Numerical evaluation of the performances of the ventilation system in a blast furnace casthouse

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Abstract
The blast furnace casthouse is a typical heavy-polluting factory building of a steel enterprise. During the tapping process and the taphole opening, the dust concentration in the factory building’s workroom can reach tens of thousands mg/m\(^3\). Over time, the air pollutants in the workplace can have unwanted consequences on employees’ health. This paper selected a typical blast furnace tapping workshop. The flow, temperature, and soot concentration fields in the workshop are measured on site during tapping, and the distribution characteristics are obtained. The performance of the tapping smoke exhaust system is analyzed based on computational fluid dynamics. The findings are as follows: the concentration of PM2.5 in most of the work area was 80 \(\mu\)g/m\(^3\), but the concentration reached 1mg/m\(^3\) near the slag ditch, which was heavy pollution. Because the opening and closing of doors and windows was unreasonable, it was difficult for the particulate matter to accumulate in the deep and middle of the plant discharge. The PMV of the worker’s work area is about 3, and the waste heat removal efficiency is 4.2. Hence, this article’s finding provides a scientific basis for optimizing the air distribution in the blast furnace cast house’s workplace.

Keywords Blast furnace cast house · Dust · Concentration distribution · Field test · Numerical simulation · Industrial ventilation

Introduction
China is now the top steel producer globally (Tang et al. 2020). The iron and steel industry is a major air pollutant emitter and has become China’s largest industrial PM emission source (Wang et al. 2019). In order to deal with air pollution, iron and steel companies must improve flue gas management. Besides, the steel plant is a high temperature and dusty plant, and steelworkers are particularly prone to occupational health problems. Biswas et al. (2014) found that 91.66% of 213 workers may have bronchial asthma and 88.75% of chronic bronchitis after long-term exposure. Excessive heat exposure causes workers to experience sweating, thirst, insomnia, fatigue, and muscle discomfort (Krishnamurthy et al. 2017; Fahed et al. 2018). Therefore, it is significant to improve the smoke and dust control and the plant’s ventilation and heat exchange efficiency.

In response to the above problems, the ventilation of industrial plants is generally used to eliminate various gas and dust pollutants generated during the production process, to ensure that workers are in a healthy production environment (Li et al. 2016), and a sound airflow organization system is instituted to reduce fugitive emissions of smoke and dust. Since the development of computational fluid dynamics, numerical simulation has gradually become one way to study airflow organization in industrial plants. Zhang et al. (2017) research shows that CFD can be effective for the verification of ventilation design schemes, and field measurements are more realistic and representative for the acquisition of model boundary conditions. Industrial workshops are usually relatively large, and it is difficult to measure on-site in workshops. Therefore, scholars (Xue and Su 2011, Su and Wan 2011) use CFD to simulate natural ventilation in iron and steel plants, and verify
the reliability of the model by using field-tested velocity and temperature. Yang et al. (2015) used orthogonal experiments to study the temperature and velocity distribution of the steel workshop and optimize the plant. Lau and Chen (2006) conducted an experimental study in a full-scale environmental chamber, and studied the performance of underfloor air supply displacement ventilation through the analysis of temperature and velocity. Wiriyasart and Naphon (2019) used computational fluid dynamics (CFD) and field tests to analyze the temperature and air velocity distribution characteristics in a workshop with multiple heat sources to study its air quality and heat distribution. They did not analyze the current status of pollutants, but the issue of industrial plants has attracted more and more attention from society and scholars.

Wang et al. (2020) simulated the diffusion and capture process of high-temperature smoke and dust in a blast furnace tapping site through CFD, but there was no comparative verification of experimental results. Wang et al. (2013) studied the gas-solid two-phase flow under high-temperature conditions using numerical simulation methods for ironworks, analyzed the airflow organization and capture efficiency, and carried out engineering verification. Ma et al. (2015) use CFD to study the concentration distribution and residence time of particulate matter in a workshop with a ferroalloy furnace to provide guidance for the dust removal of the workshop. Cao et al. (2020) studied the temperature, velocity, and pollutant characteristics of high-polluting industrial plants based on CFD and scale-down experiments to evaluate the ventilation effect of the plant. Zhang et al. (2016) also evaluated the ventilation performance of the factory through on-site testing of auto parts factory and analysis of particle concentration, air velocity, and air temperature in the factory based on CFD. Interestingly, the analysis of all these studies proves that CFD can better simulate the flow field and particle distribution in the factory. On-site testing can provide more reliable data to verify the CFD model and provide help for ventilation performance research. For many reasons, on-site measurement is not possible, and experimental research will be selected. However, despite this much research on industrial plants’ airflow organization, there is still a gap in the field test and numerical simulation of real iron casting plants. Therefore, this research aims at the high temperature and dusty industrial plant of the blast furnace tapping site, and analyzes the temperature, velocity, and particle characteristics of the plant through on-site measurement and CFD.

As a means of minimizing this vacuity, the article takes a blast furnace tapping place. It conducts field tests on the ventilation velocity and wall temperature of the workshop’s doors and windows, as well as the velocity field, temperature field, and particle concentration field in the workshop, and obtains the distribution data and boundaries condition data during the tapping period. The paper established the computational fluid dynamics simulation model including the flow, temperature distribution, and particle propagation models to analyze the workshop’s existing ventilation system’s performance. The simulation analysis was done using the test boundary data, and the test data verified the model. The analysis reveals the iron removal workshop rules and provides a scientific basis for improving the ventilation system.

Field measurements

The cast house state

This paper’s research target of studied site is a blast furnace tapping house of a steel plant in Hubei, whose crude steel production capacity is about 4 million tons/year. There are two 2600m³ medium-sized blast furnaces in the iron and steel plant. In this paper, the tapping platform of blast furnace No. 1 is selected as the primary research object. No. 1 casting yard workshop is 85m long, 63m wide, 25m high, and covers about 5355m². The specific content is shown in Fig. 1. The plant’s primary ventilation method is natural ventilation; air enters the plant from the bottom door windows and is naturally discharged from the top skylight. A small number of dust hoods are arranged near the dust production point for mechanical ventilation and dust removal. Furthermore, the blast furnace tapping yard is equipped with three taps. These three taps worked continuously during regular operation, with an average tapping time of 2h daily.

The plant’s main dust-producing points are tapholes, iron ditch, skimmer, slag ditch, and mobile swing nozzle. Aiming at these smoke and dust emission points, a dust hood is arranged above each taphole for mechanical ventilation to collect a large amount of smokes and dust emitted from the taphole and the front iron trough; surfaces of the trough platform are all covered and flattened. The iron ditch and the slag ditch are covered with iron plates to prevent the diffusion of particulate matter into the workshop. The skimmer’s side suction hood and the dust removal hood of the swing nozzle are arranged under the platform to capture a large amount of smoke and dust generated during molten iron flow. This paper focuses mainly on the ventilation and dust removal above the platform of the iron casting plant. The skimmer’s side suction hood and the swing nozzle’s dust removal hood under the platform are not in the research scope.

Measurement methods and devices

Measurement methods

The field measurement of this study has two purposes: (1) to provide boundary conditions for numerical simulation and (2) to analyze the distribution of particle field, temperature field, and flow field within the workshop based on the measurement
results, and to determine the reliability of the model method through comparison with the simulation results.

For the measurement of boundary conditions, the researchers used a hand-held portable thermometer and anemometer to measure the air’s temperature and velocity inlet doors and windows. They used an infrared thermometer to measure each wall’s temperature and the blast furnace surface, dust hood surface, pipe surface, and other places in the workshop.

For the distribution measurement of the particle field, temperature field, and flow field in the workshop, four typical cross sections are selected as shown in Fig. 2; during the field measurement, the 2# taphole was tapping, so two sections were selected near the 2# taphole. They are, respectively, located on the cross section where the iron ditch and the dust hood are located to study the influence of the iron tapping hole on the temperature and particle concentration in the workshop. The third cross section is located above the iron plate of the slag ditch on the west side and passes through the center of the blast furnace. Moreover, the fourth cross section passes through the iron dividing ditch corresponding to the 1# and 3# tapholes. These four cross sections have significant characteristics that symbolized the particle field’s distribution, temperature field, and flow field of the entire plant.

Considering the difficulty of measurement and the operator’s breathing belt’s height, the measurement points are located 1.5m above the cast iron platform’s ground, selecting 7
points for the first, second, and third lines, respectively. Measurement points were unevenly distributed due to items stacked at the workshop’s open space and other environmental complexities. During the measurement, the $3^\#$ taphole was under maintenance, so the fourth section only selected four points at the western side. The temperature, velocity, and particle concentration were measured at each measurement point. Data obtained were used to study the distribution of various physical quantities in the factory building and compare with the simulation results to determine the model’s reliability.

**Measurement instrument**

Most of the instruments used in field measurement are portable, hand-held instruments. The testo605i wireless temperature and humidity measuring instrument were used the temperature measurement of the air; the testo835-T2 high-temperature infrared thermometer and the testo865 infrared thermal imager were used the temperature measurement of the walls and the surface of the equipment in the workshop. The velocity is measured using the testo405i wireless mini hot-wire anemometer, and the TSI 8534 inhalable particle analyzer is used to determine the particle concentration in the factory. The rangefinder is used to determine the location of the measuring point. The measurement range, accuracy, measurement technology, and specific implementation standards of each instrument are shown in Table 1.

**CFD model**

**Flow model**

In engineering, the Reynolds time-average equation after time-averaging the control equation is often used to study the airflow, and the turbulence model is introduced to deal with the turbulent motion of the airflow (Wang et al. 2015).

$$\frac{\partial (\rho \mathcal{Q})}{\partial t} = \text{div} \left( \rho \mathcal{Q} \mathbf{u} \right) = \text{div} (\Gamma \nabla \mathcal{Q}) + S$$

where $\mathcal{Q}$ is a general variable, which can represent solution variables such as $u$, $v$, $w$, $T$; $\Gamma$ is the generalized diffusion coefficient; $S$ is the generalized source phase.

The two-equation model is widely used in engineering, including the standard $k-\epsilon$ model, RNG $k-\epsilon$ model, and Realizable $k-\epsilon$ model. Among them, the realizable $k-\epsilon$ model can better simulate rotating uniform shear flow; unbounded shear flow, including mixed layer, plane, and circular jet; channel flow and flat plate boundary layer with and without pressure gradient; and separation flow is a significant improvement of the standard $k-\epsilon$ model (Shih et al. 1995). The realizable $k-\epsilon$ model consumes computer resources between

| Instrument                  | Measuring range          | Accuracy              | Measuring technology                                   | Executive standard               |
|-----------------------------|--------------------------|-----------------------|--------------------------------------------------------|----------------------------------|
| testo605i wireless mini temperature and humidity measuring instrument | -20 to +60 °C, 0 to 100% RH | ±0.8 °C (−20 to 0 °C), ±0.5 °C (0 to +60 °C); ±(1.8% RH + 3% measurements) | NTC (negative temperature coefficient) Thermistor capacitive humidity sensor | ISO 9001:2008; ISO/IEC 17025:2005 |
| testo835-T2 high temperature infrared thermometer | -10°C to +1500°C | ±2.0°C or ±1% measurements | Type K (NiCr-Ni) infrared temperature measurement | ISO 9001:2008; ISO/IEC 17025:2005 |
| testo865 thermal imaging camera | -20°C to +280°C | ±0.12°C | Infrared image output | ISO 9001:2008; ISO/IEC 17025:2005 |
| TSI8534 Inhalable particulate matter analyzer | 0.001 to 150 mg/m³ | ±5% | Light-scattering laser photometer and optical particle counter (OPC) | ISO 9001:2008; ISO/IEC 17025:2005 |
| UNI-T Unitech 120m rangefinder | 0 to 120m | ±2mm | Laser Ranging | ISO 12103-A1; GB/T 14267-2009 |
the two types. Liu (2015) comparatively studied three models, showing that the realizable k-ε model has the best simulation results in tall industrial plants under the action of heat pressure. Also, Huang et al. (2019) demonstrated that the realizable k-ε turbulence model is suitable for high-temperature buoyant jets. After analysis, the paper adopted the realizable k-ε model to reflect better the flow state of the blast furnace’s flow field. Due to the extensive temperature range designed in this paper, the airflow is subject to the buoyancy caused by the large density difference, necessitating selecting the full buoyancy effects option.

Moreover, since high-temperature objects are up to 1200°C in the simulated plant, there is a large temperature difference, so the density is mainly a temperature function. Therefore, an incompressible ideal gas density processing method is used (Zhou et al. 2019). Considering the influence of radiation on the industrial thermal environment (Wang et al. 2014), the Do radiation model is adopted.

This paper also adopts the SIMPLE algorithm based on pressure, considering the energy equation and gravity. The direction of gravity is the Z axis’s positive direction, and the acceleration of gravity is $-9.81 \text{m/s}^2$. Thus, adopting the body force weighted pressure interpolation format, which is mainly suitable for volume force flow. For the accuracy of calculation, the momentum equation and energy equation adopt the second-order upwind discrete format.

**Particle dynamic model**

Liu and Ji (2006) found that the iron casting yard’s indoor air particulate matter accounts for 91.4% of PM10, and PM2.5 accounts for 25.5%. Similarly, Liu et al. (2015) found that the main component of PM10 discharged into the atmosphere during ironmaking is PM2.5. Therefore, this article focuses on the particulate matter with a diameter of 2.5 microns.

The dust-bearing airflow in the iron casting yard is composed of high-temperature gas and soot particles, which are gas-solid two-phase flow. The gas-solid two-phase flow simulation is generally divided into Eulerian-Eulerian and Eulerian-Lagrangian methods. Euler method treats the particle phase as a continuous phase to solve the particle conservation equation. Lagrangian method regards the air phase as a continuous phase to solve the time-averaged N-S equation and the particle phase as a discrete phase and obtains the motion orbit of a single particle by solving the momentum equation of the particle (Zhao et al. 2008). For the high-temperature dust-containing airflow with the volume fraction of particulate matter less than 10% in this paper, the Lagrangian method is generally used. Therefore, the DPM model is used for the simulation of the solid phase. The fluid is regarded as a continuous phase, and the discrete phase is solved by tracking a large number of particles in the flow field. This paper uses the random trajectory model and the unidirectional coupling discrete phase model to simulate the particle phase turbulent diffusion flow. Likewise, the Lagrangian method is used to track the particle trajectory; the dynamic particle equation is generally given as:

$$\frac{m \, \text{d}v}{\text{d}t} = F_d + F_g + F_T + F_b + F_{\text{saffman}} + F_p + F_R \quad (2)$$

where $m$ is the mass of the particle, $v$ is the velocity of the particle, $t$ is the time, $F_d$ is the fluid drag force received by the particle, $F_g$ is the gravity received by the particle, $F_T$ is the thermophoretic force received by the particle, $F_b$ is the Brown force received by the particle, $F_{\text{saffman}}$ is the Saffman lift force on the particle, $F_p$ is the pressure gradient force on the particle, and $F_R$ is the heat radiation force on the particle.

When the volume fraction of particles in the dust-containing airflow is less than 10%, particles’ interaction can be ignored. Because the high-temperature airflow has a large temperature gradient, the thermophoretic force caused by the temperature gradient needs to be considered, and the Brownian force and Saffman lift due to the velocity gradient in the flow field.

In his article, Liu (2016) mentioned the particles’ composition in the blast furnace casting yard, as shown in Table 2.

It can be seen from the table that the main component of the particulate matter discharged from the iron field is Fe$_2$O$_3$, so the particulate matter parameter is taken as the iron oxide parameter, the density is 4580 kg/m$^3$, the thermal conductivity is 0.55 W/m·K, and the specific heat capacity is 710 J/kg·K.

**Boundary conditions**

According to the iron casting yard characteristics, the airflow generally enters from the lower door window and flows freely from the side windows and roof skylights.

| Table 3 Skylight boundary condition |
|------------------------------------|
| **Boundary conditions** | DMP-injection |
| Roof windows and side windows | Outflow | Escape |

| Table 2 Smoke composition |
|---------------------------|
| Ingredient | Fe$_2$O$_3$ | TFe | CaO | MgO | SO$_2$ | P | Burn ashes | FeO |
| Proportion (%) | 59.76 | 48.9 | 5.38 | 0.3 | 5.06 | 0.013 | 13.84 | 9.12 |
The air inlet adopts the speed inlet’s boundary condition; its temperature is the outdoor measured ambient temperature, and its speed is the speed measured on-site. The speed boundary conditions are defined in Tables 3 and 4. The boundary conditions for the plant’s fixed wall are the first type of boundary conditions, and the specific parameter values are shown in Table 5.

During regular tapping, the most smoke and dust are released from the tap hole, and a large amount of soot is also emitted from the slag ditch cover on the spot, so the two smoke and dust emission points selected at the slag ditch cover are set as the dust-producing area as shown in Fig. 3. According to the literature (Liu 2016), the main ditch’s dust output is about 39.1kg/h, the initial speed of smoke and dust is 0-2.3m/s, and the slag’s dust output ditch is about 3.1kg/h. The speed tested in the field is about 0.8m/s, and the content of PM2.5 is about 20%. These particle mass flow and speed settings are shown in Table 6.

### Table 4 Door and window boundary conditions

| Position number | Boundary conditions | Velocity magnitude (m/s) | Temperature (°C) | DMP-injection |
|-----------------|---------------------|--------------------------|-----------------|---------------|
| East 23         | Velocity-inlet      | 1.20                     | 29              | Escape        |
| 24              |                     | 1.20                     |                 |               |
| 25              |                     | 1.20                     |                 |               |
| 26              |                     | 1.30                     |                 |               |
| 27              |                     | 1.00                     |                 |               |
| 28              |                     | 0.90                     |                 |               |
| 29              |                     | 1.50                     |                 |               |
| 30              |                     | 0.90                     |                 |               |
| 31              |                     | 0.90                     |                 |               |
| West 1          | Velocity-inlet      | 0.15                     | 30              | Escape        |
| 2               |                     | 0.12                     |                 |               |
| 3               |                     | 0.12                     |                 |               |
| 4               |                     | 0.25                     |                 |               |
| 5               |                     | 0.10                     |                 |               |
| 6               |                     | 0.15                     |                 |               |
| 7               |                     | 0.20                     |                 |               |
| 8               |                     | 0.20                     |                 |               |
| 9               |                     | 0.40                     |                 |               |
| 10              |                     | 0.30                     |                 |               |
| 11              |                     | 0.60                     |                 |               |
| North 13        | Velocity-inlet      | 0.80                     | 29              | Escape        |
| 14              |                     | 1.00                     |                 |               |
| 15              |                     | 1.20                     |                 |               |
| 16              |                     | 0.80                     |                 |               |
| 17              |                     | 1.00                     |                 |               |

### Table 5 Wall and pipe boundary conditions

| Position number | Boundary conditions | Temperature (°C) | DMP-injection |
|-----------------|---------------------|-----------------|---------------|
| East wall       | Wall                | 35              | Trap          |
| West wall       |                     |                 |               |
| North wall      |                     |                 |               |
| Floor 32–33     |                     | 34              |               |
| P               |                     | 31              |               |
| O               |                     | 40              |               |
| LM              |                     | 80              |               |
| D               |                     | 40              |               |
| E,H             |                     | 1100            |               |
| A,C,H           |                     | 750             |               |
| K,N             |                     | 110             |               |
| B,H             |                     | 55              |               |
|                |                     |                 |               |

### Table 6 The mass flux and initial velocity of the particulate matter

| Position                  | Particle mass flow | Initial velocity |
|---------------------------|-------------------|------------------|
| Producing dust source 1   | 0.002kg/s         | 2m/s             |
| Producing dust source 2   | 1.5e-4kg/s        | 0.8m/s           |
| Producing dust source 3   | 1e-5kg/s          | 0.8m/s           |
Results

Measurement results

To provide boundary conditions for the numerical simulation, the speed of the factory building’s windows, the temperature of the external walls, and the walls of the internal facilities were measured with an anemometer and a thermometer. The specific measured values are shown in Tables 3, 4, and 5. To verify the CFD model, an anemometer, a thermometer, and a particle analyzer were used to determine the particle concentration, velocity, and temperature on the four characteristic lines of the 1.5m plane in the blast furnace casting yard. The details are shown in Figs. 4, 5, and 6. During the measurement period, due to the large plant and the large number of measurement points, it is impossible to measure the temperature, speed, and particle concentration of all points at the same time, so measurement errors will occur.

CFD model validation

Grid independence verification

The grid’s quantity and quality are the key factors affecting the numerical simulation of the factory building. Because there are many irregular geometric figures inside the factory building, the overall shape is relatively complicated, and it is not easy to generate hexahedral meshes, so tetrahedral meshes are used for division in the calculation. Therefore, the paper uses the Tetrahedrons method to generate a full tetrahedron
Because the plant has a cylindrical surface such as a blast furnace and pipes, it adopts Curvature’s distribution method. The grids of heat source, air inlet, and air outlet are densely divided, and the grid inside the plant is relatively sparse. The accuracy of the two-phase flow simulation for the grid is also very high, so the grid divided in the calculation area must be sufficiently fine. A coarse grid will cause errors in the tracking of particles. Moreover, too much grid will require higher computer performance and a waste of valuable resources. To address this issue, the paper divided the calculation area into three different numbers of grids and compared the numerical simulation results under different numbers of grids to determine a grid that meets the calculation requirements and has high accuracy level faster calculation speed. The three different grids are as follows: 4.6 million, 9.89 million, and 11.4 million.

Comparing the measured speed on the fourth line, as shown in Fig. 7, it can be seen from the figure that from 4.6 million to 11.4 million, the speed change trend corresponding to the 4.6 million grid is relatively large. However, the speed change trends corresponding to 9.89 million and 11.4 million grids are similar. It proves that the grid number’s accuracy is 9.89 million, and the accuracy is high enough. At this time, increasing the number of grids does not make much sense, as it will slow down the calculation speed. In this paper, the grid division uses a grid growth rate of 1.2, the global size is 301mm, and the heat source surface and the inlet and outlet are 250mm, and the number of generated grids is 9.89 million for numerical simulation calculation.

Numerical simulation verification

The measurement points of air temperature, velocity, and particle concentration are as described in “Measurement methods and devices.” The numerical simulation results are compared with the experimental results shown in Figs. 8, 9, and 10. For the first line, there are relatively few obstructed objects around, and the distance to the doors and windows is relatively small, so the measured temperature and concentration are relatively uniform, and because of the suction effect of the dust hood, the surrounding speed is large, and the average relative errors of temperature, velocity, and particulate matter are 3.1%, 28%, and 25.3%, respectively. The average relative error of the measured temperature, velocity, and particulate matter in the second line is 3.1%, 27%, 29.9%, respectively. Because it is located under the dust hood, the temperature is higher, and the speed and the concentration are also higher. The consistency of the speed comparison results of the third line is poor. The relative error of the speed of the second, fifth, and sixth measuring points reaches 100%, which is extremely large. The average relative error of temperature is 6.6%, and the average relative error of particulate matter is 40.7%. The main reason for the large error is that the workshop itself is very complicated, and the model simplified the support around the blast furnace, mud bombardment, and other objects. In the simulation model, the resistance is reduced. There is no obstruction behind the slag ditch so that the airflow quickly enters the back of the blast furnace. It will lead to higher speed, lower concentration, and lower temperature. For the fourth line temperature, the average relative error of velocity is 44% and 1.1%, and the average relative error of particulate matter reaches 59.8%. The reason for the great error is that the simplification of the plant allows the airflow to reach the depth of the plant without hindrance, making the particulate matter in the depths of the plant. Accumulation, the calculated result is larger than the experimental measurement, and the particle concentration calculated by the third line is smaller. Although there are certain errors between the simulation results and the experimental values, the numerical simulation results in this paper are considered acceptable considering the complexity of the plant.

Error! Reference source not found. Line1 to Line4

Fig. 6 Temperature distribution at different measuring positions (Z=1.5m)

Fig. 7 Grid independence verification
Performances of the ventilation system

The results of temperature, velocity, and PM2.5 concentration field

Since the z=1.5m plane is precisely where most people breathe, the flow field, temperature field, and concentration field can best reflect human feelings. Figure 11 shows the temperature distribution on this plane. It can be observed from the figure that the temperature in most areas is below 31°C. Due to the sweep of the longitudinal airflow, the plume caused by the heat source affects the rear right of the casting yard, and so, the high-temperature area appears on the right of the slag ditch (about 33°C); most of the rear temperature is below 31°C, which is suitable for workers to operate. The surrounding area above the main operational ditch is as high as 40°C,
and the temperature of the non-working main ditch also reaches 750°C, so the surrounding temperature above it is also as high as about 35°C.

As shown in Fig. 12, the plant’s largest concentration point is the area where the main ditch of the blast furnace is connected. Also, a high concentration area appears on the slag ditch’s right side; this is due to the main ditch’s high-temperature zone and the suction effect of the dust hood above it. There is an apparent high-speed zone at the left front of the main ditch, making it easier for the airflow to bypass the left side of the blast furnace and reach the rear of the casting yard. However, as the pressure in the factory building’s depths increases, the speed starts to decrease, leading to a larger concentration of particulate matter behind the blast furnace. According to CRAES (2012), the indoor PM2.5 concentration limit is 75μg/m³, and the concentration of the entire respiratory area is basically below 80μg/m³, which is considered mild pollution.
Analysis of Figs. 11 and 12 shows the influence of obstacles in the factory building on airflow (Zou et al. 2005). When the air flows through obstacles, it circumvents and generates vortex areas, leading to a gradual reduction in airflow speed, which causes the air distribution in the ventilated space to be very uneven. Hence, the more the airflow goes deep inside the workshop, the harder it is to drive the airflow, making it difficult for air to circulate smoothly and drain from the skylight, leading to particulate matter accumulation and rising temperature.

Figures 13 and 14 reflect specific characteristics of the iron yard’s temperature, velocity, and particle concentration in height direction. From the diagram, it can be observed that the temperature on the left and right sides of the dust hood keeps rising; when the height of the workshop is below 6.8 meters, the temperature is around 31°C. However, due to the irregular timing of airflow discharged, the temperature of the high-temperature airflow above the plant will rise to about 35°C; when it is close to the wall of the plant, the updraft cannot be eliminated in time, thus turning back down to produce a large vortex, resulting to a high concentration area appearing at the middle of the plant. Moreover, due to the suction of the dust hood and the large disturbance of the longitudinal airflow, the concentration of particulate matter in the right area of the middle part is significantly higher than that of the left part, and the concentration distribution is uneven.

The plant’s pollutants are mainly due to the smoke and dust emitted by the taphole that cannot be removed in time by the dust hood. The particulate matter will escape from the dust hood with the airflow, and some particulate matter will be deflected to the north and discharged from the skylight on the north side. Since the particulate matter generated in the slag ditch is far away from the dust hood, it will follow the airflow and accumulate inside the workshop, and because the speed in the depth of the workshop is relatively low, it is difficult to discharge the particulate matter.

The analysis of Figs. 13 and 14 shows the influence of the vent on the airflow. When the air enters from the bottom window, part of it is taken away by the dust hood, and the other part is taken away from the skylight. However, the vent’s wrong location will make it difficult for airflow to exit the skylight, causing particles to accumulate in the height of the plant.

Human thermal comfort

The human body’s health, self-feeling, and working ability depend on the comfort of the room. In industrial buildings, the human body’s thermal comfort directly affects workers’ labor efficiency and health. PMV is a recognized thermal environment evaluation index; however, the PMV calculation model contains many variables and the calculation is very complicated; this paper adopts simplified algorithm (Ou et al. 2018). According to Eqs. (3) to (6), the cloud map 15 is obtained, and it can be observed that the PMV in the active area of the human body is mostly around 3. Therefore, the thermal comfort of workers is relatively low.

\[
\begin{align*}
\frac{PMV}{K_M} &= 3.05[5.733-0.007(M-W)-P_a] \\
&+ 0.42(M-W-58.15) + 1.73 \\
&\times 10^{-2}M(5.867-P_a) + 1.4 \\
&\times 10^{-3}M(34-t_a) + h_{cr}f_{cl}(t_{ak}-t_o)F_{cl} \\
\end{align*}
\]

\[
h_{cr} = h_c + 0.69 h_t
\]
Fig. 15 PMV value of the z=1.5m plane

\[
t_o = \frac{0.69h_tc_t + hct_a}{0.69h_t + hc} \quad (5)
\]

\[
F_{cl} = \frac{1}{1 + 0.155h_{cr}f_{cl}I_{cl}} \quad (6)
\]

where \( M \) is the human energy metabolism rate, W/m\(^2\); \( W \) is the mechanical work done by the human body, W/m\(^2\); \( P_a \) is the partial pressure of water vapor around the human body, KPa; \( t_a \) is the ambient temperature of the human body, °C; \( h_{cr} \) is the comprehensive sensible heat transfer Thermal coefficient; \( h_c \) is the convective heat transfer coefficient, (W/m\(^2\)·°C); \( h_r \) is the linear radiation heat transfer coefficient, (W/m\(^2\)·K); \( t_{o} \) is the converted temperature, °C; \( t_r \) is the average environmental radiation temperature; \( t_{sk} \) is the average human skin temperature, °C; \( F_{cl} \) is the basic heat transfer efficiency of clothing; \( f_{cl} \) is the area coefficient of clothing; and \( I_{cl} \) is the effective thermal resistance of clothing Fig. 15.

### Ventilation effect

The ventilation effect is related to two factors: the amount of fresh air sent in and the other is the form of airflow organization. The following uses the waste heat removal efficiency, the effective ventilation ratio, and the actual number of new air changes to evaluate the iron yard room’s ventilation effect. The calculation results are shown in Tables 7, 8, and 9.

The PMV value is too large for workers, and the plant’s waste heat is also a pollutant. Therefore, the waste heat removal efficiency is used to investigate the efficiency of energy utilization in the form of airflow organization (Zhu 2010); this is defined as:

\[
\eta_h = \frac{t_e - t_s}{\overline{t_a} - t_s} \quad (7)
\]

where \( t_e \) is the exhaust air temperature, \( t_s \) is the supply air temperature, and \( \overline{t_a} \) is the average temperature of the working area.

This plant adopts the form of combining the local exhaust of the smoke hood with natural ventilation. The exhaust air volume was increased to eliminate particulate matter, prone to short-circuiting of the natural exhaust vents. Xing et al. (2018) proposed two parameters, sufficient ventilation volume and effective ventilation ratio. When the effective ventilation ratio is less than 1, it indicates that the natural ventilation opening is short-circuited; the definition is given as follows:

\[
G_e = |G_{jp} + G_{zp}| = G_{zj} \quad (8)
\]

\[
\eta_e = \frac{|G_e/G_{jp}|}{1} \quad (9)
\]

where \( G_e \) is the effective ventilation volume, \( G_{jp} \) is the mechanical exhaust volume, \( G_{zp} \) is the natural exhaust vent ventilation volume, \( G_{zj} \) is the natural air inlet ventilation volume, and \( \eta_e \) is the effective ventilation ratio.

Luo and Zhao (2007) put forward the concept of actual fresh air changes. The number of fresh air changes is

| Exhaust air temperature | Exhaust air temperature | Average temperature of the working area | Waste heat removal efficiency |
|-------------------------|-------------------------|----------------------------------------|-----------------------------|
| °C                      | °C                      | °C                                     |                             |
| 33.2                    | 29                      | 30                                     | 4.2                         |
integrated into the sewage efficiency, taking into account the amount of fresh air sent into the room and the ventilation system's ability to remove pollutants. It is characterized by the frequency of pollutants discharged by the system in a steady-state, that is, the system's driving force to eliminate pollutants relative to a uniform mixing condition. The definition is as follows:

\[ n_{ROAC} = \varepsilon \cdot n_{OAC} = \frac{C_e - C_s}{\bar{C} - C_s} \]

where \( C_e \) is the pollutant concentration at the exhaust outlet, \( C_s \) is the pollutant concentration at the air outlet, \( \bar{C} \) is the average pollutant concentration in the room, \( Q_f \) is the hourly fresh air volume, and \( V \) is the room volume.

**Conclusion**

This paper selected a typical blast furnace tapping workshop and conducted on-site measurement to obtain the characteristics of the flow, temperature, and soot concentration fields in the workshop during the tapping period; it established a numerical simulation model based on computational fluid dynamics and further analyzed the performance of the taphole smoke exhaust system. Based on the result and finding, the paper draws the following conclusions and recommendations:

(1) The temperature in the workers’ breathing zone in the entire plant is mostly below 31°C, while the temperature in the vicinity of the slag ditch, iron ditch, and blast furnace is around 33°C, with the highest temperature reaching 40°C, which is still very high. Through the evaluation of the thermal comfort of the breathing area by PMV, the comfort is low, and it feels scorching; the concentration of PM2.5 is mostly below 80\( \mu \)g/m\(^3\), for workers, and the conditions of the entire breathing area are acceptable.

(2) The plant’s main problem is that when the 2# iron ditch is working, the dust hood is at the front of the plant. Due to longitudinal airflow interference and obstacles, high temperatures usually appear at the rear of the plant, especially when the right part of the slag ditch reaches about 33°C, making people feel uncomfortable. The deepest area has a high concentration of particulate matter. Also, because the plant is relatively high and the airflow organization is unreasonable, it is difficult for particulate matter to be discharged from the skylight, which accumulates in the middle of the plant, and makes the temperature very high.

Given the problem of high temperature and particulate matter accumulation on the right side of the blast furnace in the plant, the paper recommends the following actions:

(1) To consider increasing the number of vents deep inside the plant to make the airflow in the workshop’s depth smoother.

(2) Regarding particulate matter accumulation in mid-air, it is observed due to the airflow organization being unreasonable. The best option in addressing this problem is to change the area, direction, location, and other parameters of the vents to allow the airflow organization to more reasonable. Another option is to consider revamping the dust hood to make the plant cleaner.

**Table 8** Effective ventilation ratio

| Mechanical exhaust volume m\(^3\)/s | Natural exhaust vent ventilation volume m\(^3\)/s | Natural air inlet ventilation volume m\(^3\)/s | Effective ventilation ratio |
|-----------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------------|
| 110.25                            | 201.55                                        | 308.89                                        | 2.8                        |

**Table 9** The actual number of fresh air changes

| Ventilation m\(^3\)/h | Number of fresh air changes | Air outlet concentration mg/m\(^3\) | Exhaust vent concentration mg/m\(^3\) | Respiratory zone concentration (Z=1.5m) mg/m\(^3\) | Actual fresh air changes |
|-----------------------|----------------------------|------------------------------------|----------------------------------------|---------------------------------------------------|--------------------------|
| 1112001.512           | 7.9                        | 0.03                               | 0.115                                  | 0.176                                              | 4.6                      |
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