CROSS CORRELATION MASS FLOWMETER USING PULSE HEATING

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Abstract: The aim of this study is the development of a novel nonintrusive mass flowmeter for the moved bed gravity flow of the new process, i.e.: DRI (Direct Reduction Process for Iron Ore) and the synthetic naphtha making reactor reducing the coke coal and petroleum. One of the authors already developed cross correlation method, steady state heat transfer method and PZT acoustic emission method. This paper describes a prototype of a new cross correlation method using a pulse heating marking signal based on T. Moriyama’s patent application.

Keywords: cross correlation, heat transfer, pulse heating and stand pipe

1 INTRODUCTION

The aim of this study is the confirmation of the nonintrusive mass flow measuring methods of stand pipe in the new process plants that are DRI (Direct Reduction Process) and the synthetic naphtha making reactor reducing the high quality coke coal and petroleum. It is required for high pressured, high temperature and corrosive feed conditions. It is very important for the distributed mass flow control into the plants same as PCI (Pulverized Coal Injection system) developed by the author in [1], [16]. The process plants and the test equipment are shown in Fig. 1.

As the working pressure is 0.45 and 1.10 MPa for PCI and the new plants, respectively, the author selected the moved bed gravity flow using the stand pipe [14]. The mass flow ratio $\mu$ of gravity flow by moved bed is as follows: cf cf

$$
\mu = \frac{\rho_{\text{gb}}}{\rho_{\text{ga}}} \times \left[ \frac{\rho_{\text{Sn}} - \rho_{\text{Sh}}}{\rho_{\text{Sn}} - \rho_{\text{ga}} (P_1 + 1/P_n + 1)} \right] \left( \frac{P_1 + 1}{P_n + 1} \right)
$$

Figure 1: Process, test equipment and location S-1

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$$
\( \bar{n}_{sb} \): solid bulk density \([g/cm^3]\)  
\( \bar{n}_n \): solid net density \([g/cm^3]\)  
\( \bar{n}_g \): gas density at normal pressure \([g/cm^3]\)  
\( P_w \): working pressure \([10^5 Pa \text{ abs}]\)  
\( P_n \): normal pressure \([10^5 Pa \text{ abs}]\)  

Table 1: Characteristics of test feed materials

<table>
<thead>
<tr>
<th>Feed material</th>
<th>Silica pellet</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size ( d_p ) [mm]</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Weight ( W_p ) [mg]</td>
<td>7.6</td>
<td>16</td>
</tr>
<tr>
<td>Net density ([g/cm^3])</td>
<td>2.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Bulk density ([g/cm^3])</td>
<td>1.5</td>
<td>6.0</td>
</tr>
</tbody>
</table>

The cross correlation method (S-1), the heat transfer method (S-2) and PZT AE method (S-3) are selected by the author. S-1 is studied by M.S.Beck et al [2] for the solid gas two phase flow. S-2 is studied by J.H.Laub [3] for gas or liquid flow and the author et al [4] for solid gas two phase flow. S-3 is studied by T.Horiuchi for the stand pipe [5]. S-1 3 have been studied by the author and his staff for the pipe(15.7, 20 and 40ø) feeding the same material.

2 PAST EXPERIMENTAL APPARATUS

The nonintrusive sensors S-1 3 and the stand pipe are shown in Fig. 1. The actual mass flow rate \( G \) is measured using a weight scale and stop watches for S-1 3. The amount of the feed material is 100 kg (3 min for 2000 kg/h) per each test feed.

S-1 is a cross correlation method using Dk-13 by Endress Hauser and Iwatsu's SM-2701+SR 6310 FFT analyzer. \( d = 40 \text{ mm} \). The distance \( d \) of sensors A, B in Fig. 2 is 8 mm. S-2 (S-2A, S-2B) is a heat transfer method, The distance between two sensors is 700 mm and the heater is 600 mm long and below 85 V x 4.5 A. S-3 is an AE signal method using NF Circuit Inst.'s PZT (Plumbium Zirconate Titanate Zr/Ti 53/47) 900S, 922, 912, the bandpass filter, Yokogawa's 3131 DC amplifier and WX2A 1 100 ms first order lag filter and a pneumatic controller.

![Figure 2: Sensors (S-1A,S-1B) and signals (x(t),y(t))](image1)

![Figure 3: Auto correlation and cross correlation for 40ø, 5 wt% steel marker and 8 mm distance](image2)

3 EFFORTS OF EXPERIMENTS

Fig. 3 shows a sample of the cross correlation of \( x(t) \) and \( y(t) \) for 5 wt % and 40ø. "XB= " in the Figure means \( \delta_m \).

The calculation formulas are as follows:

\[
\phi_{xy} = \frac{1}{T_1} \int_0^T x(t) y(t + \tau) dt \\
\omega_s = \frac{d}{\tau_m} \cdot \delta_m = \tau_m \cdot \delta_s \cdot \frac{d\phi_{xy}}{d\tau} = 0 \\
G^* = \rho_s \bar{n}_s \omega_s \cdot A
\]

\( u_s, \delta_m, G, \omega_s, \bar{n}_s \) and A are solid velocity, delay time, measured massflow rate, solid velocity bulk density and solid velocity and the area of the inside of the pipe, respectively. (1) makes \( G \) from \( u_s \). It is found out that the accuracy is ±2 \% for full scale but the solid particles move slightly to horizontal direction in 40 ø.

Fig. 4 shows the relation between the sensor locations and the heat flow for the method. \( G \) is actual mass flow rate, \( T_s \) is settling time, T is the temperature difference \( (T_{cw} - T_{ch}) \).

\( q_t < 85 \text{ V x } 4.5 \text{ A} = 382.5 \text{ W}, \ q_c = GC_p T, C_p = 0.326 \text{ Wh/kg K} \text{ and } \delta_s = 0.904 \text{ W/m kg K} \).
As \( q_h = G C_p (T_{c2w} - T_{c1w}) \), \( \zeta = q_c / q_h > 1 \). As \( Bi(\text{Bio Number}) = \frac{\delta d}{\varepsilon} = 0.012 \), \( q_{c1w} = q_{c2w} << 1\% \) of \( q_h \), the pellets temperature is as follows:

\[
T_{c1w} = T_{c1} \quad \text{in wall side,} \quad T_{c2w} = T_{c2} \quad \text{in h zone} \quad \text{in Fig. 4. The temperature of inside the zone is equal to} \quad T_{c1w} \quad \text{and} \quad q_c = \frac{q_c}{\zeta} G C_p (T_{c2w} - T_{c1w}) \quad \text{in the h zone.}
\]

\[
\zeta = q_c / q_h = \frac{q_{cn}}{q_h} = \frac{(6/4) D_i^2}{(D_i^2 - (D_i - 2h)^2)}
\]

\[h = 0.5*D_i(1-(\zeta-1)/\zeta)^{0.5}\] is a boundary layer of heat transfer. \( h \) is equal to the thickness of a few silica pellets.

The measuring data and the calculated data are shown in the white circles of Fig. 5 and Table 2 with the data of the 15.7 test. The accuracy is \( \pm 1.4 \% \) for full scale except the mark 1 and 2 in the Table and Figure. The black circles in the Figure are additional data at 40.

The experimental formula is as follows:

\[
G = \begin{cases} 
2830/T & \text{at } T_{hw} = 35 \\
3410/T & \text{at } T_{hw} = 40
\end{cases}
\]

Equations (2) make measured value \( G \) for \( G \)

The accuracy = \( \left[ \frac{(G - G_m)}{G_{\text{max}}} \right] \times 100 \% \) (3)

The point 1 in Fig. 5 shows the unsteady error and the point 2 shows the error caused by heat loss.

The comparison table between S-1 and the others is shown in Table 3. The heat transfer method only is no calibration system for changing the size distribution of the feed material.
Table 2: Data and calculation of heat transfer method

<table>
<thead>
<tr>
<th>$u_s$</th>
<th>G</th>
<th>$T_{tw}$</th>
<th>$d_{m}$</th>
<th>T</th>
<th>$T_s$</th>
<th>$G^*$</th>
<th>($%$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cm/s</td>
<td>kg/h</td>
<td>W</td>
<td>K</td>
<td>min</td>
<td>kg/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.6</td>
<td>26</td>
<td>37</td>
<td>90</td>
<td>13.0</td>
<td>4.0</td>
<td>36</td>
<td>+5.0</td>
</tr>
<tr>
<td>7.7</td>
<td>36</td>
<td>38</td>
<td>90</td>
<td>11.4</td>
<td>3.0</td>
<td>41</td>
<td>+2.5</td>
</tr>
<tr>
<td>12</td>
<td>55</td>
<td>37</td>
<td>90</td>
<td>9.5</td>
<td>3.0</td>
<td>49</td>
<td>-3.0</td>
</tr>
<tr>
<td>31</td>
<td>147</td>
<td>38</td>
<td>90</td>
<td>3.5</td>
<td>2.0</td>
<td>134</td>
<td>-6.5</td>
</tr>
<tr>
<td>39</td>
<td>181</td>
<td>37</td>
<td>90</td>
<td>2.7</td>
<td>2.0</td>
<td>174</td>
<td>-3.5</td>
</tr>
<tr>
<td>43</td>
<td>199</td>
<td>37</td>
<td>90</td>
<td>2.5</td>
<td>2.0</td>
<td>188</td>
<td>+5.5</td>
</tr>
</tbody>
</table>

$G^* = 470/T$ for $15.7^o$

| 7.4   | 222 | 35   | 202   | 10.4| 18.1 | 272  | +2.5   |
| 11    | 334 | 35   | 270   | 8.4 | 12.0 | 337  | +0.2   |
| 17    | 506 | 35   | 231   | 5.7 | 7.8  | 497  | -0.5   |
| 32    | 970 | 35   | 320   | 3.0 | 4.1  | 943  | -1.4   |
| 62    | 2000| 35   | 349   | 1.8 | 1.9  | 1470 | -21    |

$G^* = 2830/T$ for $40^o$

| 14.0  | 438 | 40   | 168.2 | 8.0 | 7.3  | 445  | +0.4   |
| 22.7  | 710 | 40   | 177.0 | 5.1 | 6.7  | 698  | -0.9   |
| 34.4  | 1077| 40   | 168.2 | 3.3 | 5.8  | 1079 | +0.1   |
| 40.9  | 1278| 40   | 168.2 | 2.8 | 5.2  | 1271 | -0.3   |
| 46.7  | 1479| 40   | 177.0 | 2.4 | 4.7  | 1483 | +0.2   |
| 53.8  | 1681| 40   | 177.0 | 2.1 | 3.7  | 1695 | +0.7   |
| 59.8  | 1870| 40   | 177.0 | 1.9 | 3.5  | 1873 | +0.2   |
| 61.4  | 1920| 40   | 180.0 | 1.8 | 3.3  | 1977 | +3.0   |
| 61.7  | 1929| 35   | 180.0 | 1.8 | 3.1  | 1977 | +2.6   |

$G^* = 3560/T$ for $40^o$

Table 3: Comparison table for three methods

<table>
<thead>
<tr>
<th></th>
<th>S-1</th>
<th>S-2</th>
<th>S-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead time</td>
<td>1 min</td>
<td>0 min</td>
<td>0 min</td>
</tr>
<tr>
<td>Time constant</td>
<td>0 min</td>
<td>12 min</td>
<td>2 sec</td>
</tr>
<tr>
<td>Accuracy</td>
<td>2.0 %</td>
<td>0.9 %</td>
<td>1.6 %</td>
</tr>
<tr>
<td>Precision</td>
<td>Good</td>
<td>Checked</td>
<td>Good</td>
</tr>
<tr>
<td>Specification</td>
<td>+ Marker</td>
<td>None</td>
<td>+ Filter</td>
</tr>
</tbody>
</table>

4 NEW TEST PLANT

The aim of this test is the challenge for more suitable measuring method [17-4] based on the above-mentioned methods. Because the cross correlation method is suitable for the marker of the feed material and the steady state heat transfer method is suitable for the change of the feed specification.

The test pipe size is $44/40^o$, and heat condition is a pulse heating power ($80\ V \times 4.56\ A = 364.8\ W \times 1/2\ c/min$ (app. 0.0083 Hz). The distance between the primary sensor $\theta_1$ and the secondary one $\theta_2$ is 100 mm. The locations of the sensors are shown in Fig. 8.

5 EFFORTS OF THE NEW TEST

The primary temperature $\theta_1$ is 74.8 and secondary temperature $\theta_2$ is 38.0. The calculation formula is based on Equation (1). $x(t)$ is $\theta_1$, $y(t)$ is $\theta_2$. The cross correlation function is $\theta_{12}$ between $\theta_1$ and $\theta_2$. $d$ is the distance between $\theta_1$ and $\theta_2$. $u_{st}$ is the value concerned with $u_s$. For $\theta_{12}$ based on $\frac{d\theta_{12}}{dt} = 0$, $u_{st} = d/\tau_m$. The relation between $u_{st}$ and $u_{st}$ is $u_{st}^* = 10^{0.39} u_{st}^{1.58}$ (4) based on the Least Root Mean Square method and shown in Fig. 8 and Table 4. $u_{st}^*$ means the value on Equation (4). Fig. 9 and Table 4 include the data of the past cross correlation method using steel marker. Fig. 8 is a sample of $\theta_{12}$. 
Figure 6: Test equipment and location $\ell_1$ and $\ell_2$.

Figure 8: Auto correlation and cross correlation for 40\degree, cross correlation method using pulse heating.

6  FUTURE STUDY

The relation between the accuracy and the first 1 cycle sampling data should be checked.

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REFERENCES


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