plates are installed to prevent dust run over, side hoods are installed, three piece hood is changed to one piece hood which is five meters taller than present hood (orange triangle in the figure), and airflow rates are further increased, the capture efficiencies of these cases are increased as shown in Figure 7. When new hood configuration is used without airflow rate increase, the capture efficiency is increased to 90.4%. As the airflow rate is further increased up to 36,000 m$^3$/min, the capture efficiency is also increased up to 97.8% and this improvement is good enough. After the discussion on this improvement with operators, it was found that the installation of this improvement would be interfered by the present valve station because of the tall height of the hood. The final alternative is to use the present canopy hoods as it is but to add two side hoods (bright green circle in the figure) and to increases the flow rates up to 37,660 m$^3$/min as shown in Figure 8. The capture efficiency is 94.3% that is not so high even at the highest airflow rate. Even if this case does not shown highest capture efficiency, it is the only practical countermeasure among the cases considered above and is still good enough to prevent visible dust emission. It is noticeable from the two figures that show the trajectories of dust particles before and after improvement that the number of dust particles emitted through the monitor is drastically decreased.
Effectiveness of Improvement for No.2 Steel-Making Plant in Kwangyang Works

When this new design is compared with previous design done before this study, airflow rate of 3,000 m³/min is reduced and this saves 1.5 million dollars of investment and one hundred thousand dollars per year of operating cost. After the implementation of this countermeasure, the amount of dust captured at the bag filter is increased from 25 to 30 tons per day and it is about 20% increase. The monthly number of visible dust emission through monitor is also reduced from average of 70 to 3. The concentration of dust around the level of crane decreased so that the operation of crane becomes easier and finally the productivity is increased.

Solutions for Present State of No.2 Steel-Making Plant in Pohang Works

The trajectory of dust particles for the present state before improvement is shown in the following Figure 9. This figure shows that large amounts of dust particles are captured by direct and charging hoods and the rest large amounts of dust particles still pass through the monitor. The capture efficiency of this case is 68.5 % that is also relatively low and this causes visible dust emission.

Numerical Simulation for Improved States of No.2 Steel-Making Plant in Pohang Works

Five cases with different hood configurations and at different airflow rates are examined for improvement and are summarized in the following Figure 10. When the airflow rate is increased to 25,000 m³/min and large canopy hood is used (pink square in the figure), the capture efficiency is increased to 90 % that is much higher than that of present state. As hoods above pouring pit are added and airflow rate is increased to 40,000 m³/min (beige circle in the figure), the capture efficiency is increased to 93.2 %. When one side hood is added beside the canopy hood without airflow rate increase (light purple rhombus in the figure), the capture efficiency is increased to 95.1 %. The capture efficiency of the dedusting system by changing large canopy hoods to extra large canopy hoods is increased to 96.5 % (green triangle in the figure), and this is the case selected as a final countermeasure for improvement.

The trajectory of dust particles for this case is shown in the following Figure 11. This figure also shows that most of dust particles are captured by direct, charging, and canopy hoods and only small amounts of dust particles are discharged to the environment through the monitor. This small amounts of dust particles discharged through monitor may rarely cause visible dust emission.
Effectiveness of Improvement for No.2 Steel-Making Plant in Pohang Works

The implementation of this improvement had been finished early December 2004 and measurements for the quantitative estimation of improvement are under way. On other hand, it is confirmed by sight that the visibility range is much longer than before and the air in the plant building looks clean.

CONCLUSION

Method of design with CFD instead of conventional design method has been used to decide adequate hood configuration and airflow rate for a dedusting system at steel making plant with converter. This method visualizes the behaviour of gas and dust particles as well as quantifies the capture efficiency of a dedusting system. The implementation of the countermeasures suggested by this design method leads to the reduction of investment and operating cost. It is also confirmed that the number of visible dust emission is reduced and working area is maintained cleaner after implementation of improvement.

REFERENCES


