Design of a Circular Slot Hood for a Local Exhaust System and its Application to a Mixing Process for Fine Particles and Organic Solvents

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Abstract: The characteristics of airflow (pressure loss and entry loss factor) were measured around a circular slot hood for its application to a local exhaust system. Centerline velocity, defined as the ratio of air velocity on the centerline of the slot hood to average slot face velocity, was found to be independent of the airflow rate. The relationship between the centerline velocity and the ratio of centerline distance to slot width was also found to be independent of the slot size. The empirical centerline velocity equation for the circular slot hood was thus constructed to design the local exhaust system. Recommended values for airflow rate into the circular slot hood and the average slot face velocity were found to be 20.14 m³/min and 8.55 m/sec, respectively. The optimum air velocity at a capture point was also found to be 5% of the average slot face velocity, i.e. 0.43 m/sec, and the effective ventilation with the hood was achieved with these values. The local exhaust system with the circular slot hood was installed for a mixing process of fine particles and organic solvents in a magnetic coating works. The effectiveness of the circular slot hood was confirmed by measuring the concentrations of airborne particles and vapors before and during the operation of the local exhaust system.

Key words: Local exhaust system, Circular slot hood, Pressure loss, Entry loss factor

Introduction

A hood is an essentially important part of a local exhaust system. Among various types of hoods, a rectangular slot hood has been widely used on batch processing units such as metal surface treatment, alkaline degreasing, electrolytic galvanizing, electrolytic polishing, glazing, high temperature drenching, metal surface etching, and organic solvent rinsing. A circular slot hood is supposed to be effective in eliminating hazardous materials during these processes, because the top openings of the chemical reactors, electrolysis vessels and hoppers are mostly in round and also periodically and frequently opened to insert raw materials. Data on the airflow characteristics around a circular slot hood and size are needed to design a local exhaust system employing circular slot hoods for such manufacturing processes. Dalla Valle1), Silverman2), Fletcher3, 4) and Conroy3) provided the characteristics of airflow around a rectangular slot hood, but no experimental data on airflow characteristics are available for a circular slot hood except those reported by Iwasaki6). According to the report by Labour Ministry of Japan7), various types of hoods including booth, enclosure, rectangular and rectangular slot hoods are used in the manufacturing processes surveyed. These hoods are often operated improperly and allow hazardous pollutants to enter the environment, because the inlet shapes of these hoods are not matched to the round top opening on mixing reactors, vessels and hoppers.
In an attempt to effectively eliminate hazardous airborne pollutants from a chemical reactor or a mixing vessel with a round opening, the present study was undertaken to design a circular slot hood and to examine its airflow characteristics in relation to the slot sizes prior to application to manufacturing processes. To determine the optimum conditions for the airflow characteristics and slot size experimentally in the laboratory, a local exhaust system employing a circular slot hood was installed in a manufacturing process for magnetic coating materials where fine particles were thrown into a mixing vessel and mixed with organic solvents. Measurements of the concentration of fine airborne particles and organic solvents in the environmental air of the workplace were carried out before and during use of a local exhaust system with a circular slot hood. These environmental measurements confirmed the effectiveness of the circular slot hood devised to eliminate hazardous pollutants from the mixing vessel with a round hopper on top of vessel.

**Experimental Methods**

An example of a circular slot hood which we constructed in the present study is shown in Figure 1. The airflow characteristics were measured to determine the size specifications for the hood. A hollow cylinder simulating the mixing vessel equipped with a round hopper at the top of the vessel was placed beneath the center of the hood as shown in Figure 1 and the airflow characteristics around the slot opening were measured. Four hoods with slot widths of 1.75, 25.00, 37.50 and 50.00 mm were examined. Face velocities were measured for each hood at four different airflow rates. The splitter vane indicated by dotted lines in the plenum box and served to regulate face velocity. The hood was connected to the same experimental apparatus as those used in the previous study. Centerline velocities were measured by means of a hot-wire anemometer with high sensitivity in the low velocity range (response frequency: 10 kHz, velocity range: 0.07–150 m/sec, tungsten wire of L=0.15 mm, D=5 μm), and diagrams of velocity contours were constructed. A probe of the anemometer was fixed on a traverse (horizontal type or vertical type) with moving precision of 1/20 mm. The probe was calibrated by pulsed-wire anemometry prior to the measurement.

**Results**

**Characteristics of centerline velocities in a circular slot hood**

It was found for hoods of different slot widths that a relationship between the slot centerline velocity and the slot centerline distance was constant and independent of any airflow rate. A remarkable decrease in slot centerline velocity was observed within a distance of 50 mm from the slot opening in the hood face, but it was almost constant at a point farther than 120 mm from the opening.

The airflow around the hood was affected by the width of the slot. The slot centerline velocity decreased with the increase in centerline distance, and this tendency became more remarkable with the decrease in slot width, but the effect of the slot width on the centerline velocity was relatively small at points farther away.

The relationship between centerline velocity \((V_s/V_o)\times100\) and the ratio of centerline distance \(X_s\) to slot width \(W\) was indicated on a graph with logarithmic scales (Fig. 2). The gradient of the regression line was approximated as \(-1\), and the centerline velocity equation for the circular slot hood examined was derived as follows:

\[
(V_s/V_o)\times100 = 31W/X_s
\]

where

\(X_s::\) centerline distance from the slot hood opening (m)
\(V_o::\) average slot face velocity at the slot hood opening (m/sec)
\(V_s::\) slot centerline velocity at the point of \(X_s\) (m/sec)
\(W::\) width of the slot (m)

Further, the area of the slot \((A)\) is the product of \(W\) multiplied by the circumference of the slot \((L=1.57 m)\), and the rate of airflow into the hood \((Q)\) is then calculated by means of the
following equations.

\[ Q = 60WLVo \] ...................(2)

\[ V_r = 5.17 \times 10^{-3}Q/LXs \] ...................(3)

\[ \cdot \quad Q = 194LXsVs \] ...................(4)

A recommended flow rate can be obtained by substituting each value into equation (4). For example, the recommended flow rate for the circular slot hood will be 20.56 m³/min when the capture point is located at a point of 150 mm from the opening, and the capture velocity is estimated at 0.45 m/sec. In this case, the total flow rate for ventilation is obtained by multiplying the number of hoods by 20.56.

Entry loss factor and coefficient of entry

The flow rate in the circular slot hood (Q m³/min) is calculated by using the following equation.

\[ Q = AV = CeA\sqrt{(2g/|\gamma|)Ps} \] ...................(5)

where

- **Ps**: static pressure at position 1d (d is the diameter of the straight pipe connected to the hood) downstream of the take off (mmAq)
- **V**: velocity of airflow in the pipe (m/sec)
- **Ce**: coefficient of entry (-)
- **A**: cross section area of the pipe (m²)
- **|\gamma|**: specific weight of air (Kg/m³)
- **g**: gravitational acceleration (m/sec²)

\[ \gamma = \frac{\text{specific weight of air}}{\text{gravitational acceleration}} \]

\[ |\gamma| = \frac{\text{specific weight of air}}{\text{gravitational acceleration}} \]

\[ \text{Ps} = \text{Ps}_\text{total} \]

\[ \text{Ps}_\text{total} = \text{Ps} + \text{Ps}_\text{entry loss} \]

\[ \text{Ps}_\text{entry loss} = \frac{Ps - \text{Ps}_\text{duct}}{\text{Ps}_\text{duct}} \]

The average static pressure behind the take off of the hood is the difference between the average static pressure at the position 50 d downstream of the take off and the friction loss in a straight pipe of 50 d long.

Figure 3 shows the relationship between the entry loss factor and the aspect ratio for the slot on a logarithmic scale graph. A linear regression curve could be drawn in Figure 3. This chart can be used for designing a circular slot hood (the practicable range for slot width in this chart is 18.8–50.0 mm).

Application of Circular Slot Hood to a Mixing Process

Magnetic coating materials are made of a mixture of fine particles of chromium oxide, iron oxide and carbon black with organic solvents, such as methyl ethyl ketone (MEK), methyl isobutyl ketone (MIBK) and toluene. Figure 4 shows...
an introducing process with a hopper of these materials in a factory. Organic solvents were supplied to a mixing vessel through a volumetric piping system. Fine particles of chromium oxide, iron oxide, and carbon black were weighed and thrown into the vessel from a hopper positioned at the top of the vessel. As shown in Figure 4, the fine particles were being dispersed into air from the opening of the hopper during the introduction process. Organic solvents in the vessel were also being evaporated by rising temperature during the mixing process and leaked out through gaps in the vessel. On the basis of our prior knowledge of the airflow characteristics of the circular slot hood obtained in laboratory experiments, a local exhaust system was designed and installed with a circular slot hood for the process of mixing magnetic coating materials to effectively reduce air contamination by fine particles and organic solvents.

Selection of dust collection equipment

Because most of the airborne particles were of iron oxide submicron in diameter and mixed with vapors of organic solvents, a bagfilter unit with a pulse jet reconditioner was used as the dust collector. The bagfilter unit was operated under conditions of 1.3 m³/min/m² and 200 mmAq as pressure loss. The dusts in the air stream were collected on the surface of fabric filters, which were periodically cleaned by means of a pulse jet of compressed air through venturi-tubes and nozzles. No air cleaner for organic solvent vapors was used in the local exhaust system because the concentrations of organic solvent vapors were low enough in the working environment.

Design of ductwork and selection of fan pressure ratings

The whole ductwork of the local exhaust system for the process of manufacturing magnetic coating materials is shown in Figure 5. In the ductwork, six circular slot hoods for the mixing vessels and one booth type hood for the weighing process are connected to the dust collector through branched and main ducts. The air stream is generated with a turbo fan. The "Static Pressure Balance Method," which provides a desired airflow without the use of blast gates, was employed. At each junction, the static pressure necessary to achieve the desired flow in one stream (SP) should be equal to the static pressure in the joining air stream (SP'). As shown in Figure 5, balanced static pressures (SP') were obtained within 1–2% tolerance. The velocity of airflow was kept constant over 20 m/sec to prevent a sediment of dusts in the ducts. Because the weighing procedure and the mixing process are operated at different times in this factory,
the circular slot hoods and the booth type hood cannot be used simultaneously. For this reason, the airflow rate of this system was set at 123.36 m³/min, equivalent to the total airflow rates of the six circular slot hoods. The static pressure of the fan was estimated at 412 mmAq from the calculation of pressure loss in this system.

**Velocity contours and stream lines**

Figure 6 shows velocity contours and streamlines of airflow measured around the inlet of the circular slot hood and the hopper. Each velocity contour indicates the percentage of the average face velocity and decreased remarkably within a short distance close to the slot opening or the edge of the plenum box. At the center normal line of the round opening in the hopper, the velocity was 5% of average face velocity. It was recommended that the airflow velocity at each circular slot hood should be set at 0.43 m/sec, equivalent to 5% of average face velocity, in order to effectively capture dispersed dusts and organic solvent in the mixing process.

**Evaluation of the installed exhaust system**

Following the method described in the guidelines, the airborne concentrations of the fine particles and organic solvents were measured in the vicinity of the mixing process before and during operation of the local exhaust system with the circular slot hoods. As indicated in Figure 7, eleven sampling points (1 - 11) were selected at 150 cm above the floor, and four points (12 - 15) were set close to the openings of the hopper. Total airborne dusts (including iron oxide dust) were collected on glass fiber filters with a high-volume air-sampler at a sampling flow rate of 0.39-0.49 m³/min for about 150 min. Chromium oxide dust was separately measured by a high-volume air-sampler at flow rates of 0.45–0.46 m³/min for 5–8 min. Since chromium oxide was introduced into the vessel within ten seconds at each operation, the sampling was carried out intermittently. Throwing chromium oxide into the mixing vessel was done 27-48 times in a work day. The samplings of the particles and organic vapors were repeated four times, the first two before and the latter two during the operation of the local exhaust system. The quantitative analysis of chromium oxide was carried out by atomic absorption spectrophotometry. Quantitative analysis of toluene, MEK and MIBK in the air at the sampling spots during the mixing process was carried out with detection tubes.

The concentrations of total airborne dust, chromium oxide, iron oxide, toluene, MEK and MIBK are shown in Table 1. Before operation of the ventilation, the concentrations of total dusts and chromium oxide in the vicinity of the mixing vessel (12 - 15) far exceeded the threshold limit values of 4 mg/m³ and 0.5 mg/m³ issued by J.S.O.H, respectively. The concentrations of the organic solvents also exceeded the threshold limit values at some sampling points before the ventilation operation. It was confirmed that these high concentrations of total airborne dust, chromium oxide, MEK and toluene were reduced to levels below the threshold limit values during the operation of the exhaust system, i.e. concentrations of 133.54 and 113.16 mg/m³ total dust and 64.96 and 58.77 mg/m³ chromium oxide at 12, 13 were decreased to 1.37 and 1.34 mg/m³ and 0.025 and 0.020 mg/m³, respectively. For organic solvents, the concentrations were also greatly reduced by the circular slot hood. Features of the ventilation effect are visually shown in Figure 8a and 8b. It can be concluded that the circular slot hood is remarkably effective for the elimination of ducts and solvents from mixing processes when it is properly designed.
Discussion

The slot centerline velocity in the circular slot hood is expressed in equation (1) in which the centerline velocity (Vs) can be calculated by inserting the specific Xs value into the term for the slot centerline distance from the slot hood opening. Table 2 shows the observed and calculated values for centerline velocities. Since the calculated centerline velocities from equation (1) were approximately equal to the observed ones from the laboratory experiment for any Xs values, equation (1) is properly adapted to a regression equation. The equation by Silverman\(^2\) gave approximately the same values as the observed velocities for a circular slot hood with a cylinder, but the velocities for a circular slot hood without a cylinder were apparently different from those given by Silverman\(^2\). The calculated velocities obtained by Dalla Valle’s equation\(^1\) were smaller than those from equation (1) or observed velocities, and the difference increased with the increase in Xs. This difference might be caused by the difference in the velocity measuring method. The velocity in front of the slot hood was measured with a hot-wire anemometer in the present study, while Dalla

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Table 1. Evaluation of ventilation effects by environmental measurements

<table>
<thead>
<tr>
<th>Measuring point No.*</th>
<th>Concentration of organic solvent [ppm]</th>
<th>Concentration of dust [mg/m(^3)]</th>
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<tbody>
<tr>
<td></td>
<td>MEK(^1)</td>
<td>MIBK(^2)</td>
</tr>
<tr>
<td>①</td>
<td>197.2</td>
<td>8.9</td>
</tr>
<tr>
<td>②</td>
<td>205.3</td>
<td>11.4</td>
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<tr>
<td>③</td>
<td>274.6</td>
<td>12.7</td>
</tr>
<tr>
<td>④</td>
<td>209.2</td>
<td>12.5</td>
</tr>
<tr>
<td>⑤</td>
<td>120.0</td>
<td>5.4</td>
</tr>
<tr>
<td>⑥</td>
<td>211.0</td>
<td>9.8</td>
</tr>
<tr>
<td>⑦</td>
<td>312.0</td>
<td>11.1</td>
</tr>
<tr>
<td>⑧</td>
<td>293.4</td>
<td>12.2</td>
</tr>
<tr>
<td>⑨</td>
<td>110.9</td>
<td>5.6</td>
</tr>
<tr>
<td>⑩</td>
<td>150.9</td>
<td>10.3</td>
</tr>
<tr>
<td>⑪</td>
<td>204.4</td>
<td>11.4</td>
</tr>
<tr>
<td>⑫</td>
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<td></td>
</tr>
<tr>
<td>⑬</td>
<td></td>
<td></td>
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<tr>
<td>⑭</td>
<td></td>
<td></td>
</tr>
<tr>
<td>⑮</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*see Fig. 7. B.V.: before ventilation, D.V.: during ventilation. \(^2\): TLV=200 ppm, \(^3\): TLV=50 ppm, \(^4\): TLV=50 ppm, \(^5\): TLV=4 mg/m\(^3\), \(^6\): TLV=0.5 mg/m\(^3\).

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Fig. 8. Introducing raw material into a hopper equipped with a local exhaust system with a circular slot hood
a) before ventilation, b) during ventilation.
Valle measured the velocity pressure with a special Pitot tube and a Whalen gauge and calculated the velocities from the measured velocity pressure. It is known that with the Pitot tube and Whalen gauge, error often occurs in the low velocity range below 5 m/sec.

Deviations in the plots from the regression line became relatively large in the 175–250 mm range in Xs (Fig. 2). This is because the direction of airflow at the center of the round opening becomes perpendicular to the centerline of the slot hood.

As shown in Figure 3, the entry loss factor (Fh) for the circular slot hood was in inversely linear proportion to the aspect ratio of the slot (W/L), but according to the ACGIH manual, the Fh value for a rectangular slot hood is constant at 1.78 when the W/L is below 0.2. The Fh values ranging from 0.1 to 0.6 obtained in the present study were much smaller than the Fh value of 1.78 obtained with the rectangular slot hood. The difference between the two types of hood is considered to be attributable to the contribution of the flanged opening and the plenum box to the Fh values in the circular slot hood. In a previous study on the characteristics of pressure loss, the author reported that round openings with flanges reduced the Fh value by half of those without a flange. The plenum box is thought to function like a flange at the opening.

As shown in Table 1, the concentrations of fine airborne particles and three organic solvents were reduced remarkably to levels below the threshold limit values (TLV) during operation of the local exhaust system with the circular slot hood. Concentrations of total airborne dust and chromium oxide were particularly reduced at the sampling points close to the mixing vessel. This indicates that the circular slot hood effectively eliminated the dispersed fine particles when putting the raw materials into the mixing vessel. The concentrations of airborne MEK exceeded the TLV of 200 ppm at many sampling points before operation of the local exhaust system with the circular slot hood, but the concentrations of MEK were also effectively reduced to far below the TLV. The average concentrations of MEK, MIBK and toluene at all the sampling points were 10.12, 2.74 and 4.2 ppm, respectively, during operation of the local exhaust system. The saturated vapor pressures for MEK, MIBK, and toluene were 71, 16 and 22 mmHg at 20°C, respectively. The most volatile MEK of the three gave the highest airborne concentration before and during operation of the local exhaust system. The concentrations of MIBK and toluene were below or close to each TLV even before operation of the local exhaust system. This is due to their lower volatility.

Since the Fh value for the circular slot hood is far smaller than that of a rectangular slot hood reported previously, a circular slot hood can be operated under conditions of smaller pressure loss and less power for a fan giving a higher cost performance.

In conclusion, a circular slot hood properly designed can be applied effectively to many batch manufacturing processes in reactors, mixing vessels and hoppers equipped with round openings at the top.

### Table 2. Comparison of centerline velocities ($\frac{V}{V_0} \times 100$)

<table>
<thead>
<tr>
<th>Centerline distance Xs (mm)</th>
<th>Velocity in circular slot hood*</th>
<th>Velocity in rectangular slot hood*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>observed (in laboratory)</td>
<td>calculated (equation 1)</td>
</tr>
<tr>
<td></td>
<td>observed (in factory)</td>
<td>calculated (Silverman) 3)</td>
</tr>
<tr>
<td>15</td>
<td>51.07</td>
<td>51.67</td>
</tr>
<tr>
<td>25</td>
<td>31.56</td>
<td>31.00</td>
</tr>
<tr>
<td>40</td>
<td>20.00</td>
<td>19.38</td>
</tr>
<tr>
<td>50</td>
<td>15.61</td>
<td>15.50</td>
</tr>
<tr>
<td>75</td>
<td>10.46</td>
<td>10.33</td>
</tr>
<tr>
<td>100</td>
<td>7.90</td>
<td>7.75</td>
</tr>
<tr>
<td>125</td>
<td>6.28</td>
<td>6.20</td>
</tr>
<tr>
<td>150</td>
<td>5.12</td>
<td>5.17</td>
</tr>
<tr>
<td>175</td>
<td>4.08</td>
<td>4.43</td>
</tr>
<tr>
<td>200</td>
<td>3.05</td>
<td>3.88</td>
</tr>
<tr>
<td>225</td>
<td>2.15</td>
<td>3.44</td>
</tr>
</tbody>
</table>

*: W=25 mm. 1) $\frac{V}{V_0} \times 100 = \frac{31 W}{Xs}$, 2) $\frac{V}{V_0} \times 100 = \frac{100 W^2}{5Xs^2 + W^2}$, 3) $\frac{V}{V_0} \times 100 = 16.5 (W + 1 \text{ [inch]}) / Xs$
Acknowledgments

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