NIPPON STEEL TECHNICAL REPORT No. 69 APRIL 1996

UDC697.957:628.854

# New Design Concept for Working Environment Based on Numerical Heat Transfer and Fluid Flow Technology

Kazutoshi Ishii*1 Hiroaki Kawakami*1
Yoshimitsu Murahashi*2

**Abstract:**

*In recent years, Nippon Steel has strategically diversified its operations by manufacturing steel products of higher quality and added value and entering into new businesses such as electronics, advanced materials and chemicals. These businesses require increasingly strict specifications for production areas, as represented by improvement in the operating environment for precision production equipment and the assurance of air cleanliness throughout plants. To meet these requirements with minimum specifications, Nippon Steel focused on "air flow" in production areas, In 1985, it commerced development and application of sophisticated engineering technology by utilizing numerical heat transfer and fluid flow analysis. The working environment engineering technology developed since then is described here.*

## 1. Introduction

The engineering of civil engineering facilities and buildings in the steel industry traditionally tackled the challenges of reducing construction costs, shortening construction time, and raising construction quality while considering several design conditions different from those of general buildings, such as large load, high heat, and severe vibration.

As such steel products as coated sheet increased in quality and added value, the need arose for securing good operating conditions for automatic precision machines and improving working conditions at dusty plants. Given these trends, improving the quality of air at steel plants and other factories emerged as a new engineering issue.

Specifically, locally allowable temperature levels are set to prevent the heat-induced failure and malfunction of precision equipment, and allowable dust concentrations (cleanliness) in plants are specified to prevent product yield from dropping due to fine dust particle buildup. Situated at steelworks are many items of dust-generating equipment, such as blast furnaces, coke-oven batteries, sinter machines, and basic oxygen furnaces. Therefore, calls were issued for reducing the amount of airborne dust in working areas.

Around 1985, Nippon Steel focused attention on "air flow" to meet the push for improved air quality. Targeting the development of advanced technology to cope with every conceivable environmental problem, the company improved technology while making good use of engineering and construction opportunities.

*1 Technology Development Bureau
*2 Head Office

Described here is the concept of developing working environment design technology to meet a wide spectrum of needs from steel manufacture to electronics and other new businesses.

## 2. New Concept of Working Environment Design Technology and Basic Policy of Technology Development

In ventilation design that addresses working environment design technology, a design method was traditionally adopted in which the air of the entire plant was changed, based on gravity ventilation theory, for example, to meet specified requirements such as temperature[1].

Under the traditional design method, ventilation requirements specified for individual areas within the plant building could not be met, so that the ventilation of the entire plant building was designed to meet the most stringent requirements specified for a given area. In other words, the traditional design method provided unnecessarily frequent ventilation in places with a lenient temperature criterion.

The authors took note of invisible air flow and thought that if air flow was understood and if efficient air flow was intentionally created, temperature, cleanliness, and other detailed requirements for small areas could be satisfied. That is, to meet such detailed design requirements and to provide a minimum-specification production area, it is indispensable to predict air flow properties in localized plant areas and develop air flow control technology for specific purposes.

Based on this idea, "establishment of technology for predicting (analyzing) and controlling air flow properties in detail at arbitrary points in plants by applying heat transfer and fluid flow analysis technology" was set as the basis for the new working environment design technology. The following policy was formulated for developing technology:

(1)Develop and apply heat transfer and fluid flow analysis technology in two steps.

(2)Solve the conservation equations of air quantity, temperature, and velocity as basic equations for heat transfer and fluid flow analysis, and establish technology for analyzing plant building ventilation in pursuit of large-scale air flow and analyzing large pressure spaces in the first step.

(3)Based on the conservation equations of air quantity, temperature and flow as applied technology, use technology for analyzing turbulence in pursuit of large-scale air flow and that for analyzing dust diffusion to study particle motion in air. Then, work on this technology in the second step.

Efforts are made to advance design technology, mainly analytical technology, by repeating technology development in a manner shown in **Fig. 1**. Technological developments for analyzing ventilation, pressure space, turbulence, and dust diffusion are described between Chapters 3 to 6.

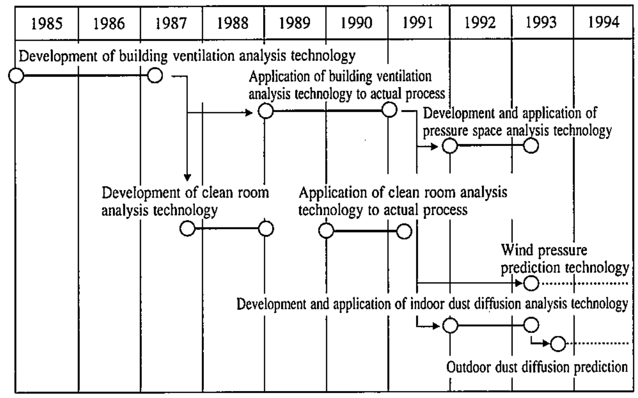


**Fig. 1** Chronology of development of working environment design technology

## 3. Development of Technology for Ventilation Design of Large Plants

### 3.1 Background

In general, the ventilation of plants and warehouses is designed by assuming that the temperature and pressure distributions are constant in the building, in order to change the air in the entire building.

The temperature and pressure distributions greatly vary within steel plant buildings where large heat sources are unevenly arranged, as represented by continuous hot-dip galvanizing lines and continuous annealing lines. The technical limits of the conventional ventilation design method that assumes constant temperature and pressure distributions within plant buildings became obvious. One example is a device that was initially designed as an air exhaust device, but actually worked as an air supply device through which rain and snow entered.

### 3.2 Basic concepts of technology development (See Table 1)

With the traditional ventilation design method that assumes constant temperature and pressure distributions in buildings, the magnitude relations between heat quantity, air supply equipment, and air exhaust equipment can be taken into account, but their positional relations such as rain and snow entry positions are ignored.

The ventilation design method proposed here acknowledges the fact that heat quantity, air supply and exhaust equipment are arranged in a given three-dimensional space and it basically clarifies three-dimensional air flow in a large space. The authors thought that if completed, the new ventilation design method would be able to solve all the technical limits of the conventional ventilation design method and minimize equipment specifications of greater efficiency.

### 3.3 Actual steps of technology development

3.3.1 Establishment of three-dimensional ventilation simulation technology

Three-dimensional heat transfer and fluid flow are described by the Navier-Stokes equations. It was considered difficult to obtain mathematically strict solutions of the Navier-Stokes equations. The recent progress of computers has made it possible to find solutions by numerical analysis, using the general-purpose heat transfer and fluid flow analysis code PHOENICS (CHAM of Britain)[2,3], for example. PHOENICS was used in the present study.

The accurate simulation of the ventilation conditions of plant buildings depends on the setup of constants peculiar to specific buildings, such as the actual opening ratio and resistance coefficient of ventilating openings and the amount of solar heat absorbed through exterior finishing materials, Furthermore, the reflection in the Navier-Stokes equations of the amount of convective and radiant heat generated by equipment in the buildings must also be considered.

The number of constants concerning buildings and heat sources was initially reduced by making use of conventional ven-

**Table 1** Description and development steps of working environment design technology

Step 1

| | | |
|---|---|---|
| Applicable space | Large natural ventilation space | Large pressure space |
| Evaluation item | Air flow direction and temperature | Air pressure in building |
| Technology | Technology for predicting and controlling air temperature and flow at arbitrary points in a space by taking air supply and exhaust area and arrangement as parameters | Technology for predicting and controlling air pressure at arbitrary points in a space by taking roof and wall gap area ratio as parameters |
| Basic equation | Conservation equations of air quantity, temperature, and velocity | |
| Applied equation | • • • • | • • • • |

Step 2

| | | |
|---|---|---|
| Applicable space | Clean room space | Indoor dust diffusion space |
| Evaluation item | Completely vertical laminar flow | Dust diffusion |
| Technology | Technology for predicting and controlling vertical laminar flow through microflow simulation by taking floor opening ratio as the parameter | Technology for predicting and controlling dust concentration at arbitrary points in a space by taking mechanical dust collection capacity as the parameter |
| Basic equation | Conservation equations of air quantity, temperature, and velocity | |
| Applied equation | Turbulent flow model basic equations | Gas diffusion basic equations |

tilation design technology. Analyzed values were compared and verified with measured values in actual buildings. Finally, the values of the model constants were sequentially established by applying sensitivity analysis used in mathematical optimization. As a result, a simulation technology was successfully established that can simulate air temperature within ±1°C and air flow direction almost equal to the actual air flow direction, as shown in **Fig. 2**.

As shown in **Fig. 3**, numerical analysis found that rain and snow infiltration is caused by the backflow of air through monitors in low-rise bays influenced by high-rise bays where the heat source capacity is predominantly large. Elimination of monitors produced the double benefit of improved ventilation performance and reduced equipment cost.

3.3.2 Proposal for efficient ventilation design

Constructing analytical models for heat transfer and fluid flow analysis generally takes much time and labor. When analyzing Navier-Stokes equations, the computing time greatly depends on how the start point of convergence calculation or initial values are given.

For efficient analysis, it is essential to set the initial values of design conditions as close as possible to the optimum solution to be obtained according to the building shape, heat source distribu-

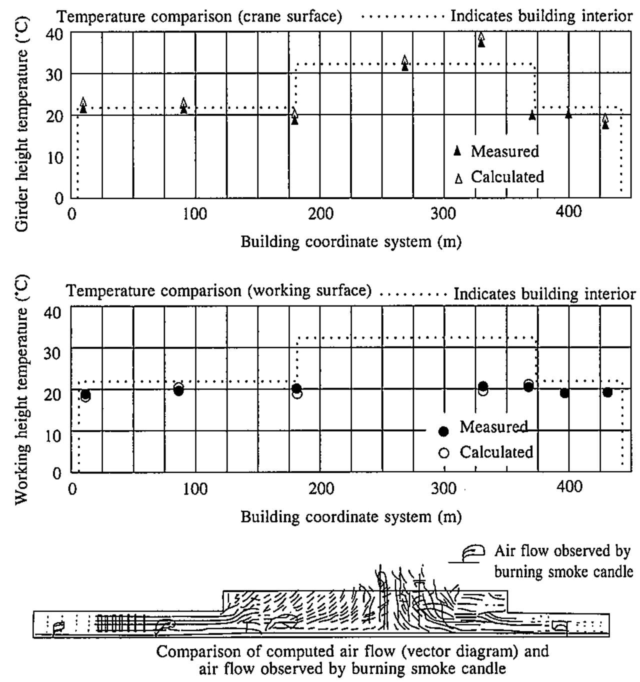


**Fig. 2** Results of verification of three-dimensional ventilation simulation technology

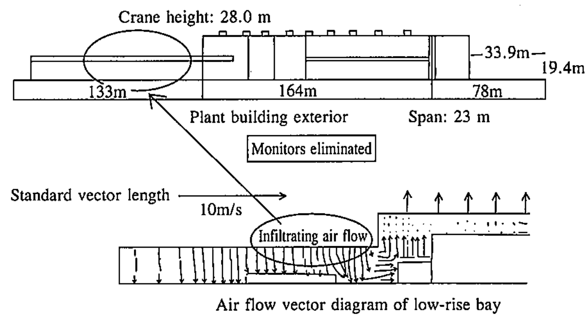


**Fig. 3** Reflection of analytical results in standard model

tion, and heat generation amount.

Take the building of a rolling mill, for example. It was found that the building shape, heat source distribution, and heat generation volume can be classified into three categories. A standard model with the arrangement of ventilating equipment was built for each category. The relations between the standard ventilation area and room temperature distribution, and between the ventilating equipment area and room temperature distribution were normalized as shown in **Fig. 4**. This was to clarify the effects of various factors on building ventilation.

These efforts allowed ventilation design based on heat transfer and fluid flow analysis to be efficiently performed by slightly correcting the initial values of the standard model of the building concerned.

### 3.4 Summary

Using the ventilation design for steel plants, minimum specifications for ventilating equipment can be studied by analyzing heat transfer and fluid flow in basically all plant buildings. This is one

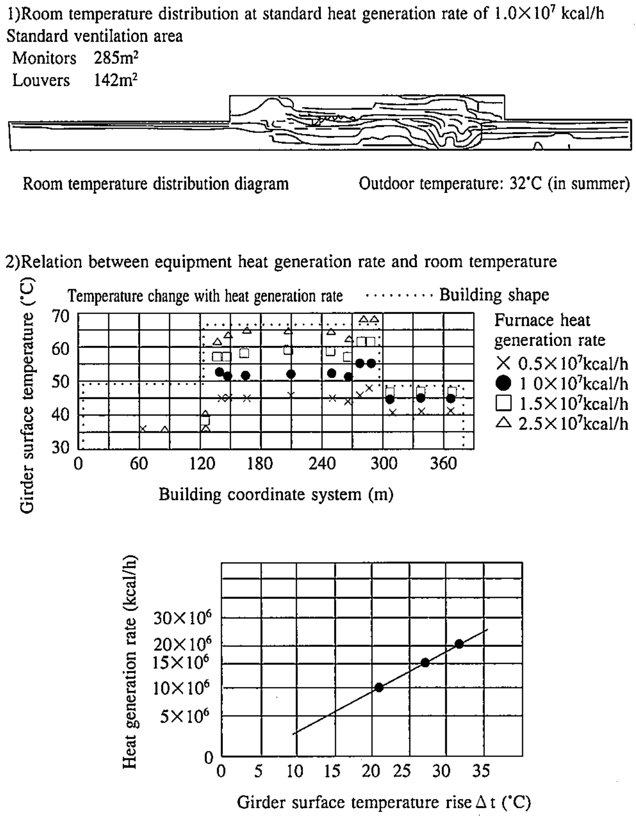


**Fig. 4** Analysis diagram showing effect of factors associated with building ventilation

outcome of advancing complex and time-consuming heat transfer and fluid flow analysis technology to the level where it can be applied to practical ventilation design technology.

## 4. Development of Clean Design Technology at Large Plants

### 4.1 Background

In processes where steel strip is painted or laminated, entrapment of dust in the air degrades steel quality and yield. These plants require a clean room of about Class 100,000. The Class 100,000 specification is lower than that specified for semiconductor plants. If plant ventilation were designed with filters and interior materials to general clean room specifications (Class 1 to Class 10,000), huge costs would be incurred.

Rather than taking the conventional clean room approach, the authors attempted to achieve a high level of cleanliness by making minimal alterations to steel plant buildings covered with metal roofing and wall materials.

### 4.2 Basic concept of technology development

In general clean rooms, interior and exterior finishing materials are used to prevent the entry of dust from outdoors where there are large amounts of dust, and filters are used to remove dust indoors where there are less amounts of dust.

The cleanliness of steel plants is far lower than that of general clean rooms. The authors thought that the cleanliness requirements of steel plants could be met by taking measures against external dust entering the plant with ventilation air.

Specifically, steel plant buildings are sealed by adding a minimum of improvements to the traditional metal roofing and siding specifications and by maintaining the interior at a positive pressure. Cleanliness-raising technology was developed from this new point of view.

### 4.3 Actual steps of technology development

4.3.1 Quantitative determination of roof and wall seal tightness

Based on conventional metal roofs and walls built by overlapping steel sheets of less than 1 mm thickness, a simple sealed construction was devised where rubber seals are installed in the overlaps between the steel sheets. To achieve the sealed construction, the relationship between the air flow rate and positive pressure was investigated using the model room shown in **Fig. 5**. The ratio of the gap area to the roof and wall area (hereafter referred to as the gap area ratio) to reproduce this relationship was analytically derived.

Installation of rubber seals in the overlaps between the roof and wall steel sheets reduced the gap area ratio from 0.46% to 0.01% and produced a high degree of air tightness as shown in **Fig. 6**.

4.3.2 Study of maintaining positive pressure in buildings by optimizing mechanical ventilation capacity

The minimum condition required to prevent the entry of outdoor dust into a building is to ensure air flow through openings to

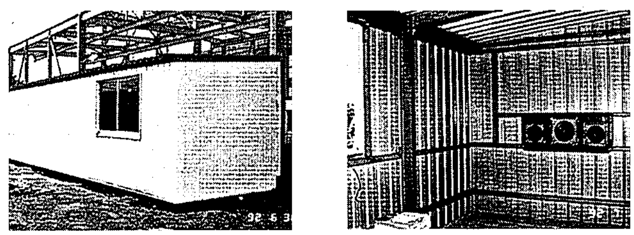

**Fig. 5** Model room for evaluation of gap area ratio

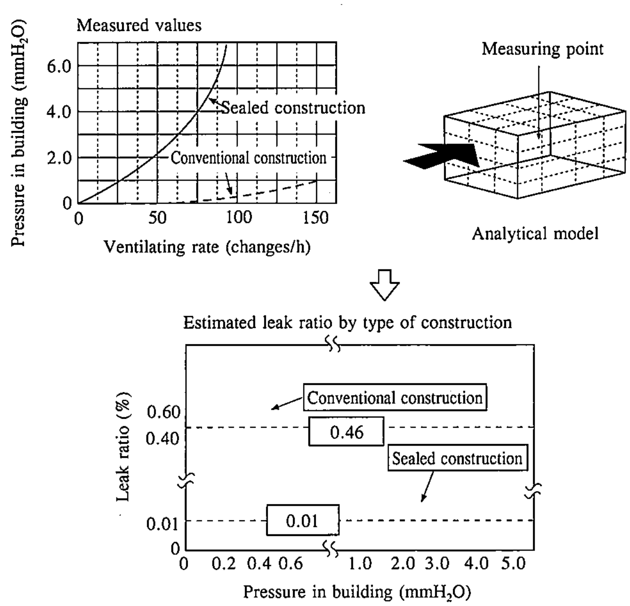


**Fig. 6** Results of experimental and analytical evaluation of gap area ratio

the outside.

Actual buildings must be provided with product entry and exit shutters, connecting underground pits, and other openings that reduce air tightness, such as shown in **Fig. 7**. Ventilating openings must also be provided to ensure the guaranteed temperature of instrumentation.

The amount of air required to maintain the plant building under positive pressure was studied by considering these conditions and using the gap area ratio determined as described above. If the air supply and exhaust rates were set at 3,000 m$^3$/min (downward flow at the upper right) and 890 m$^3$/min (through the roof ventilating openings), it was found that outdoor air flow could be obtained in the tension reel (TR) and payoff reel (POR) pits and that the guaranteed temperature of 50°C for crane instrumentation could be satisfied as shown in **Fig. 8**. These analytical results agree well with the experimental results.

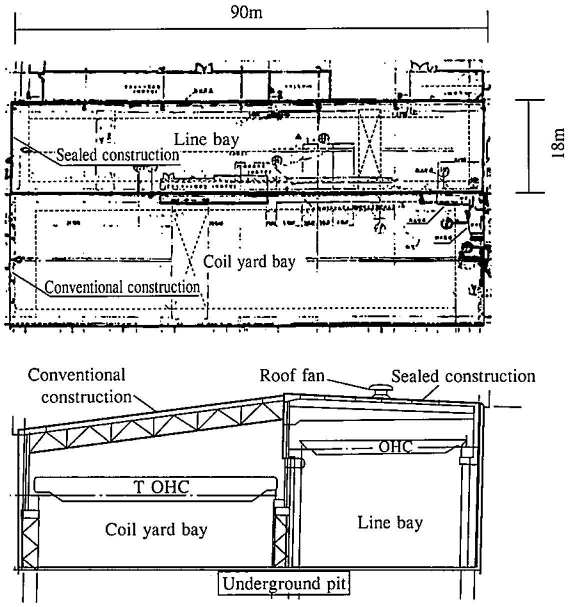


**Fig. 7** Outline of plant building

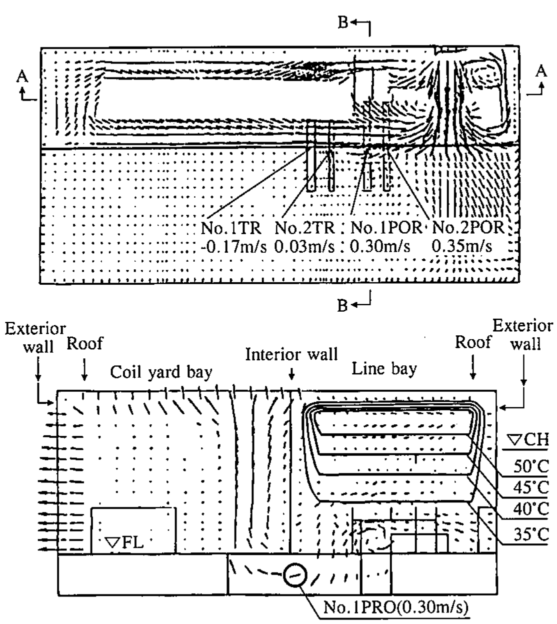


**Fig. 8** Results of air flow analysis (at 33°C in summer)

### 4.4 Summary

The term "gap area ratio" was introduced into the analytical technology, and the optimum relationship between the seal tightness of the roof and wall steel sheets and the amount of air required to maintain the plant building under positive pressure was quantitatively determined. By tackling this problem from a new perspective, these techniques have helped Nippon Steel achieve a level of cleanliness unrivaled by its competitors in the steel industry.

## 5. Development of Super Clean Room Design Technology

### 5.1 Background

A factor crucial to new business success in the electronics field is product development speed. Electronic parts and semiconductor manufacturers are undertaking research and development at a breakneck pace, but they do not generally disclose their R&D results. This means that Nippon Steel must develop and implement its own super clean room design technology.

### 5.2 Basic concept of technology development

A super clean room requires an almost completely dust-free space with one or less dust particles of 0.1 μm diameter per 1 ft$^3$ of air as indicated by the design rules given in **Table 2**.

To achieve a clean room with such high efficiency, not only the entry of dust from outside the plant building but also the accumulation of dust generated within the plant building must be arrested. It is essential to produce stable, vertically downward laminar flow streams with a divergence angle of 14° or less[4] in the room.

An efficient two-step approach is taken to develop the super clean room design technology. The first step involves establishing microflow simulation technology that can determine in detail the effect of turbulent vortices produced by the viscous drag of the wall and equipment surfaces, among other things. The second step involves determining detailed clean room specifications, such as air inlet and outlet setup conditions, required to produce stable vertical laminar flow streams by utilizing the established analytical technology.

### 5.3 Actual steps of technology development

5.3.1 Establishment of microflow simulation technology

The K-$\varepsilon$ turbulent flow equations or the conventional Navier-Stokes equations into which equations to grasp the effect of turbulent vortices follow. In the equations, the model constants are $\sigma_1$, $\sigma_2$, $C_1$, $C_2$, and $C_D$.

Transport equation of turbulent energy K

$$\frac{\partial K}{\partial t}+\frac{\partial K U_j}{\partial X_j}=\frac{\partial}{\partial X_j}\left\{\frac{V_t}{\sigma_1}\frac{\partial K}{\partial X_j}\right\}+V_t S-\varepsilon$$

**Table 2** Super clean room design technology

| Area | | Cleanliness (particles/ft$^3$) | Particle diameter (μm) |
|---|---|---|---|
| Back | | Class 10,000 | 0.5 |
| Bay | Work | Class 100 | 0.3 |
| | Process | Class 1 | 0.1 |

Transport equation of turbulent dissipation rate $\varepsilon$

$$\frac{\partial \varepsilon}{\partial t}+\frac{\partial \varepsilon U_j}{\partial X_j}=\frac{\partial}{\partial X_j}\{\frac{V_t}{\sigma_2}\frac{\partial \varepsilon}{\partial X_j}\}+C_1\frac{\varepsilon}{X}V_t S - C_2\frac{K\varepsilon}{V}$$

Relation between turbulent vortex kinematic viscosity coefficient $V_t$, turbulent energy K, and turbulent dissipation rate $\varepsilon$

$$V_t=K^{1/2}L=\{C_D\frac{X^2}{\varepsilon}\}$$

Concerning the model constants $\sigma_1$, $\sigma_2$, and $C_2$ considered to affect the occurrence of turbulent vortices, the values of analysis by a parametric study were matched with the experimental values. The results are shown in **Fig. 9**. When $\sigma_1 = 0.9$, $\sigma_2 = 1.3$, and $C_2 = 1.92$, the computed turbulent flow properties agreed well with the measured turbulent flow properties.

5.3.2 Attempting creation of stable vertical laminar flow

When dust from operators and equipment is accumulated in the clean room as already described, it is raised by turbulent flow, sharply reducing the cleanliness of the clean room. For a super clean room, clean air must be vertically supplied from the entire ceiling, and dust and air in the room must be very rapidly removed through floor grating openings and underground air outlets. The air outlets are generally installed in underground wall surfaces due to equipment constraints. Air flows horizontally near the air outlets. This air flow obstructed the formation of completely laminar flow.

The conditions required for the stable formation of vertical laminar flow were obtained by using the microflow simulation technology while focusing on the change in pressure resistance stemming from the opening ratio of the floor grating. As a result, it was found that if the grating opening ratio was set at 25% as shown in **Fig. 10**, the formation of divergent flow under the influence of air outlets could be minimized to produce stable vertical laminar flow.

The results of field measurements are shown in **Figs. 11** and **12** and in **Table 3**. The divergent flow angle of 15° was observed in some portions, but full vertical laminar flow with a divergent flow angle of 14° or less was accomplished in other portions. An almost perfect, dust-free space was thus created.

**5.4 Summary**

In the past, construction of clean rooms involved expensive gratings with the function of adjusting the opening ratio. Much cost and labor were expended in adjusting the opening ratio of the

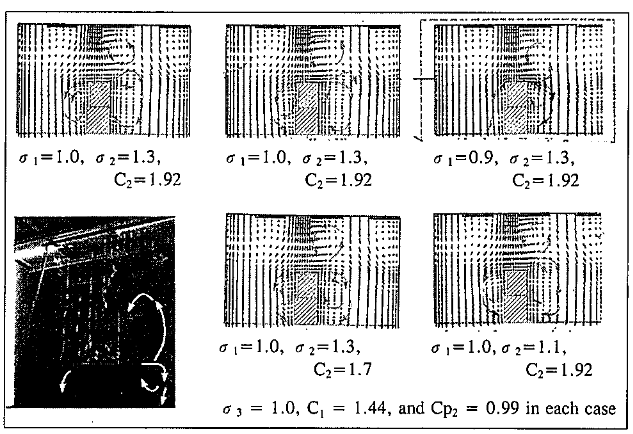


**Fig. 9** Analysis of turbulent flow properties

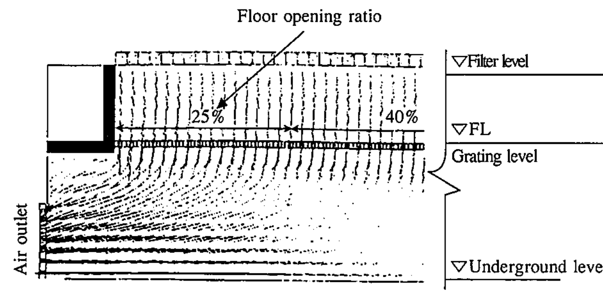


**Fig. 10** Results of air flow analysis in bay area (initial stage)

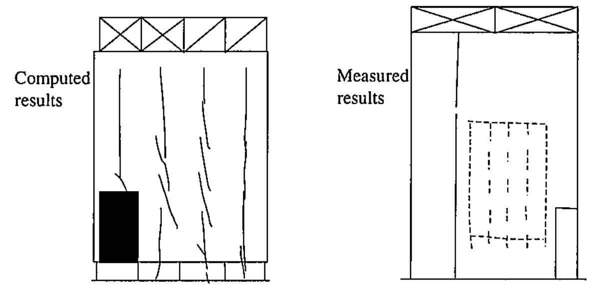


**Fig. 11** Verification of air flow properties in bay area (final stage, transverse section)

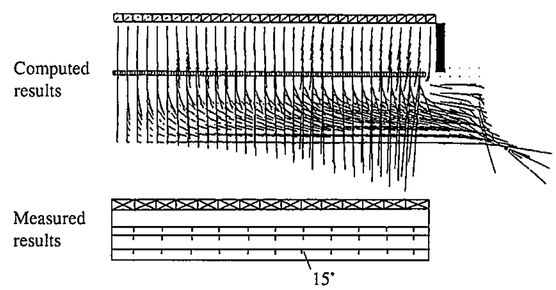


**Fig. 12** Verification of air flow properties in bay area (final stage, longitudinal section)

**Table 3** Results of cleanliness evaluation

| Area | | Dust particle diameter (μm) | Measurement No. | Dust particle concentration (particles/ft³) | | | | Remarks |
|---|---|---|---|---|---|---|---|---|
| | | | | 1st | 2nd | 3rd | Avg | |
| Bay | Process | 0.1 | 1 | 0 | 0 | 0 | 0 | |
| | | | 2 | 0 | 0 | 0 | 0 | |
| | | | 3 | 0 | 0 | 0 | 0 | |
| | | | 4 | 1 | 0 | 0 | 0.3 | ≦1 |
| | | | 5 | 0 | 0 | 0 | 0 | |

grating in the test run and adjustment phases of the clean room.

Now that technology is established for accurately predicting and controlling fully vertical laminar flow, Nippon Steel can eliminate surplus equipment, such as a grating adjusting the opening ratio, and reduce the labor required in the test run and adjustment phases. It is significant that Nippon Steel's original super clean room design technology has been developed in a short time.

## 6. Development of Technology for Analyzing Dust Diffusion in Plant Buildings

### 6.1 Background

The conventional dust emission control method for blast furnaces (BFs), basic oxygen furnaces (BOFs), and electric arc furnace (EAF) consisted of first accumulating dust from the furnace in the plant building attic space and then discharging it outdoors in small amounts. Temporarily storaging dust in the building degraded the working environment. In addition, a huge mechanical dust collection capacity was required to collect dust diffused throughout the plant building.

To improve the conventional ventilation method, a study was made of a new ventilation system capable of simultaneously achieving improvement in the working environment and reducing the mechanical dust collection capacity by mechanically collecting dust in local positions while utilizing the strong upward air flow created by natural ventilation from the dust source. See **Figs. 13** and **14**.

### 6.2 Basic concepts of technology development

To create the new ventilation system, it is necessary to understand the air flow direction and velocity that change from time to time with the combination of natural ventilation and local mechanical dust collection, and to understand dust diffusion in the plant building.

Specifically, advanced analytical technology can quantitatively predict and evaluate the diffusion of airborne dust particles under the influence of air flow, in addition to the air flow properties discussed in the preceding chapters. Next, the creation of a ventilation system that can handle on a common platform of dust diffusion analysis technology of mechanical dust collecting equipment designed by the mechanical engineers and a natural ventilating equipment designed by architectural engineers was studied. This system will achive efficient dust removal.

### 6.3 Actual steps of technology development

6.3.1 Establishment of dust diffusion analysis technology

When predicting dust diffusion, it is most important to clarify the relationship between the dust particle size and density, and ascertain the air flow at which the dust in question diffuses with air flow in the plant building or behaves differently from the air flow in the plant building.

The results showed that many of the dust particles range from 1 to 100 μm in diameter and that these dust particles settle at a constant speed under the influence of air viscosity. In other words, it was found that dust does not change in kinetic energy during settlement under gravity and that dust diffusion can be understood by developing the conservation law of the advection and diffusion of materials in a unit space as shown in **Fig.15**, instead of solving complex equations of motion concerning dust diffusion.[5-9]

As shown in **Figs. 16** and **17**, the dust diffusion analysis technology could simulate the status of dust diffusion with practical accuracy under multiple operating conditions of a steel plant, and could analyze dust diffusion in approximately the same time as air flow.

6.3.2 Study of efficient ventilation system

Using the analytical technology developed, an optimum plant building ventilation system that combines natural ventilation and local mechanical dust collection was discovered, as shown in **Fig. 16**.

In the steel plant investigated, the new ventilation system could locally draw high concentrations of dust by local dust collection methods before diffusion throughout the plant building, even when the mechanical dust collection air flow rate was reduced to about 80% of the past level. The system reduced the

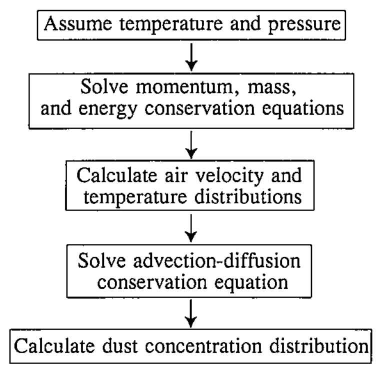


**Fig. 15** Flow chart of dust diffusion analysis

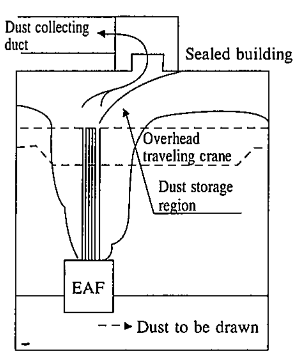


**Fig. 13** Conventional building dust collection method

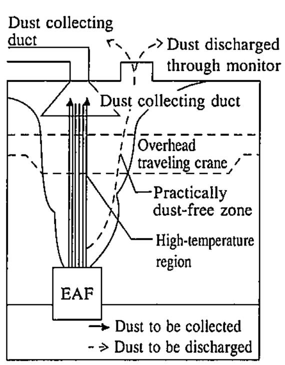


**Fig. 14** New building dust collection method

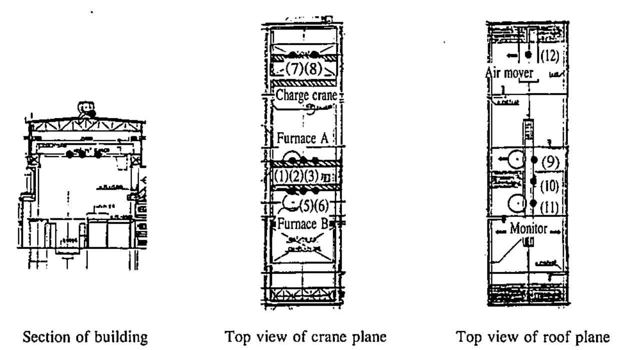


**Fig. 16** Outline of plant building

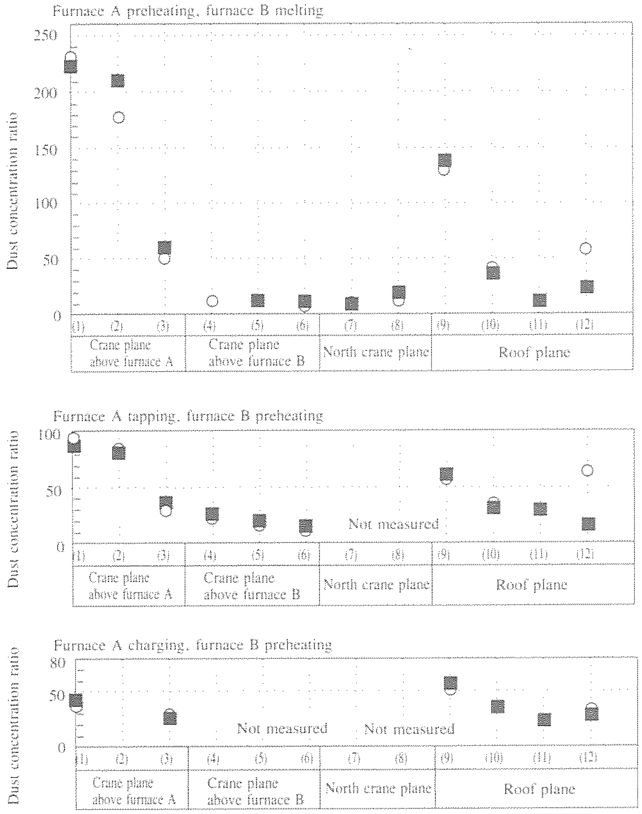


Fig. 17 Results of dust diffusion simulation (■: computed, ○: measured)

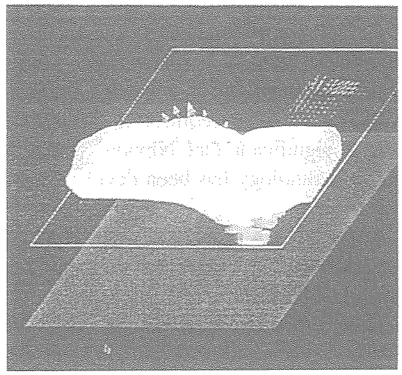

Fig. 18 Simulation results of natural ventilation

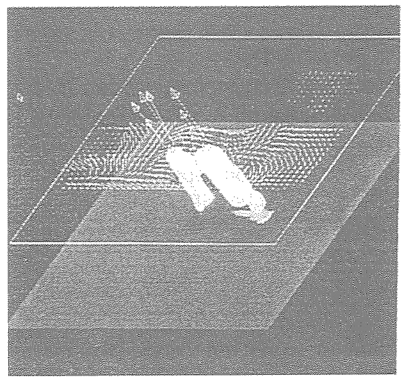

Fig. 19 Simulation results of natural ventilation and local mechanical dust collection in combination

dust concentration to one-fifth of the present level at the operating floor where workers are stationed (see **Figs. 18** and **19**). It was also found that dust carried out of the roof monitors by natural ventilation was reduced to an invisible extent in nearby and outlying areas.

If the mechanical dust collector were installed in a position that did not interfere with plant operation or crane travel, or at an intermediate position between the furnace and the roof plane, the volume of air to be drawn by the mechanical dust collector could be reduced to about 60% of the present level. As a result, electric power and other running costs as well as equipment costs could be substantially reduced.

### 6.4 Summary

In this project, technology was established for tracking not only air flow as in the past, but also dust that diffuses together with air flow. A new method of improving the working environment by combining natural ventilation and local mechanical dust collection was proposed with quantitative data.

## 7. Conclusions

New working environment design technology has been systematically established as a result of experiment, analysis, measurement, and evaluation repeated by positioning accurate air flow prediction and control as basic air flow control technology, and by making effective use of engineering and construction opportunities.

When we turn our attention from indoor to outdoor space, needs for reducing dust emissions from steel plants to surrounding areas became apparent. When paying attention to the relationship between airborne particles and air flow, it is necessary to clarify all natural phenomena associated with air, such as dew condensation by water vapors and entry of water droplets into plant buildings.

The authors will continue their steadfast efforts to expand the menu and applicability of their working environment design technology on the basis of air flow.

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