

Jet Flow Characteristics of 3-Slot Nozzle at Gas Wiping Process in CGL

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Abstract:

The single-slot gas wiping is commonly used in coating weight control of continuous galvanizing lines (CGL). In the gas wiping process, it requires more efficient coating controllability and avoiding surface defects on the steel sheet. A multi-slot nozzle with two auxiliary slots arranged on the two sides of the main slot attracts attention. JFE steel investigated relationship between the mixed jets behavior and the wiping capability. This study revealed that the velocity difference between the center slot jet flow and the ambient gas decreases due to the auxiliary slot jets, and diffusion of the jet flow is suppressed due to a reduction in the turbulent kinetic energy at the two sides of the center slot jet, then the wiping capability can be improved.

1. Introduction

Gas wiping is used for coating weight control in Continuous Galvanizing Lines (CGL) which produce coated steel sheets for automobiles, building materials and electric appliances. Because the impinging gas jet wipes the excess molten zinc from the steel strip, gas wiping provides a noncontact method for controlling the coating weight. Gas wiping has advantages such as uniformity in the width direction, the ability to produce a thin plating and economy. Usually, a single-slot gas nozzle (hereinafter, 1-slot nozzle) is installed above the molten zinc pot. The gas wiping mechanism is essentially established theoretically¹⁻⁴.

From those results, control of the gas jet pressure in gas wiping should make it possible to increase the CGL

line speed in order to realize higher productivity. However, wiping performance is limited by the need for a thin plating capability⁵) and the problem of the surface defect called splashing⁶). In recent years, multi-slot gas nozzles have been investigated with the aim of overcoming these problems⁷⁻⁸). However, the influence on wiping performance and changes in the formation of the three jets depending on the velocity of the auxiliary slot jets have not been clarified.

The main objective of the present study is to clarify the mechanism of jet mixing with a 3-slot nozzle developed by JFE Steel and the effect of jet mixing characteristics on coating weight control. The impinging pressure distribution and the jet formation were analyzed under several pressure conditions by Computational Fluid Dynamics (CFD), and wiping performance was examined by using the same model wiping apparatus as in previous studies⁹⁻¹⁰).

2. Mathematical Model of Coating Thickness

As a mechanism of coating thickness control by gas wiping, the following concept is known²⁻³). As shown in **Fig. 1**, the impinging pressure of the gas wiping jet on a steel strip causes a pressure gradient, and this pressure gradient and the shear stress of the wall jet that flows along the steel strip surface act on the molten zinc layer adhering to the strip after the strip passes through the zinc pot. The liquid film thickness is predicted by this gas wiping mechanism under the following basic assumptions:

- ① The fluid flow in the liquid coating film flow can

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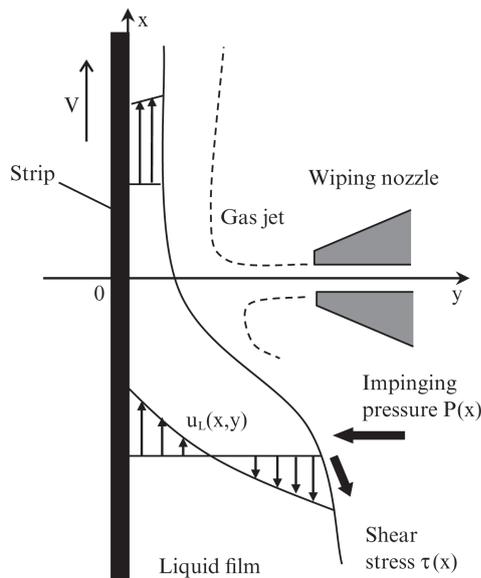


Fig. 1 Analytical model of gas wiping

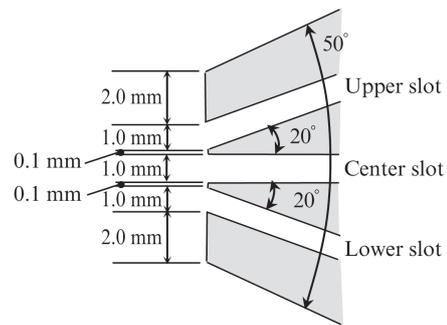


Fig. 2 Tip shape of 3-slot gas wiping nozzle

determine dp/dx and τ^{11}). On the other hand, there are few studies on the jet characteristics of multi-slot nozzles such as 3-slot nozzles. As a form close to that, earlier studies have examined the mixing and diffusion behavior of a coaxial circular jet¹¹).

be described by a steady state, two-dimensional equation of incompressible, constant viscosity. The flow perpendicular to the strip is sufficiently small relative to the flow parallel to the strip.

② Surface tension, oxidation effects, strip surface roughness and interfacial alloy formation can be neglected.

③ There is no slip between the fluid coating and the strip at the strip-fluid interface.

Solving the equation of motion of the coating liquid film under these assumptions, the film thickness can be expressed as:

$$T = \frac{S + \sqrt{S^2 + 4G}}{2G} \dots\dots\dots (1)$$

where, $T = t\sqrt{\rho_L g / \mu_L V} \dots\dots\dots (2)$

$$S = \tau / \sqrt{\rho_L \mu_L V g} \dots\dots\dots (3)$$

$$G = 1 + (dp / dx) / \rho_L g \dots\dots\dots (4)$$

T , S and G are non-dimensional numbers related to gas wiping. T is the non-dimensional film thickness, S is the non-dimensional wall shear stress, G is the non-dimensional pressure gradient, μ_L is the viscosity of the coating liquid, ρ_L is the density of the coating liquid, g is the acceleration of gravity, P is the impinging pressure, t is the local film thickness and V is the strip travel velocity. The pressure gradient (forced by the wiping jet) dp/dx and wall shear stress τ decide the coating film thickness. In the case of a 1-slot nozzle, the combination of the slot nozzle gap, the jet pressure and the distance between the strip and the nozzle tip uniquely

3. Experimental Procedure and Numerical Analysis

3.1 3-Slot Nozzle

In comparison with 1-slot nozzles, the jet characteristics of 3-slot nozzles are affected by a number of parameters, such as the nozzle geometry and gas jet conditions. A previous study⁹) by some of the same authors indicated that the distance between the main slot and the auxiliary slots has a remarkable influence on the formation of the jets after the three jets merge. In particular, wiping performance was improved by shortening the distance between the main slot and the auxiliary slots. **Figure 2** shows a schematic diagram of the tip shape of the 3-slot gas wiping nozzle used in this paper. Based on the previous report, the distance between the main slot and the upper/lower auxiliary slots was set at 0.1 mm. In addition, it is estimated that the jet angle of the auxiliary slot (angle of the main slot and the auxiliary slots) greatly influences jet formation. Since wiping performance improves as the nozzle outer angle becomes more acute¹²), wiping performance is expected to change due to factors other than the slot jet if the outer angle is changed from the 50° of the nozzle used in the previous study. Therefore, in the present study, one kind of 3-slot nozzle with a nozzle outer angle of 50° and upper/lower nozzles with jet angle inclinations of 20° arranged symmetrically above/below the center slot was tested. A photograph of this nozzle is shown in **Photo 1**. Here, the gaps D of the center, upper and lower slots were all 1.0 mm, and the slot width was 250 mm.

3.2 Experimental Gas Wiping Simulator

Wiping performance was investigated by using the

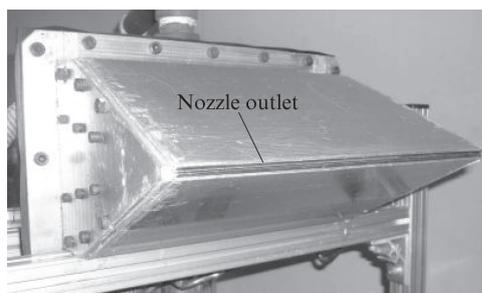


Photo 1 Photograph of 3-slot wiping nozzle

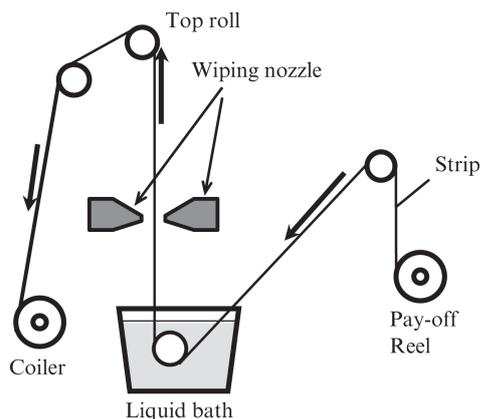


Fig. 3 Experimental gas wiping apparatus

previously-developed gas wiping simulator⁹⁻¹⁰). The arrangement of the experimental apparatus is shown in **Fig. 3**. In this apparatus, the strip in coil form is paid off from the pay-off reel and immersed continually in the coating liquid bath. The coating weight of the liquid is controlled by mutually-opposed wiping nozzles arranged above the coating bath, and the strip is then coiled by the coiler. Wiping conditions such as the nozzle jet angle, wiping gas pressure and distance between the strip and nozzle can be set optionally. In this experiment, the tilt angles of the two wiping nozzles were fixed at 0.0° (i.e., horizontal).

Paraffin having a melting point of approximately 60°C was used as the coating liquid, and the bath temperature during the experiment was 90°C , that is, approximately 30°C higher than the melting point. The liquid paraffin cooled about 10°C while passing the wiping nozzles but did not solidify before the strip arrived at the top roll, which was located 1.5 m above the wiping nozzles. **Table 1** shows a comparison of the physical properties, gas wiping conditions and non-dimensional numbers T , G and S of the molten zinc used in the actual CGL and the paraffin used in this experiment. Because the non-dimensional numbers T , S and G of the simulator were within the ranges of those of the CGL, and the coating thickness obtained with the simulator was in good agreement with the value predicted from the mathematical model men-

Table 1 Physical properties of coating materials, conditions of coating process and values of dimensionless numbers

	CGL	Wiping simulator
Coating material	Zinc	Paraffin ^{*1} (HNP-5)
Operation temperature ($^\circ\text{C}$)	460	90
Coating density (kg/m^3)	6 623	759
Coating viscosity ($\text{Pa} \cdot \text{s}$)	0.00294	0.0071
Coating surface tension (N/m)	0.81	0.0026 ^{*2}
Nozzle - strip distance (mm)	5-10	10
Transfer speed (m/s)	1.0-2.5	0.67
Plenum pressure (kPa)	10-70	1.5 (center slot) 0-1.0 (upper, lower slot)
T	0.024-0.074	0.03-0.04
S	0.5-3.0	0.6-1.0
G	50-500	230-460

*1 NIPPON SEIRO CO. HNP-5

*2 Maker's publication

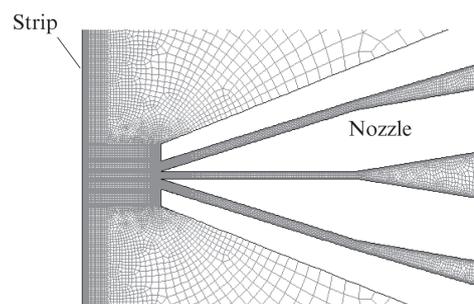


Fig. 4 Example of mesh for CFD analysis

tioned above⁹), it is thought that hydrodynamic similarity is established between the CGL and the simulator. When zinc is coated on a steel strip, an alloying reaction may occur. However, no such reaction occurs at the interface of the paraffin and the metal. This means that verification purely in terms of gas wiping theory is possible. In this experiment, the coating weight was measured by comparison of the coating weight before/after delamination in order to quantify the mean coating weight of a relatively large area precisely.

3.3 Numerical Simulation of Wiping Gas Jet

The formation of the jet from the nozzle slot to the strip was investigated by two-dimensional steady analysis using the commercial code Fluent 14.5. Realizable $k-\epsilon$ was adopted as the turbulent model because it is considered more suitable for analysis of a two-dimensional jet than the standard $k-\epsilon$ model¹³). Enhanced wall treatment, which combines the standard wall function model with the near wall model, was adopted

for treatment of the near wall¹⁴). An example of the calculation mesh is shown in Fig. 4. The mesh number was approximately 80 000. The validity of this CFD analysis was confirmed by comparing the analysis results with the measured impinging pressure distribution¹⁰.

4. Experimental Results and Discussion

4.1 Influence of Auxiliary Slot Jets on Wiping Performance

The paraffin wiping experiment was carried out under the conditions shown in Table 1. The header pressure of the center slot was fixed at 1.5 kPa, and the upper/lower slot jets were injected individually or simultaneously at pressures from 0.2 kPa to 1.0 kPa.

Figure 5 shows the experimental results. The results for the upper/lower slot pressures of 0.0 kPa indicate the coating weight in the case of injection only from the center slot. In comparison with the cases of individual injection of the jet from the upper or lower slot,

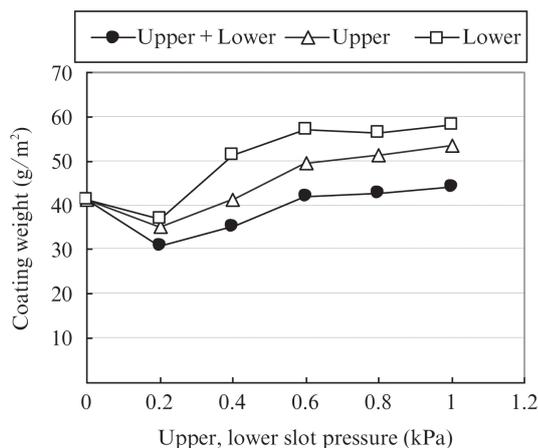


Fig. 5 Coating weight in paraffin wiping experiments with 3-slot wiping nozzle

the greatest improvement in wiping performance was achieved in the case of simultaneous jetting from the upper and lower slots in this gas pressure range, and a thin coating film was obtained. Comparing injection of only the upper slot jet with only the lower slot jet, a somewhat thinner paraffin thickness was achieved with the upper slot jet. Focusing on the influence of gas pressure, the coating weight was the lowest at the upper or lower slot pressure of 0.2 kPa with all jet patterns, and the coating weight increased when the gas pressure exceeded 0.2 kPa. With the conventional 1-slot nozzle, the coating weight decreases as the wiping gas pressure increases, as predicted from the mathematical model of gas wiping presented above. However, with the 3-slot nozzle, these results showed that increasing the jet pressure does not necessarily lead to an improvement in wiping performance due to variations in the formation of the center jet flow caused by the upper/lower slot jets.

Figure 6 shows the calculated impinging pressure distributions obtained by CFD. Here, the x direction position on the horizontal axis is translated to a non-dimensional position by the slot gap D . As the slope of the impinging pressure distribution becomes steeper, the non-dimensional number G in the gas wiping equation (4) increases, which means that wiping performance improves. Therefore, the jet characteristics at the upper and lower slot pressure of 0.2 kPa, which reduced the coating weight in comparison with the 1-slot nozzle, and the jet characteristics at 1.0 kPa, which increased the coating weight in comparison with the 1-slot nozzle, were investigated in detail. Fig. 6(a) shows the calculated impinging pressure distributions when the center, upper and lower slots are jetted together. In comparison with jetting from only the center slot, when the pressure of the upper and lower slots is 0.2 kPa, the maximum pressure increases without an accompanying increase in the width of the impinging pressure distribution, and the impinging pressure dis-

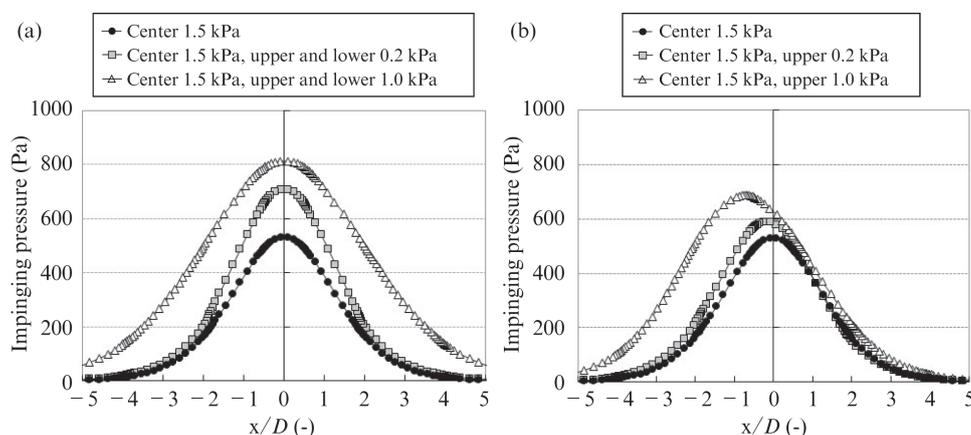


Fig. 6 Calculated impinging pressure distribution on strip surface

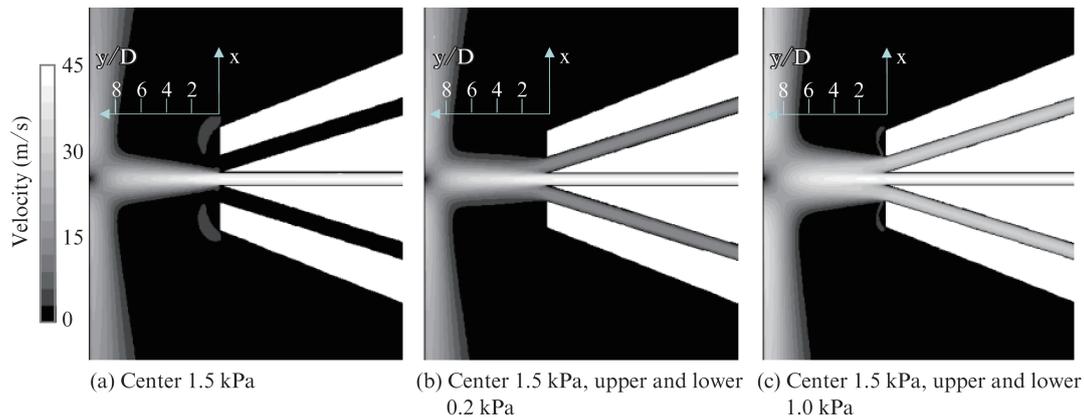


Fig. 7 Velocity contours of 1-slot and 3-slot jet

tribution is steeper than the distribution with only the center slot. However, at the upper/ lower slot pressure of 1.0 kPa, a further increase in the maximum impinging pressure is

observed, but the width of the impinging pressure distribution also increases, becoming more than double, and the pressure gradient becomes somewhat more moderate. Fig. 6(b) shows the impinging pressure distributions when the center and upper slot were jetted together. Due to the upper slot jet, the pressure distribution becomes asymmetrical, and the x position of the maximum pressure shifts slightly to the lower side ($x/D < 0$) of the center slot position. Furthermore, the jet flow is formed with different pressure gradients on the upper side ($x/D > 0$) and the lower side ($x/D < 0$). It is estimated that this variation in jet formation will influence wiping performance.

4.2 Jet Flow Formation of 3-Slot Nozzle

As an example of the formation of the jet flow by mixing of the flows from the three slots from the nozzle tip to the strip, the velocity contours calculated by CFD are shown in Fig. 7 (a) for the center slot pressure of 1.5 kPa, in (b) for the center slot pressure of 1.5 kPa and upper/lower slot pressures of 0.2 kPa and in (c) for the center slot pressure of 1.5 kPa and upper/lower slot pressures of 1.0 kPa. In this simulation, the gas jet velocity is 42 m/s at 1.5 kPa, 15 m/s at 0.2 kPa (35.7% of center slot velocity) and 32 m/s at 1.0 kPa (76.2% of center slot velocity). In comparison with (a), the decrement of the center slot jet weakens in (b) and (c), and the high jet velocity is kept until further to the rear. Thus, in the region near the nozzle, it is possible to compare the jet flow mixing behavior by using the velocity distribution. However, a simple comparison of mixing behavior by using only the velocity distribution is difficult in the wall jet region near the strip because the dynamic pressure of the jet flow is converted to static pressure on the strip in the wall jet region, and

the jet directions and half-width of the wall jet also change. Therefore, in this paper, the jet mixture process was investigated by the total pressure distribution, which was defined as the sum of the dynamic pressure and static pressure in the CFD analysis. The total pressure transition from the nozzle tip to the near-strip region ($y/D=0-8$, nozzle tip is $y=0$) is shown in Fig. 8. This figure shows the calculated result for (a) only center slot with pressure of 1.5 kPa (1 jet), (b) and (c); center slot + upper/lower slots (3 jets) and (d) and (e); center slot + upper slot (2 jets).

In (b), where the upper/lower slot pressures are 0.2 kPa, peaks of the dynamic pressure due to the upper and lower slot jets can be seen after jetting ($y/D=0$), but these peaks disappear quickly at $y/D=2$ due to merging of the three jets, and the jet takes a shape approaching that of single jet. Because the velocity difference between the center jet and the ambient gas is reduced by the slow jets from the upper/lower sides, the decrement of the center jet is suppressed and the impinging pressure near the strip increases. Wiping performance is improved by this kind of jet formation. In (c), where the upper/lower slot pressure is 1 kPa, the peaks caused by the upper/lower jets remain at $y/D=4$. After this point, complete mixing occurs and jet diffusion progresses. Under this condition, the pressure distribution is gentler than that of the 1-slot jet.

In (d), which is a 2-slot arrangement with the upper slot pressure of 0.2 kPa, jet formation is the same as in (b) on the upper side ($x/D > 0$) and the same as (a) on the lower side ($x/D < 0$). In this case, the peak of the total pressure does not increase so effectively because suppression of center jet diffusion is insufficient with only one auxiliary jet. These results indicate that supplying slow auxiliary jets from both sides of a center jet is effective for suppressing diffusion of the main slot jet. In (e), which is the 2-slot arrangement with the upper slot pressure of 1.0 kPa, the pressure gradient at $x/D < 0$ changes to an extremely sharp form due to

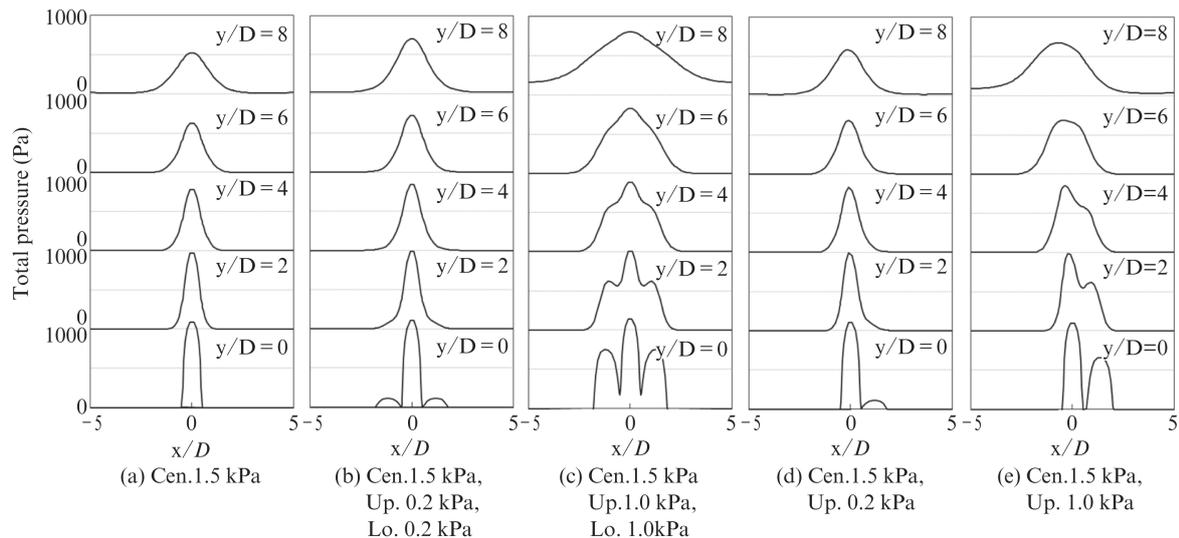


Fig. 8 Total pressure distributions between nozzle tip and strip with single, 2-slot and 3-slot jets

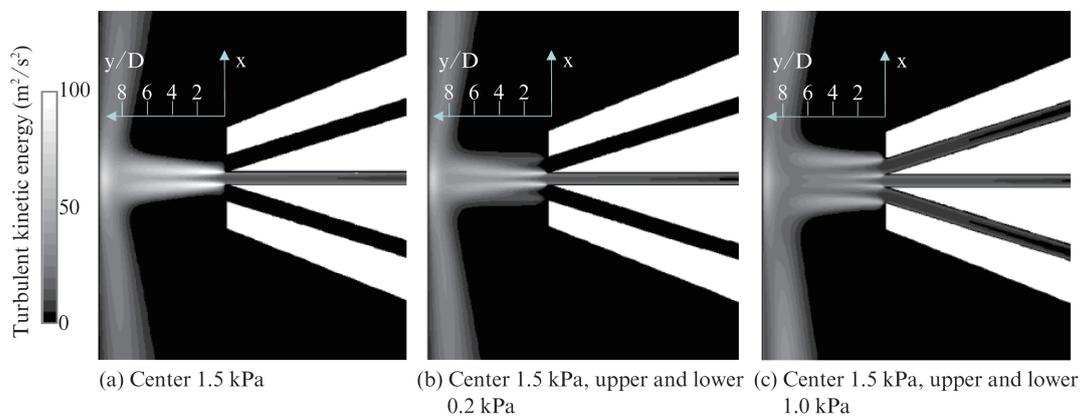


Fig. 9 Turbulent kinetic energy contours of 1-slot and 3-slot jets

deviation of the center jet to the lower side. This behavior can be observed until about the $y/D=4$ position, that is, before the two jets mix completely. Although this jet pattern might appear to improve wiping performance, the pressure gradient moderates quickly after the two jets mix, and wiping performance deteriorates at $y/D=10$.

In order to estimate the diffusion of the two-dimensional jet flow discussed above more directly, the turbulent kinetic energy (k of the $k-\varepsilon$ model) calculated by CFD will be compared. **Figure 9** represents the turbulent kinetic energy distributions under the same conditions as in Fig. 7. For the center slot jet, under condition (a), i.e., jetting into a static gas, the large velocity difference on the two sides of the jet causes strong turbulent kinetic energy. On the other hand, under condition (b), that is, low-speed jetting with auxiliary jets, the turbulent kinetic energy on the two sides of the center slot jet decreases due to the lower velocity difference with the ambient gas. Moreover, since remarkable turbulent kinetic energy is not generated on the outer sides of the upper/lower slot jets, this energy does not

have a large influence on the jet width after mixing. Comparing the integral value of the turbulent kinetic energy in the flow field from the nozzle tip to the strip ($-4 \leq x/D \leq 4$, $0 \leq y/D \leq 10$), assuming the value of (a) is 100, the value of (b) is reduced to 79.3, or a reduction of about 20%. However, in the case of (c), which is the case of high-speed auxiliary jets, the width of the mixed jet increases to the equivalent of the width of the three jets due to the increased turbulent kinetic energy at the outside of the auxiliary jets in comparison with that at the sides of the center jet. As a result, the integral value of (c) is 84.7. In other words, the turbulence in the total flow field increases under condition (c) in comparison with (b).

5. Conclusion

In order to clarify the function of the auxiliary slot jets in the wiping performance of a 3-slot nozzle, gas wiping experiments were performed with liquid paraffin, and a CFD analysis was carried out. The results are summarized as follows.

- (1) When the center slot pressure was 1.5 kPa, wiping performance was improved by upper/lower slot pressures in the range of 0.2–0.4 kPa. However, wiping performance gradually deteriorated with further increases in the upper/lower slot pressure. Simultaneous use of the upper and lower slot jets improved wiping performance.
- (2) The pressure gradient is sharp under jet conditions that improve wiping performance (upper/lower slot pressure: 0.2 kPa), and the pressure gradient is moderate under jet conditions that deteriorate wiping performance (upper/lower slot pressure: 1.0 kPa).
- (3) The velocity difference between the center slot jet flow and the ambient gas decreases due to the auxiliary slot jets, and diffusion of the jet flow is suppressed due to a reduction in the turbulent kinetic energy at the two sides of the center slot jet. If the auxiliary jet velocity is set low, for example, to around 35% of the center jet velocity, the jet width does not spread after mixing of the three jets. However, if the auxiliary slot jet velocity is increased, the outer edge of the auxiliary slot jets becomes the outer edge of the mixed jet, and in effect, the width of the mixed jet spreads. As a result, the impinging pressure gradient becomes more moderate and wiping performance deteriorates.

As described above, in gas wiping with multi-slot nozzles, the center slot diffusion behavior and the width of the mixed jet change remarkably depending

on the flow of the upper/lower auxiliary slot jets, and wiping performance is affected by these changes. Thus, in addition to estimation of the impinging gas pressure, this study revealed that the turbulence in the flow field is also an important parameter for designing a 3-slot nozzle and optimizing its operational conditions.

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