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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.: the synthetic naphtha and hydrogen making reactor and DRI (Direct Reduction for Iron Ore) reducing petroleum and coke coal. 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 (JPA 1999-23339). The steady state heat transfer type is improved ale to +-0.8 % full scale in this paper and it is the most available for the new process till the third oil crisis or reconstruction of coke. This new prototype should be more useful for the derivative temperature against choking the feed powder on the surface of the temperature sensors. .

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

1. INTRODUCTION

The aim of this study is the confirmation of the nonintrusive massflow 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 massflow 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, respectivelly, the author selected the moved bed gravity flow using the stand pipe [14]. The mass flow ratio μ of gravity flow by moved bed is as follows: [16]

$$\mu = \frac{\rho_{Sb}}{\rho_{gn} \times \left\{ \dfrac{\rho_{Sn} - \rho_{Sb}}{\rho_{Sn} - \rho_{gn}(P_1 + 1/P_n + 1)} \right\} \left(\dfrac{P_1 + 1}{P_n + 1} \right)}$$

ρ_{sb} : solid bulk density [g/cm^3]
ρ_{sn} : solid net density [g/cm^3]
ρ_{gn} : gas density at normal pressure [g/cm^3]
P_1 : working pressure [10^5 Pa abs]
P_n : normal pressure [10^5 Pa abs]

μ will be 60 and 62 for 1 and 10 MPa against 7.5 and 0.78 of two phase flow, respectively. μ will be 2900 and 28 for 0 and 10 MPa for the following materials shown in **Table 1**.

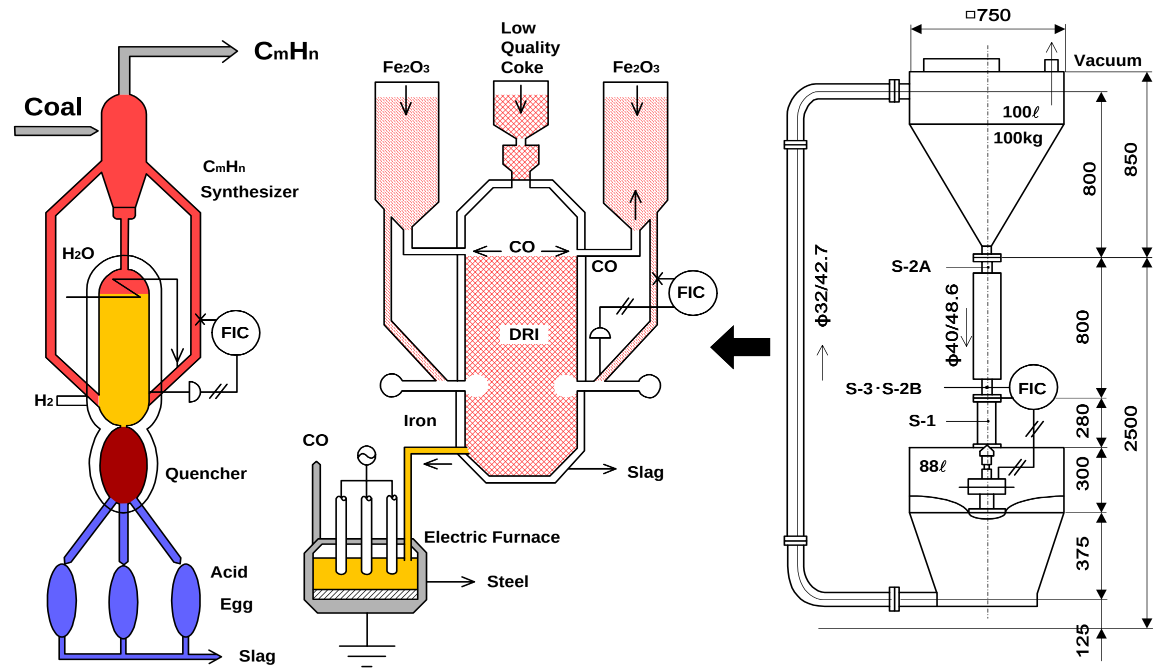


Fig 1. Process, test equipment and location S-1~3.

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 etal [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 40φ) feeding the same material without any sensing holes [6~14].

Table 1 Characteristics of test feed materials

Feed material	Silica pellet	Steel
Size d_p [mm]	1.8	1.6
Weight W_p [mg]	7.6	16
Net density [g/cm^3]	2.5	7.5
Bulk density [g/cm^3]	1.5	6.0

2. PAST EXPERIMENTAL APPARATUS

The nonintrusive sensors S-1 ~S-3 and the stand pipe are shown in Fig. 1. The actual massflow 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. Di is 40 mmφ, The distance d of sensors A, B in **Fig. 2** is 8mm. 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 a AE signal method using NF Circuit Inst.'s PZT (Plumbium Zirconate Titanate Zr/Ti 53/47) 900S, 922 , 912, the bandpass filter, Yokogawa's 3131DC amplifier and WX2A 1~100 ms first order lag filter and a pneumatic controller.

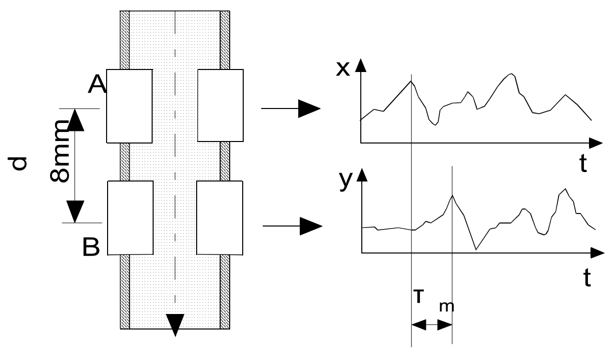


Fig 2. Sensors (S-1A,S-1B) and signals (x(t),y(t))

3. EFFORTS OF EXPERIMENTS

Fig. 3 shows a sample of the cross correlation of x(t) and y(t) for 5 wt% and 40φ. " XB= " in the Figure means τ_m. The calculation formulas are as follows:

$$\phi_{xy} = \frac{1}{T}\int_0^T x(t)y(t+\tau)dt$$

$$u_s = d/\tau_m, \quad \tau = \tau_m \quad at \quad \frac{d\phi_{xy}}{d\tau} = 0$$

$$G^* = \rho_{sb} A u_s \tag{1}$$

u_s, τ_m, G^*, u_s, ρ_{sb} 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 φ in [13].

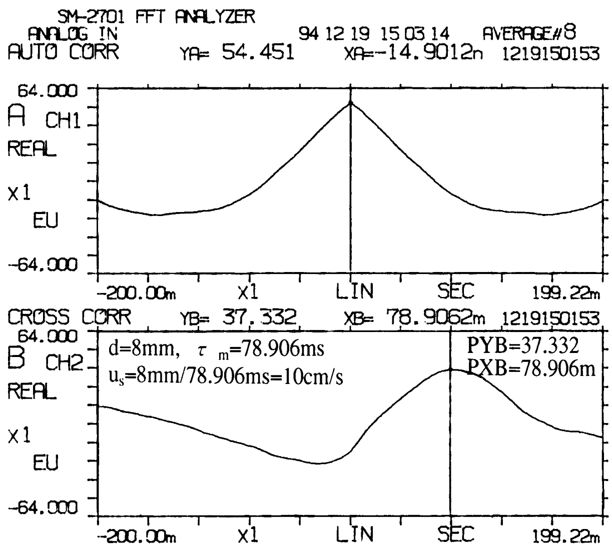


Fig 3. Auto correlation and cross correla tion for 40φ, 5 wt% steel marker and 8 mm distance

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_{c2w}-T_{c1w}),

q_h < 85 V x 4.5 A = 382.5 W,

$q_c = GC_pT$, C_p = 0.326 Wh/kg·K and

λ_p = 0.904 W/m·kg·K. As $q_h = GC_p(T_{c2w}-T_{c1w})$,

$\eta = q_c/q_h > 1$. As Bi(Bio Number) = $\alpha d/\lambda$ = 0.012, $q_{c1w} = q_{c2w} << 1\%$ of q_h , the pellets temperature is as follows:

$T_{c1} = T_{c1w}$ in wall side, $T_{c2} = T_{c2w}$ in h zone in Fig. 4. The temperature of inside the zone is equal to T_{c1w} and $q_c = \eta q_h = \eta GC_p(T_{c2w}-T_{c1w})$ in the h zone.

$\eta = q_c/q_h = q_{cn} = (\pi/4)Di^2/(Di^2-(Di-2h)^2)$

$h = 0.5*Di(1-(\eta-1)/\eta)^{0.5})$ 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 15.7φ test. The accuracy is ±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 °C.

The experimental formula is as follows:

$G^* = 2830/T$ at $T_{hw} = 35$ °C

$= 3178/T$ at $T_{hw} = 40$ °C (2)

Equations (2) make measured value G^* for G

The accuracy = $[(G^* - G) / G^*max]\times 100$ [%] (3)

The point 1 in Fig. 5 shows the unsteady error.

Table 2 Data and calcuration of heat transfer method

u_s cm/s	G Kg/h	T_{hw} °C	q_h W	T K	T_s min	G* kg/h	(3) %
G* = 470/T for 15.7φ							
5.6	26	37	90	13.0	4.0	36	+5.0
7.7	36	38	90	11.4	3.0	41	+2.5
12	55	37	90	9.5	3.0	49	-3.0
31	147	38	90	3.5	2.0	134	-6.5
39	181	37	90	2.7	2.0	174	-3.5
43	199	37	90	2.5	2.0	188	+5.5
G* = 2830/T for 40φ							
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* = 3178/T for 40φ							
23	689	40	156	4.6	6.6	691	+0.1
28	863	40	168	3.7	5.2	859	-0.2
32	961	40	180	3.3	4.9	963	+0.1
38	1165	40	208	2.7	4.6	1177	+0.6
42	1284	40	195	2.5	4.6	1271	-0.7
44	1339	40	183	2.4	3.8	1324	-0.8
52	1578	40	182	2.0	3.4	1589	+0.6
61	1861	40	192	1.7	2.1	1869	+0.5
64	1927	35	192	1.6	1.2	1986	+3.2

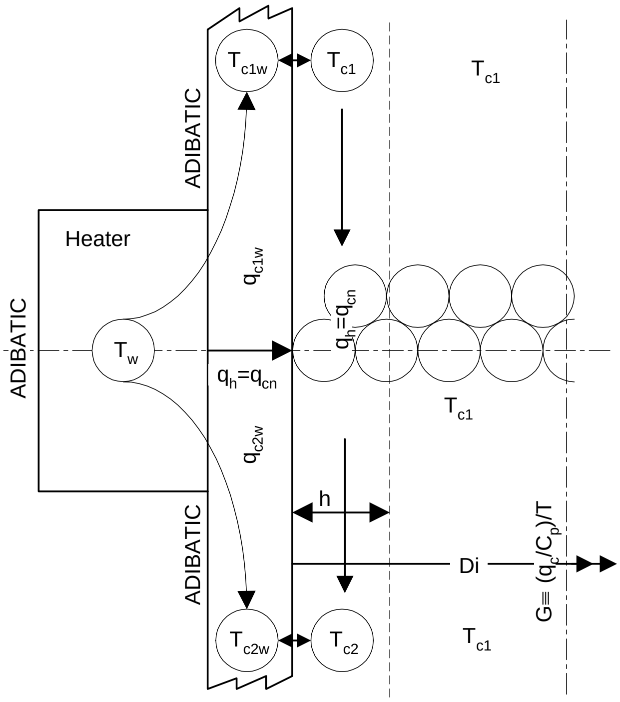
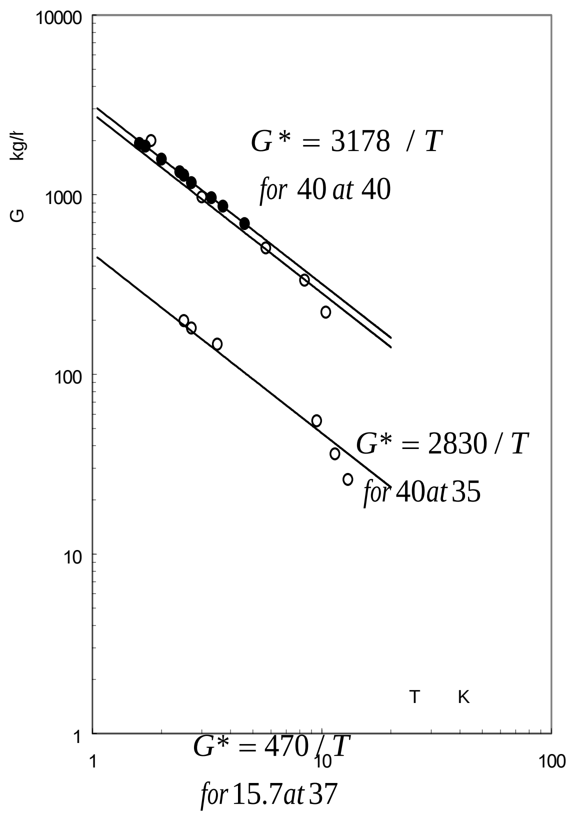


Fig 4 Sensors ($T = T_{c2w}-T_{c1w}$) and heat flow



Fige 5 Relation between T and G based on Table 2

The dynamic characteristics are as follows:

$\rho_w V_w C_{pw} dT_{c2w}/dt = q_h - C_{ps} G(T_{c2w} - T_{c1w})$ as V, C_p, w and s are volume, specific heat, wall and solid, respectively. Then, if G decreases, the time constant will be increased as follows:

$T(s)/q_h(s) = K_w/(1+T_w s), K_w = 1/C_{ps}G, T_w = \rho_w V_w C_{pw}/C_{ps}G$, using Laplace Transform, when G is constant.

$T = (q_h/C_{ps}G)(1-\exp(-C_{ps}Gt_m/\rho_w V_w C_{pw}))$, $t_m = L/u_s$ and L is the distance between the locations T_{c1w} and T_{c2w}.

The signals of S-3 are shown in AE signals 0 100 kHz. The power level and the specta have the linear relation with the massflow rate [12]. The accuracy of the all pass signal is ±1.6% for full scale. **Fig. 6** shows a kind of inverse response for up / down feed rate. The authorassumes that the distance between particles will separate for the up feed rate and the distance will be tighter for the down feed rate and the AE signal willbe reduced for a short time.

The band pass filter for the 75 kHz peak in **Fig. 7** is suitable for erasing the inverse response. However, as the accuracy decreases to ±2.8% caused by dusty pellets chaging the spectrum for the 75 kHz peak.

The comparison table between S-1 and the others is shown in **Table 3** .

The cross correlation method requires that 5~10% of the feed material to be marker material for the capacitance sensors. If the special features of actual feed material are found out, it will be very usefull. ($u_s = d/\tau_m$, $G^* = \rho_{sb} A u_s$ cf (1)) It is found out that the particles slightly move to the horizontal direction.

The steady state heat transfer method requires reducing the accuracy. The boundary layer of heat transfer method is equal to a few silica pellets as thickness. The calibration formula on the relation between $(T_{c2w}-T_{c1w})$ and G^* depends on the specific heat of the feed materials. ($G^* = \eta q_h / C_p(T_{c2w}-T_{c1w})$) cf [15]

The AE signal method is better than Sound level method for the solid state and heat proof condition. A lag filter requires a few second. AE signals depends on the size distribution of the feed material.

($u_s = A_0 + B \times$ AE signal, $G^* = \rho_{sb} A u_s$ cf [12])

The heat transfer method only is no calibration system for changing the size distribution of the feed material.

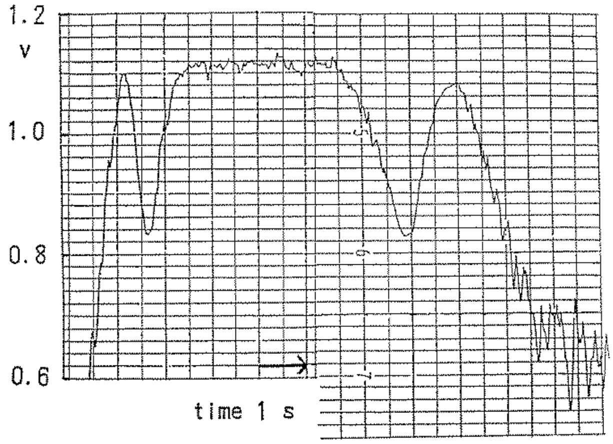


Fig 6 Inverse response of PZT AE method

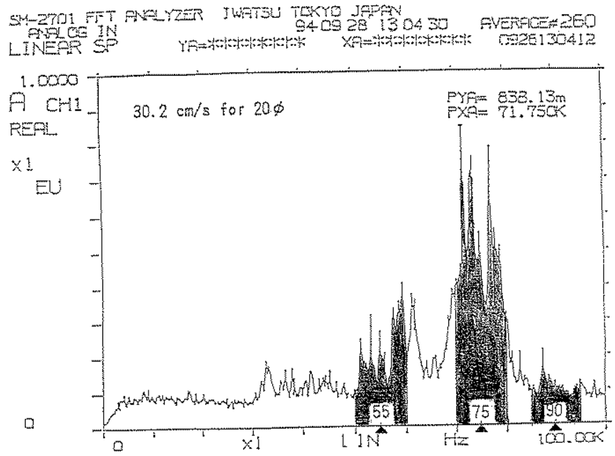


Fig 7 Spectra of PZT AE signal

Table 3 Comparison table for three methods

	S-1	S-2	S-3
Dead time	1 min	0 min	0 min
Time constant	0 min	12 min	2 sec
Accuracy	2.0 %	0.8%	1.6 %
Precision	Good	Checked	Good
Specification	+ Marker	None	+ Filter

4. NEW TEST PLANT

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

The test pipe size is 44/40φ, and heat condition is a pulse heating power(80V×4.56A=364.8W)×1/2 c/min (app. 0.0083Hz). The distance between the primary sensor θ_1 and the secondary one θ_2 is 50 mm. The locations of the sensors are shown in **Fig. 8**.

5. EFFORTS OF THE NEW TEST

The primary temperature θ_1 is 33.8~27.4 °C and secondary temperature θ_2 is 27.7~23.5 °C. The calculation formula is based on Equation(1). x(t) is θ_1. y(t) is θ_2. The cross correlation function is φ_{xy} between θ_1 and θ_2 . d is the distance between θ_1 and θ_2. u_{st} is the value concerned with u_s. Forτ_m based on $\frac{d\phi_{xy}}{dt} = 0$, $u_{st} = d/\tau_m$. The relation between u_{st} and u_s^* is

$$u_s^* = 10^{1.0} u_{st}^{1.7} \quad (4)$$

based on the Least Root Meen Square method and shown in **Fig. 9** and **Table 4**. u_s^* means the value on Equation (4). Fig. 9 and Table 4 include the data of the past cross correlation method using steel marker. **Fig. 10** is a sample of φ_{xy}.

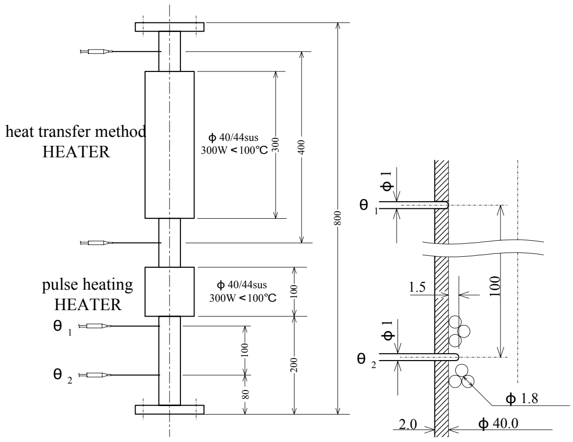


Figure 8 Test equipment and location θ_1 and θ_2

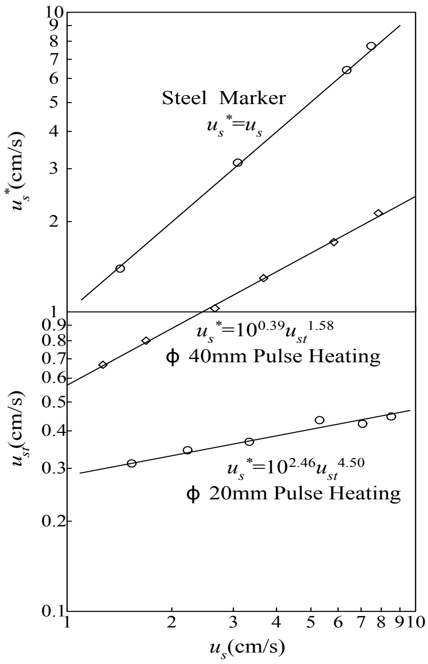


Figure 9 Relation between u_s and u_{st}

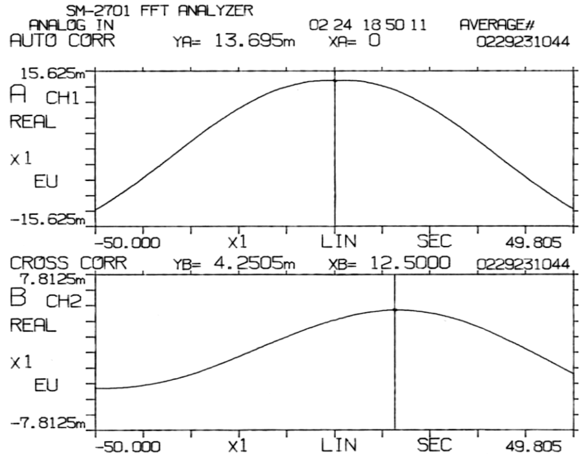


Figure 10 Auto correlation and cross correlation for 40φ, cross correlation method using pulse heating

Table 4 Relation between u_s and u_{st}

G kg/h	$\theta_{1\ max}$ °C	$\theta_{2\ max}$ °C	q_h W	u_s cm/s	u_{st} cm/s	U_s^* cm/s	Error %
83.25	72.1	49.5	364.8	1.270	0.665	1.29	0.24
110.51	70.3	51.0	364.8	1.686	0.8	1.73	0.54
173.63	61.3	46.6	364.8	2.649	1.024	2.55	-1.22
240.80	54.2	41.5	364.8	3.673	1.296	3.70	0.33
382.98	48.4	38.5	364.8	5.842	1.707	5.71	-1.63

6. CONCLUSIONS AND FUTURE STUDY

After the upper hopper is scale up and the heat wall is change to the heat conductive type, the accuracy and the first one cycle sampling data will be checked again..

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