Air Leakage from Thin-Walled Space between Circular Pipe Flange and Flat Disk

Sho YOKOYAMA$^1$ and Manabu IGUCHI$^1$

$^1$ Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan

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Abstract
Air leakage from a thin radial gap between the flange of a circular pipe and a flat disk is experimentally studied. The effects of the wettabilities of the flange and the disk on the flow coefficient are examined in detail. The height of the gap ranges from about 50 µm to 500 µm. The surface roughness of the gap is varied by coating two types of repellents. The flow coefficient relating the flow rate to the pressure drop of air passing through the gap is experimentally determined and compared with both an analytically obtained equation and an empirical equation proposed so far. As the prediction of the present data by the previously proposed equations is not satisfactory, an empirical equation is newly proposed.

Key words
Wettability, Flow Coefficient, Radial Flow, Leakage, Continuous Casting, Immersion Nozzle

1. Introduction
In the conventional materials refining processes, the refractory of reactors is usually poorly wetted by molten metal. This is intended to avoid undesirable metallurgical reactions between the refractory and molten metal. The same situation is observed inside the immersion nozzle in the continuous casting process. Argon gas is introduced into the immersion nozzle from porous materials placed above the sliding gate to form a thin film over the inner wall of the immersion nozzle. It is expected that non-metallic inclusions such as alumina (Al$_2$O$_3$) do not attach to the inner wall due to the presence of the argon film (see Fig. 1).

Meanwhile, it has been reported that when the pressure inside the immersion nozzle is lower than the atmospheric pressure, air is sucked into the immersion nozzle from the gaps of the sliding gate. The air thus sucked is very harmful for producing clean steel. On the other hand, when the pressure difference is reversed, argon gas leakage is known to occur. If the pressure difference is lower than a certain critical value, molten metal would not penetrate into the gaps because the sliding gate is poorly wetted by molten metal and therefore only argon gas leaks through the gaps. If the pressure difference exceeds that critical value, molten metal would penetrate into the gas and partly block the gaps. Argon gas leakage under this condition

Fig. 1 Schematic of the immersion nozzle in the continuous casting. Argon gas is injected into the immersion nozzle and descends along the wall to prevent inclusions from adhering to the wall. Left : Argon gas descending along the wall, Right : Argon gas leakage from the gaps of sliding gate

Fig. 2 Schematic of test section for studying air leakage from radial gap between pipe flange and flat disk (50µm $\leq$ h $\leq$ 500µm). Left : gap formed with four spacers, Right : bird’s eye view

Fig. 3 Schematic of test section. $H$ : height of an air column below the free surface
would be very complicated compared to the previous case. The final goal of our research is to understand the molten steel and argon gas behaviors in the gaps. As a first step of this research series, the former case, i.e., the case that only argon gas leaks from the sliding gate gaps was investigated in this study on the basis of water model experiments. Under this condition molten steel never penetrates into the gaps because the sliding gate is poorly wetted by it.

Many attempts have been made to understand radial flows between parallel disks. For example, a number of experiments were conducted to evaluate theoretical predictions of the pressure distribution in laminar radial flows between parallel disks [1-9]. In addition, the heat transfer characteristics in radial flows were extensively investigated [10-13]. However, little is known about the effects of surface roughness of wall materials on the flow characteristics in a thin-walled space (gap) [14-16].

We therefore focus on the phenomenon of the air leakage from a thin-walled space (gap) between the flange of a circular pipe and a poorly wetted disk as a model study of the argon gas leakage.

The purpose of this work is to examine the effect of surface roughness on the gas leakage from a sliding gate without contacting molten metal.

2. Experimental Procedure

Figure 2 indicates a schematic of an acrylic circular pipe with a flange set up vertically in a water bath where an acrylic flat disk is horizontally placed keeping a small gap above the pipe flange. The gap height between the flange and the flat disk was varied from about 50 μm to 500 μm using four spacers. The wettability of the flange and the disk was changed by coating a water-repellent material on their surfaces.

Figure 3 shows a schematic of the flange attached to the top end of the vertical pipe partially immersed in the water bath. The pipe was 300 mm in length and its inner diameter, D, was 10 mm. The flat disk was placed above the flange. By inserting four spacers between the flange and the flat disk, the gap of predetermined height was formed. The gap height, h, was varied to be about 50, 200 and 500 μm by varying the spacer height. The spacer width, W, was 1 mm. The surfaces of the flange and the flat disk were originally wetted by water. The contact angle between the acrylic resin surface and a water droplet was originally 70°. To vary its wettability, the surfaces of the flange and the flat disk were coated with two different types of repellents (HIREC® 1450: NTT Advanced Technology Corporation; repellent: Yushin Co., Ltd.). The contact angles of the surfaces after coating were varied from 70° to 147° and 110°, respectively.

As shown in Fig. 3, air is led from the pipe bottom into the test section, and the air column (or bubble) stays below the bottom of the disk, and its volume decreases gradually with time due to leakage from the radial narrow gap. Only air escapes through the gap. The exit velocity of the air was calculated from the decrease in the volume of the column. The flow coefficient, c, was determined from the exit velocity and the pressure difference.

The pressure difference, Δp, can be evaluated from the height of the air column. The relationship between the pressure difference, Δp, and the gas flow rate, Q, can be expressed in terms of the flow coefficient, c.

Experimental procedures are as follows:
1. The test pipe is partially immersed in the water bath. The air column is generated in the test section of the pipe.
2. A part of the air column leaks from the gap slowly.
3. The flow rate of air leaking from the gap is determined by measuring the height of the air column. The change in the height is measured from movies taken with a high-speed camera (IDT Japan, Inc: X-Stream™ XS-3) at 500 fps.
4. The gap height, h, is changed and the above-mentioned procedures are repeated.

The methods for determining the flow coefficient, c, will be described below in more detail.

2.1 Method for determining flow coefficient

When the spacers are absent, the flow coefficient, c, is defined as

\[ Q = 2\pi R_1 h \sqrt{2\Delta p / \rho_{air}} \]  

where

\[ \Delta p = p_1 - p_2 \]  

Here, Q is the flow rate of air, R₁ (=D/2) is the inner radius of the pipe, h is the gap height, p₁ is the pressure in the air column below the flat disk, ρair is the density of air, and p₂ is the pressure outside the gap. The pressure, p₁, can be determined by measuring the height of the air column in the pipe, H, assuming that the pressure is constant in the air column (see Fig. 3). The pressure difference, Δp, can be calculated from the height of the air column below the water surface as follows:

\[ \Delta p = \rho_{w} g H \]  

where \( \rho_{w} \) is the density of water and g is the acceleration due to gravity. The superficial velocity, \( u_{1,air} \), of the air at the inlet of the gap is determined as

\[ u_{1,air} = \frac{Q}{A} \]  

where

\[ A = 2\pi R_1 h \]  

where A is the cross-sectional area at the inlet of the gap. Namely, the superficial velocity of air, \( u_{1,air} \), was calculated by dividing a decrease in the volume of the column per second by the cross-sectional area of the inlet of the gap. The test section was divided into three subsections of 20 mm in height, as shown in Fig. 4. The air flow rate, Q, was determined at the middle position in each subsection. This 20 mm was chosen from preliminary experiments because satisfactory results were obtained.
The following Reynolds number is introduced.

\[ \text{Re} = \frac{h u_{air}}{v_{air}} \]  

(6)

where \( v_{air} \) is the kinematic viscosity of air.

Equation (6) is rewritten as

\[ h u_{air} = v_{air} \text{Re} \]  

(10)

Combining Eq. (4) with Eq. (10) gives the flow rate of air, \( Q \), as

\[ Q = 2\pi R h u_{air} = 2\pi R v_{air} \text{Re} \]  

(11)

Substituting Eq. (11) into Eq. (9) leads to the flow coefficient as:

\[ c = \left[ \frac{h}{24R_i \ln \frac{R_o}{R_i}} \right]^{\frac{1}{\text{Re}}} \]  

(12)

2.3 Measurement of the height of gap and derivation of modified equation for the flow coefficient

It is necessary to accurately measure the gap height for the evaluation of the flow coefficient. Fig. 6 shows the photographs of different gaps between the pipe flange and the flat disk, formed with three different spacers. The gap was measured using a stereomicroscope (STZ-40Tb: Shimadzu Rika Corporation) with an accuracy of ± 0.1µm. As seen from Fig. 6, the gap height and the surface roughness of the gap wall are varied with repellent coating. In what follows, we need to modify Eq. (12) for the flow coefficient, \( c \), because the gap is not uniform and the spacers are present in the gap.

An apparent gap height, \( h_{app} \), i.e., the gap height along the outer periphery of the gap was measured to determine a mean height using an image processing technique. An apparent outer peripheral length was also measured using the image processing technique. In order to include the effect of surface roughness on the apparent gap cross-sectional area, we determined a ratio of the apparent outer peripheral length to \( 2\pi R_i \) denoted by \( k \). The measured values of the apparent gap height, \( h_{app} \), and the ratio, \( k \), are listed in Tables 1 and 2 respectively. Furthermore, we have to consider the effect of the spacers on the flow rate.

By taking account of the decrease in the cross-sectional area of the gap due to the presence of the spacers, we can obtain the apparent cross sectional area, \( A_{app} \), as

\[ A_{app} = (2\pi k R_i - 4W) h_{app} \]  

(13)

The flow coefficient, \( c \), is then modified as

\[ c = \left[ \frac{h_{app}}{24R_{app} \ln \frac{R_o}{R_{app}}} \right]^{\frac{1}{\text{Re}_{app}}} \]  

(14)

Fig. 4 Measurement positions for air flow rate (○: measurement position)

2.2 Flow coefficient derived from theoretical analysis

Figure 5 (a) shows a simplified model for determining the flow coefficient for the gap between the pipe flange and the flat disk.

The pressure difference, \( \Delta p \), is given by Uzawa [7] as:

\[ \Delta p = \frac{6\rho_{air} Q}{4\pi^2 R_i^2 h^2} \ln \frac{R_o}{R_i} \]  

(7)

Uzawa focused on a flow field shown in Fig. 5 (b). The detailed deriving method should be refereed to Ref. [7].

Equation (1) is rewritten as

\[ \Delta p = \frac{2\Delta p}{\rho_{air}} = \frac{Q^2}{4\pi^2 c^2 R_i^2 h^2} = \frac{12\rho_{air} Q}{\pi h^3} \ln \frac{R_o}{R_i} \]  

(8)

Rearranging Eq. (8) gives

\[ c^2 = \frac{Q h}{48\pi R_i^2 v_{air} \ln \frac{R_o}{R_i}} \]  

(9)

Fig. 5 Schematic of radial gap between pipe flange and flat disk through which air flows out radially.
2.4 Empirical equation derived by Takenaka

Takenaka [17] obtained the flow coefficient for a gap shown in Fig. 7.

\[ c = 0.0746 \left( \frac{W}{R_{app}} \right)^{\frac{1}{2}} \text{ (20} \leq \text{ Re}_{app} \leq 200) \]  \hspace{1cm} (18)

Note that the validity of Eq. (18) is limited to the above Reynolds number range. The measured values of the flow coefficient will be compared with the predictions, Eqs. (14) and (18).

3. Experimental Results and Discussion

Figure 8 gives comparisons between the measured values of the flow coefficient, \( c \), and calculated ones from Eqs. (14) and (18). The measured values of \( c \) for \( h = 50 \) µm and 200 µm are satisfactorily predicted by Eq. (14). However, Eq. (14) cannot predict the present measured value of the flow coefficient for \( h = 500 \) µm. That is, Eq. (14) overestimates the flow coefficient. This is because the ratio of the entrance length to the gap length of 7 mm is relatively high for \( h = 500 \) µm.

Equation (18) becomes to agree with Eq. (14) with an increase in the gap height, \( h \). This is because the roughness effect on the flow coefficient becomes relatively low with
Table 1 Relationship between spacer height, \( h \), and apparent gap height, \( h_{\text{app}} \)

<table>
<thead>
<tr>
<th>Spacer height ( h (\mu m) )</th>
<th>Original (uncoated)</th>
<th>( h_{\text{app}} (\mu m) )</th>
<th>( h_{\text{app}} (\mu m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>50</td>
<td>62</td>
<td>43</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
<td>199</td>
<td>145</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>500</td>
<td>468</td>
</tr>
</tbody>
</table>

Table 2 Ratio \( k \) (-) of apparent outer peripheral length of gaps to \( 2\pi R^2 \) for three different spacer heights (the variation of \( k \) is due to the surface roughness of the disk coated with different repellants used)

<table>
<thead>
<tr>
<th>Spacer height ( h )</th>
<th>( k ) Yushin</th>
<th>( k ) HIREC 1450</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.0</td>
<td>1.16</td>
</tr>
<tr>
<td>200</td>
<td>1.0</td>
<td>1.12</td>
</tr>
<tr>
<td>500</td>
<td>1.0</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Fig. 8 Relationship between flow coefficient \( c \) and Reynolds number \( Re_{\text{app}} \). Column (a): contact angle \( \theta = 70^\circ \); column (b): contact angle \( \theta = 110^\circ \); column (c): contact angle \( \theta = 147^\circ \). From top to bottom, spacer height \( h = 50, 200, \) and \( 500 \mu m \)
the gap height, \( h \). Anyway Eq. (18) overestimate the flow coefficient and is not applicable under the present experimental conditions.

4. Conclusions
Air leakage from a small radial gap between the pipe flange and the flat disk has been investigated both experimentally and analytically. Main findings obtained in this study can be summarized as follows:

(1) The presently obtained equation, Eq. (14), can predict satisfactorily the flow coefficient in the range of gap heights from \( h = 50 \mu m \) to \( h = 200 \mu m \). This equation, however, overestimates the flow coefficient for gap heights of \( h = 500 \mu m \).

(2) The empirical equation, Eq. (18), proposed by Takenaka overestimates the flow coefficient for gap heights from \( h = 50 \) to \( h = 500 \mu m \).

References