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A study on the air knife flow with Coanda effect

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Abstract

The coating thickness in hot-dip zinc galvanizing process is of practical importance in determining the quality of product, and its control is often done using the gas wiping through an air knife system. Such a gas wiping method causes a technical problem of splashing from the strip edge to have a harmful effect on the performance of the galvanizing process and the product quality. The present study aims at investigating the effectiveness of Coanda nozzle to reduce the strip splashing problem. A blow-down wind tunnel has been used to experimentally investigate the detailed flow field near the exit of Coanda nozzle and on the strip edge. A computational work has been performed with the help of a computational fluid dynamics method. The three-dimensional, compressible Navier-Stokes equations have been solved using a fully implicit finite volume scheme. The results obtained show that Coanda nozzle effectively reduces the splashing problem, leading to improvement of the whole galvanizing process.

Keywords: Air knife; Coanda effect; Edge splashing; Gas wiping; Hot-dip galvanizing; Impinging jet

1. Introduction

In the process of a continuous hot-dip galvanizing, the gas wiping technique using an air knife system has been employed to control the coating thickness of the galvanizing, which is of practical importance in determining the product quality. According to the previous studies [1-3], the gas wiping technique gives uniform, thin coating thickness as well as shortening the whole galvanizing process, with a simple device. However, a problem of splashing from the galvanizing strip edge [4] is one of the factors to limit the performance of the process and to deteriorate the quality of the coating product. In general, it has been known that the splashing phenomenon is arisen mainly from the active interaction between the jet stream and the galvanizing liquid film, influencing the flow field at the neighbor of the strip edge [5].

In these connections, Takeishi et al. [6] investigated the detailed mechanism of splashing from the strip edge in gas wiping, and reported that a narrow nozzle slit is available to reduce the splashing, and the short distance between the nozzle lip and the strip surface is of help in yielding low pressure wiping. Thorton et al. [7] demonstrated that the maximum gradient of the impinging pressure on the strip surface is closely related to the square of coating thickness.

Fig. 1 illustrates the splashing mechanism from the strip surface in hot-dip zinc galvanizing process. The strip metal to be galvanized is moving upward through a viscous liquid bath.

Due to viscous forces, the metal strip picks up a film of liquid, and gravity acts the liquid film drain down the strip. The jet stream discharging from the air knife impinges on the metal strip with the liquid film, making the coating thickness thin and uniform. Some part of the impinging stream goes down and interacts with the thick liquid film flow near the liquid bath. Resulting wall jet causes low pressure region outside the thick liquid film, leading to a lift force. At

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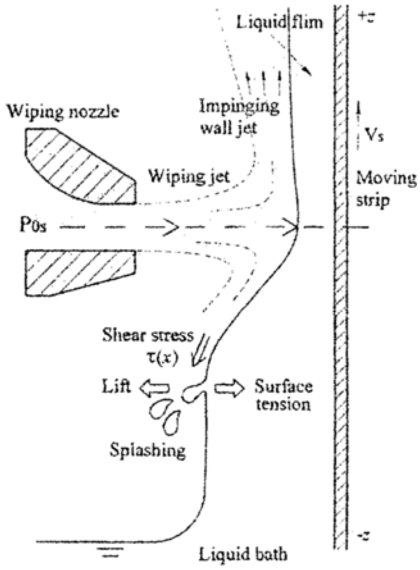


Fig. 1. Mechanism of splashing from strip surface in hot-dip zinc galvanizing process.

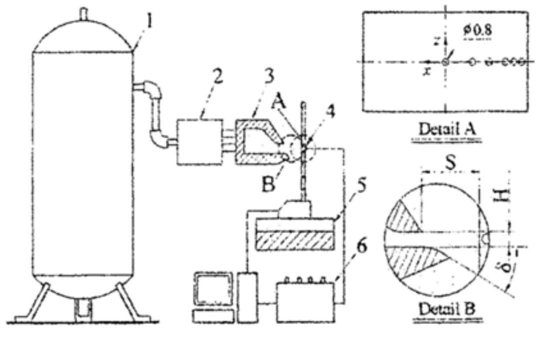
the same time, a surface tension acts on the liquid film. These two forces are key parameters to determine the splashing phenomenon.

From the flow field mentioned above, it is believed that the splashing problem can be lessened by controlling the direction of the wall jet. For the purpose of such a wall jet control, Coanda nozzle may be available to improve the performance of the galvanizing process [8]. The present study aims at investigating the effectiveness of the Coanda nozzle for the conventional air knife.

A computational work has been performed with the help of a computational fluid dynamics method. The three-dimensional, compressible Navier-Stokes equations have been solved using a fully implicit finite volume scheme. To validate the present computational results, experimentation has been carried out using a blow down wind tunnel. Several types of Coanda nozzles have been designed to find out a desirable configuration to alleviate the splashing problem, for several different supply pressures that leads to subsonic jet at the exit of nozzle. The results obtained show that the present Coanda nozzle can reduce the splashing problem in the galvanizing process.

2. Experimental work

Fig. 2 shows the schematic and specification of experimental apparatus used in the present experiment. The test rig consists of pressure tank ($6m^3$), moist trap,



① High-pressure tank ② Plenum chamber
③ Air knife system ④ Pressure measuring taps
⑤ 3-axis auto-traverse ⑥ 16CH scanning valve
H : Slit height S : Gap distance
δ : Deflection angle

Fig. 2. Schematic of experimental apparatus.

pressure regulator, air knife body, vertical strip metal, 3-axis auto-traversing unit, 16 channel scanning valve (model: DSA-3017), and data acquisition system. The width of the air knife nozzle lip is 150mm, and the width and length of the vertical strip are 130mm and 300mm, respectively. And the gap between the nozzle lip and strip surface is fixed to be constant at 10mm.

A and B parts in the figure are illustrated in more detail on the right side, the diameter of pressure tap is 0.8mm, the interval between the tap holes at the neighbor of the strip edge is denser than that for the neighbor of the center and 6 kinds of deflections of δ=0°, 9°, 12°, 15°, 30° and 45° are used.

The error of pressure sensor installed at the scanning valve is ±0.05% in full scale, and the scan rate is 200 samples per channel and second. The averaged value of measuring of 3,000 times at a measuring point of the strip surface is decided as the impinging pressure at that point. And we use 3-axis auto-traversing unit (model: MI-ATS300) to measure the impinging pressure at the strip surface.

The operating pressure is 169.3kPa(abs) which is the starting value of the edge splashing at 2.5m/s in strip velocity V_s.

Meanwhile, we performed cold test except for the molten liquid due to the limitation of the experimental apparatus.

3. Computational analysis

In the present computational work, we use the commercial code of Fluent 6.0, in which the equations of continuity, three-dimensional time dependent

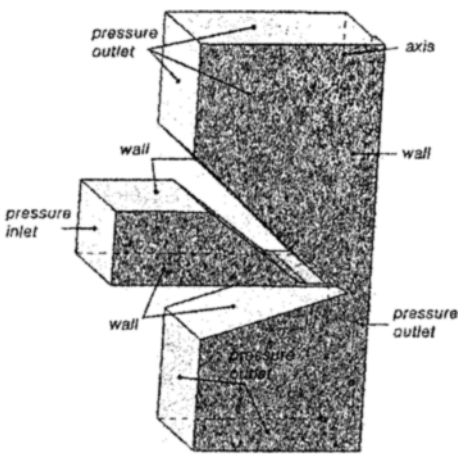
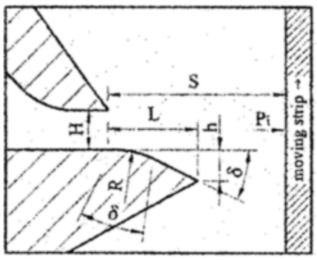


Fig. 3. Computational domain and boundary conditions.



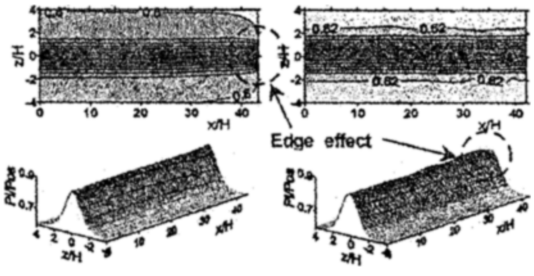
δ	H	L	R	h
0°		0	0	0.0
9°				0.8
12°				1.1
15°	1.5	6	10	1.3
30°				1.9
45°				2.9

Fig. 4. Detailed configuration of Coanda nozzle (unit: mm).

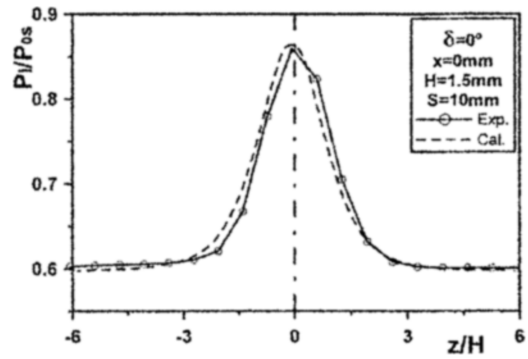
full Navier-Stokes, energy, state and so on are used as the governing equations. In calculation of viscosity of the working fluid, we use the equation suggested by Surtherland, also use the standard k-ε turbulence model to solve the turbulence stress.

Fig. 3 shows the schematic computational domain and boundary conditions specifically. The grid in the regions having the large possibility of changing in pressure, velocity and so on like an exit of air knife or Coanda nozzle surface makes densely. The numbers of mesh and mesh type are about 200 thousands and hexagon, respectively. Working fluid is air, and assumed to be thermally and calorically perfect. The downstream pressure and temperature of pressure regulator that is, the plenum chamber pressure and temperature are constant to be 169.3kPa(abs) and 300K, respectively. The symmetric condition is used on the strip centerline to reduce the exceeding computational time.

Fig. 4 shows the schematic and specification of the nozzle system using the Coanda effect with the variations of deflection angle δ used in the present experimental and computational works.



(a) Computation (b) Experiment



(c) Pressure distribution on the strip surface

Fig. 5. Validation of the present computational result (δ=0°).

4. Results and discussion

Fig. 5 shows the results of distribution of impinging pressure on the strip surface by experimental and computational works to confirm the validation of numerical method for the case of conventional air knife that is δ=0° in deflection angle(No Coanda lip). In here, the plenum chamber pressure is 169.3 kPa(abs), the air knife slit height is H=1.5 mm and the gap between the nozzle lip and strip surface is S=10 mm.

The result by computational work well agrees with that of experimental one. From this result, we can confirm the validation of numerical method used in the present study. Also as shown in the dashed circles of Fig. 5(a) and (b), the side edge effect caused by the reason of easiness of jet flowing to the surroundings well appeared in the strip edge. As a result, the impinging pressure at the neighbor of the strip edge becomes small against to that for the neighbor of the strip center.

From view point of uniformity of coating thickness, to obtain good uniformity, it is necessary to use an air knife with the variable area lip in slit.

In special, the comparison between the results by experimental and computational works in the distribution of impinging pressure along z at the strip center is shown in Fig. 5(c), from which we can find that the result by experimental work well agree with the result by computational one.

To find the optimum deflection angle of a Coanda nozzle to be used in an air knife system for the conditions of the conventional air knife system for continuous hot-dip galvanizing, we performed a first stage experiment and numerical analysis. So, at first the study for 4 kinds of deflection angles of δ=0°, 15°, 30° and 45° is performed. And, the results in the distributions of impinging pressure with the variations of deflection angle of the Coanda nozzle by the experimental and computational works are shown in Fig. 6.

As shown in figures, the larger the deflection angle is, the lower the peak value in impinging pressure is, and the position of the peak value moves to the downward of the strip. But the impinging pressures for the cases of δ=30° and 45° are so small that we are not sure whether it can use effectively for an air knife. As presented in Fig. 6(c), the peak pressure P_i/P_{0s} appears relatively high between δ=0° and 15°, and it significantly reduces as the deflection angle increases to δ=30° and 45°. Therefore we believe that optimum deflection angle can exist in between δ=0° and 15°. An air jet flowing along Coanda lip is separated from the surface after the deflection angle reaches at a value. This critical angle will be changed according as plenum chamber pressure or nozzle slit height are changed.

Therefore a range of angle that the peak value in impinging pressure maintains highly same as conventional air knife is varied. From these results, we can conclude that there exists the optimum value in the deflection of the Coanda nozzle for the given plenum chamber pressure and nozzle slit height. Because the Coanda effect is clear, and there is little pressure loss which can be confirmed from the comparison of the distribution of the maximum impinging pressure between the air knives with and without a Coanda nozzle, it is expected that the optimum value of deflection angle in the present condition may exist in the around δ=15°. So, the defection angles are decided again as δ=0°, 9°, 12° and 15° based on the result achieved from the first stage study, and the additional experiment and computational works are performed for these new 4 kinds of deflection angles.

Fig. 7 shows the distribution of stream line with the variations of deflection angle of a Coanda nozzle by computational work. The entrained flows from up and down region of nozzle clearly appear, and the jets deflected by the Coanda nozzle impinge obliquely to the strip surface in the Fig. 7(b)-(d).

From these figures, we can expect that a lump of coating liquid will be pushed more to downward and wall shear stress will be increased by deflection of jet. The splashing will be delayed or suppressed, and a cutting ability will be enhanced for the same operating condition [7].

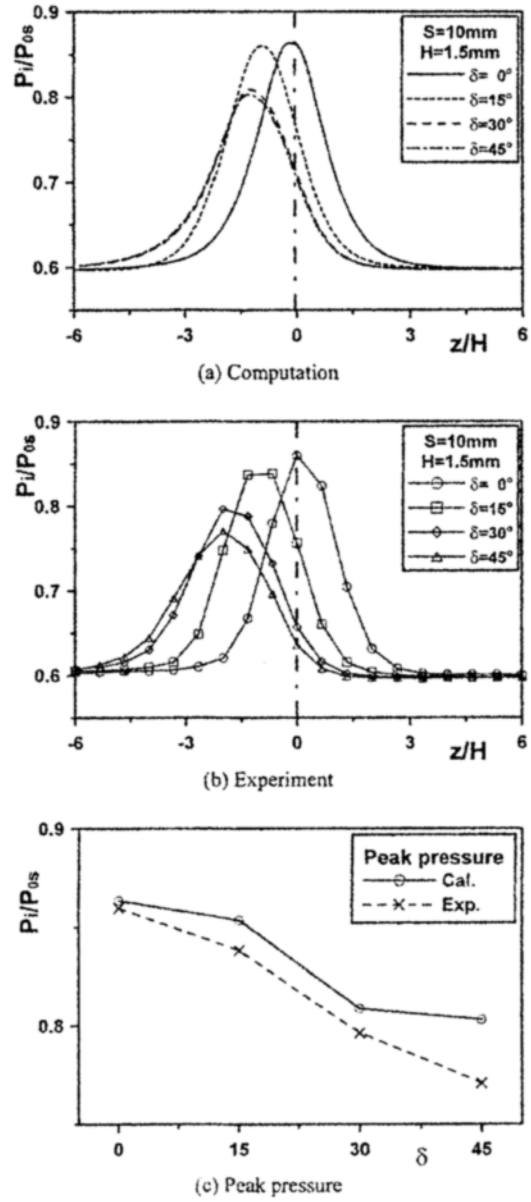


Fig. 6. Distribution of the impact pressure on the strip surface.

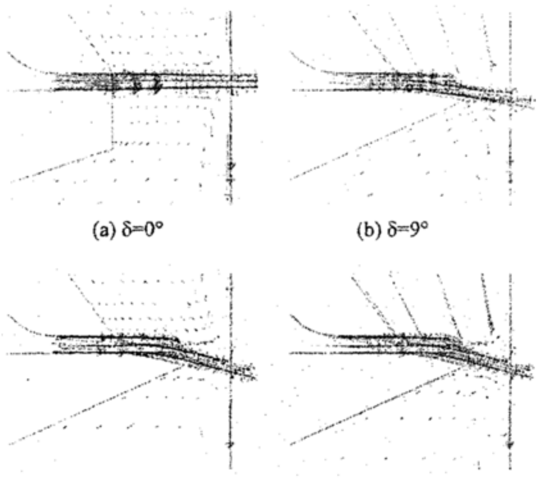
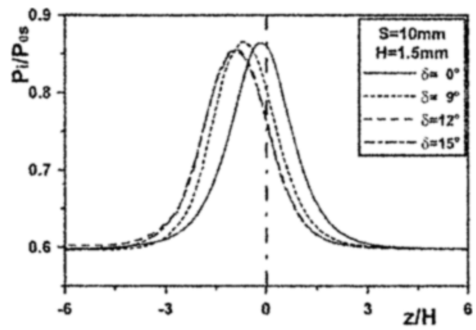

(a) δ=0° (b) δ=9°
(c) δ=12° (d) δ=15°

Fig. 7. Distribution of velocity with the variations of δ by computational works.

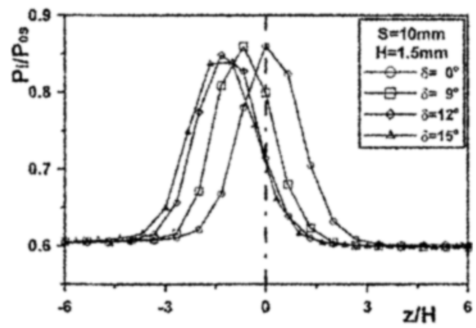
To see clearly the effect of δ, the result by computational work for the effect of deflection angle of the Coanda nozzle that is δ on the jet impinging pressure at the strip surface for x=0 mm is shown in Fig. 8. Here, the line of z=0 corresponds to the line of geometric center for the conventional air knife system.

As shown in figures, the larger the deflection angle is, the lower the peak value in impinging pressure is, and the position of the peak value moves to the downward of the strip.

It is turned out that the impinging pressure for δ=9° is comparable as that for δ=0°. Furthermore, the larger the deflection angle of Coanda nozzle is, the larger the shift distance from the line of z=0 is, but the peak value of impinging pressure becomes small. As shown in both figures, we can find that the most effective deflection angle of the Coanda nozzle for the present conditions exists at the around δ=9° because the peak value is kept up even δ=9° similar to the case of δ=0°, also beyond the optimum value of deflection angle the impact pressure decreases on the contrary with the increase of deflection angle because of the increases of traveling distance of the flow from the nozzle lip to the strip surface with the increase of deflection angle. The impinging pressure gradient at the downward region of the impinging jet for the larger deflection angle is larger than that of smaller one. Also, it is shown from Fig. 7(b)-(d) and left side dashed curves in Fig. 8 that the jet is more steeped to the bottom side. It produces the increase of the maximum gradient of the impinging pressure and wall shear stress affecting on the thin-coating [7]. Therefore this improvement of concentration and deflection to downstream of the jet through the Coanda nozzle to obtain the same cutting ability cause the decreases of the plenum chamber pressure and separation bubble, which will produce the decrease of edge splashing.



(a) Computation



(b) Experiment

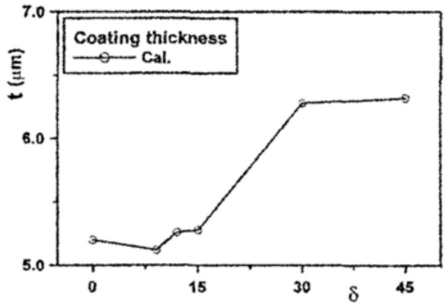
Fig. 8. Distribution of the impact pressure on the strip surface.

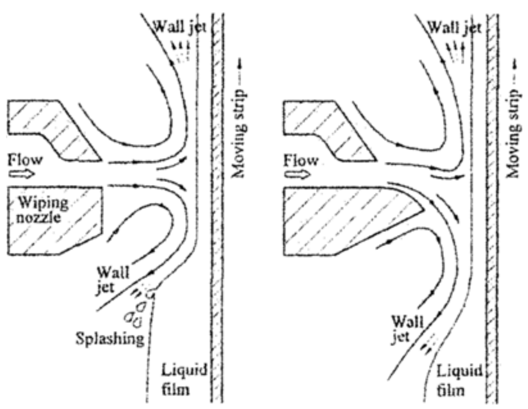
Some calculated results for the coating thickness are presented in Table 1. As indicated in Table 1, the shear stress acting on the lower part of strip becomes high and the coating thickness is thin as the deflection angle increases. It is found that δ=9° has the maximum wall shear stress and the minimum coating thickness and that the deflection angle affects the coating thickness. The coating thickness is obtained by the referring to Thorton et al. [7].

Fig. 9 shows the schematics of the flow patterns for the cases without and with a Coanda nozzle in galvanizing process. As shown in Fig. 9(a), the splashing is generated at the lower region of the strip in case of without Coanda effect. On the other hand in Fig. 9(b), the splashing is delayed or suppressed because the position of splashing region moves downstream and wall shear stress is increased, and the quality of the coating strip is improved because the liquid zinc droplet could not be splashed to the strip surface finished air knifing work.

Table 1. Computational results.

δ(°)	$P_{i,max}$(kPa)	τ_{max}, τ_{min}(N/m^2)	t(μm)
0°	45.0	421.9, -422.1	5.20
9°	45.2	391.2, -440.7	5.12
12°	43.6	373.1, -425.9	5.26
15°	43.3	372.6, -423.8	5.28
30°	36.1	308.5, -356.4	6.28
45°	35.7	299.9, -356.1	6.32





(a) Conventional nozzle (b) Coanda nozzle

Fig. 9. Schematics showing Coanda effect in galvanizing process.

Considering the flow geometry, we can deduce that the quality of the coating strip is improved by suppression of splashing and thin coating is available by the increase of the maximum gradient of the impinging pressure and wall shear stress observed at the lower region of the strip. As a result, from view point of splashing problem, it is preferable to use an air knife with a Coanda nozzle.

5. Conclusions

The present study has been performed to improve the conventional air knife system, in which is required to reduce harmful effects of the edge splashing and to shorten the whole galvanizing process with a better coating quality. Both the present measured and computational results obviously reveal the usefulness of the air knife system with Coanda effect, which is specified by the jet structure and impinging pressures. The major meaningful results obtained are summarized as follows.

1. The present computations predict well the measured flow field with and without Coanda effect.
2. The deflection angle of δ=9° is the most effective to suppress the edge splashing, and thus being able to give the thin coating. This is due to the jet deflection that causes an increase in the shear stress and pressure gradient.
3. Coanda nozzle can certainly reduce the harmful problem of edge splashing, but more systematic work is needed to find out the optimization of the Coanda nozzle.

Nomenclature

H : Slit height(mm)
L : Coanda nozzle lip length(mm)
P_{0s} : Plenum chamber pressure(kPa)
P_i : Impinging pressure(kPa)
R : Curvature radius of Coanda nozzle lip(mm)
S : Gap between nozzle lip and strip surface(mm)
Vs : Strip velocity(m/s)
t : Coating thickness(mm)
δ : Deflection angle(deg)
τ : Shear stress(N/m^2)

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