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Journal of Engineering Research, Vol. 16, No. 3, September 2011 – A.A. Akinola

## COMPUTATIONAL ACCURACY IN CALCULATING IN-DUCT ISO-KINETIC SAMPLING RATES IN A SAMPLING TRAIN USING A MICROPROCESSOR

# convecting to flow meter conditions then

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#### ABSTRACT

The microprocessor is the heart of many automated devices in use at the present time. These microprocessors are used mainly in devices where repeated and rapid rates of calculations are required. To achieve rapid rates of calculation, the microprocessor is programmed directly in machine or assembly language. This paper presents the results of work done in programming a microprocessor in the Assembly programming language to calculate iso-kinetic sampling rates in a dust sampling train. The accuracies of the calculation are examined by comparing the results of the calculations with those obtained when using a mainframe computer. The results show that the accuracy of the calculations is within -4.5 % and +2.5%

#### INTRODUCTION 1.0

There is a need to take samples of flue gas isokinetically to obtain an accurate concentration of particulate matter in a flue gas stream. Isokinetic sampling of a gas stream is the withdrawal of gas into a sampling nozzle such that the suction velocity into the sampling nozzle is equal to the local velocity at the sampling location. The established procedure is to insert an aspirated nozzle into the flue gas and adjust the sampling suction rate according. The sampling suction rate is established by taking temperature and pressure readings at the sampling point and performing a series of complex calculations to obtain the required the sampling rate (British Standard Institution 893, 1978; ASME, 1991). This process is time consuming and adjusting the sampling rate to meet iso-kinetic sampling conditions lags behind changes in the temperature and pressure conditions at the sampling point. microprocessor is ideally suited to automating the collection of process data and control of processes and can be adapted to perform the calculations

for established sampling train arrangements for sampling flue gas streams (Barron et al., 1983; Akinola and Muir, 2007).

#### THEORETICAL DEVELOPMENT 2.0

Iso-kinetic sampling conditions is obtained when the velocity of suction,  $V_s$  into the sampling nozzle is made equal to the local gas velocity, V, in the duct. The local gas velocity, V for flue gas is measured by a Pitot tube.

Using a Pitot tube, V is given by

 $V = K_p \sqrt{\frac{Th}{sP}}$  and a constant of the second secon Where

Pitot tube pressure reading

h

 $K_{p}$ 

P

S

T

Calibration factor of the Pitot tube

Static Pressure of gas in the duct

relative density of the gas in the duct

Absolute temperature of the gas in the - duct

The volumetric gas flow rate, O, measured at duct conditions which should be withdrawn through a sampling nozzle of cross-sectional area, a at isokinetic sampling conditions is given by

-

 $Q = aV \tag{2}$ 

If  $Q_{f}$  is the volumetric flow rate obtained by correcting to flow meter conditions then

$$Q'_f = Q \frac{T_f}{T} \frac{P}{P_f}$$
(3)

where

Static Pressure of in Flow meter

 $P_f$ Absolute temperature of gas at the  $T_{f}$ flowmeter

For a differential pressure flow meter, the volumetric flow rate of gas flowing through the device is given by

(4) stablished sampling

$$Q_f = K_f \sqrt{\frac{T_f H}{s_f P_f}} \tag{4}$$

Equation 6 is obtained

where

Calibration factor of the flow meter K<sub>f</sub>  $S_f$  relative density of the gas at the flowmeter Pressure drop across the flowmeter H For isokinetic sampling as is measured by a Phot (5)  $Q_f = Q'_f$ 

By substituting equations 1, 2, 3 and 4 into equation 5 and rearranging the equations,

$$H = \left[\frac{K_{p}a}{K_{f}}\right]^{2} \frac{T_{f}}{T} \frac{P}{P_{f}} \frac{s_{f}}{s} h$$
(6)

Clearly the pressure drop H across the flow meter for a given nozzle of cross-sectional area a, and a given pitot tube reading h, T,  $T_f$ , P,  $P_f$ , S, and  $S_f$ . H is also dependent on  $K_p$  and  $K_f$ . and graden a straight  $K_p$  and  $K_f$ .

Hawskley et al. (1961) indicated that for most practical situations the ratio  $S_f/S$  can be assumed to be unity without the introduction of any significant error in the computation of H. Equation 6 can therefore be written as

$$H = \left[\frac{K_{p}a}{K_{f}}\right]^{2} \frac{T_{f}}{T} \frac{P}{P_{f}}h$$
(7)

In the work presented here, data for the sampling train developed by the British Coal Utilization Research Association (BCURA) is used. The equipment is described in detail by Hawskley et al. (1961). The aspirated nozzle can be fitted with one of 5 sampling nozzles denoted A, B, C, D and E; the nozzle have cross-sectional areas, a, of 9.29 x 10<sup>-4</sup>, 6.19 x 10<sup>-4</sup>, 4.65 x 10<sup>-4</sup>, 3.10 x 10<sup>-4</sup> and 2.17 x 10<sup>-4</sup> m<sup>2</sup> respectively. For the ellipsoidal type pitot tube also described in detail by Hawskley et al. (1961), the value of  $K_p$  equal 29.995. The

value of,  $K_f$ , depends on the dimensions and proportions of the flow meter. Extensive work done by Hawskley et al. (1961) and Akinola (1985) when an orifice flow meter and the cyclone fitted with any of the 5 nozzle sizes have established the following relationship for

$$K_{f} = A_{k} + B_{k}Z^{-1}$$
(8)  
where  
$$Z = \frac{Q_{0}\mu_{0}}{\mu_{f}} = Q_{f}\frac{\mu_{0}}{\mu_{f}}\frac{T_{0}}{T_{f}}\frac{P_{f}}{P_{0}}$$
(9)

M

Pressure at NTP  $P_0$ 

Volumetric gas flow rate flowing 2 through the flowmeter corrected to 9(1)180 the collection of process that 9.T.N Temperature at NTP  $T_0$ 

Gas density at NTP Po

Viscosity of the gas at the flowmeter

 $\mu_0$  Gas viscosity at NTP The values of the regression coefficients  $A_k$ and  $B_k$  are presented in Table 1

Table 1.	Values of the Re	egre	ession Coefficients	
A <sub>k</sub> and	$B_k$ )(Hawskley	et	al.,1961;Akinola,	

Flow	$A_{k}(x \ 10^{4})$	$B_k(x \ 10^4)$
		DC/810, 10001
with	5.752	7.289
		For Nozzle E
with	5.771	7.152
with	5.832	6.729
with	5.919	6.145
	others with	
with	6.355	13.898
Orifice Plate		17.511
to cal	culating Z,	Hawskley et al
	with with with with with te to cal	with       5.752         with       5.771         with       5.832         with       5.919         with       6.355         te       9,895         to       calculating       Z,

(1961) and Akinola (1985) derived the following relationship between  $\mu_0/\mu_f$  and  $T_f$ .  $\mu_0/\mu_f = 0.184129 + (22392/T_f)$  (10)

#### 3.0 METHODS AND MATERIALS

Computer programs are developed to compute the values of the pressure drop, H, across the flow meter at isokinetic sampling conditions. A flow chart for the programs is presented in Figure 1.

Two programs are developed, one in Assembly language on a Zilog 80 (Z80) 8 MHz microprocessor and the other in FORTRAN on a VAX Mainframe computer. The FORTRAN program is considered accurate as the numbers are calculated to a very large resolution. The choice of using Assembly language in developing the program was because it is capable of performing the calculations rapidly. The Assembly language program was developed using 32-binary digits arithmetic. The numbers were represented with 32-binary digits (bits). Therefore the largest number and smallest numbers that can be represented are  $2^{16}$  and  $2^{-16}$  respectively (Leventhal, 1979; Huda, 2006)



Figure 1: Flowchart used in Calculating *H* at Isokinetic Sampling Conditions

Preliminary work done using numbers with fewer binary digits (bits) proved unsatisfactory. When using 8-bits per number, only integers between 0 and 255 inclusive could be represented. With16-bits per number, the largest and smallest numbers that could be represented are  $2^8$  and  $2^{-8}$  respectively. The results of arithmetic operations such as multiplication and division resulted in overflow

the

and underflow in the microprocessor's smallest numbers diat can be represent, yromem

Identical calculations were carried out using the two programs and their results compared. The accuracy of the Assembly language program is expressed in terms of the errors in the sampling velocity rather than errors in Hitself. This is because the objective of computing H is to achieve the correct sampling velocity. The computational error  $E_{cn}$  is defined as

$$E_{cp} = \frac{V_s(ALP) - V_s(FORT)}{V_s(FORT)}$$
(11)

where V(ALP) V. calculated using the Assembly language program  $V_{\cdot}(FORT)$ V. Calculated using FORTRAN program

The values of T,  $T_f$ , P and  $P_f$  used in the trial calculations were selected to cover the ranges obtained in practice . For values of  $T, T_f, P$  and  $P_f$  a low, an intermediate and a high values was selected. The low, intermediate and high values of T selected are 323K, 523K and 823K respectively. The low, intermediate and high values of P selected are 932.4, 1036.8 and 1142.3 cmH<sub>2</sub>O respectively. The low, intermediate and high values of T<sub>s</sub> selected are 323K, 523K and 823K respectively and The low, intermediate and high values of P<sub>f</sub> selected are 932.4, 1036.8 and 1142.3 cmH<sub>2</sub>O respectively.

The values of h used in the trial calculations were also selected to cover the ranges obtained in practice. 5 values of hequally spaced in the possible range were selected for each nozzle. More values of h were selected because in practice the values of Hare more sensitive to the changes in the values of h than to changes in any of the other variables.

For Nozzle A the values of h selected are 0.05625, 0.08750, 0.11875, 0.15000 and 0.18125, and cmH<sub>2</sub>0. he could be could and

For Nozzle B the values of h selected are 0.140625, 0.21875, 0.296875, 0.37500 and 0.453125 cmH<sub>2</sub>0.

For Nozzle C the values of h selected are 0.28125, 0.4375, 0.59375 and 0.7500 and 0.90625 cmH<sub>2</sub>0.

For Nozzle D the values of h selected are 0.5625, 0.8750, 1.1875, 1.500 and 1.8125cmH<sub>2</sub>0.

For Nozzle E the values of h selected are 1.125, 1.750, 2.375, 3.000 and 3.625 cmH<sub>2</sub>0.

#### **RESULTS AND DISCUSSION** 4.0

By keeping constant the value of one of the variables that H depends on, and varying the values of the others within the ranges mentioned above, scatter plots of the computational error  $E_{cp}$  and the pitot tube readings hare made. The results are presented for Nozzle A in Figure 2 to Figure 7; similar results are obtained for other nozzle sizes.

Figure 2 is a plot of the computational error  $E_{cn}$  against the pitot tube values h for constant values of flue gas temperature values T while the other values  $T_f$ , P and  $P_f$  are varied within the range specified above. Examinations of Figure 2 shows that there is no clearly defined relationship between the duct gas temperature, T and  $E_{cp}$ ; rather the values of  $E_{cp}$  vary randomly within the error limits indicated on the graph.

Figure 3 is a plot of the computational error  $E_{cp}$  against the pitot tube values h for constant values of flowmeter gas temperature values  $T_f$  while the other values T, P and

 $P_{f}$  are varied within the range specified in Again examinations of Figure .3 Table 2. there is no clearly defined shows that relationship between the flowmeter gas

temperature,  $T_f$  and  $E_{cp}$ ; rather the values of  $E_{cp}$  vary randomly within the error limits indicated on the graph.

Figure 4 is a plot of the computational error  $E_{cp}$  against the pitot tube values h for constant values of flue gas pressure values Pwhile the other values  $T_f$ , T and  $P_f$  are varied within the range specified in Table 2. Examinations of Figure 4 shows that there is no clearly defined relationship between the flue gas pressure, P and  $E_{cp}$ ; rather the values of

 $E_{cp}$  vary randomly within the error limits indicated on the graph.

Figure 5 is a plot of the computational error  $E_{cp}$  against the pitot tube values h for constant values of flowmeter gas pressure values  $P_f$  while the other values  $T_f$ , T and P are varied within the range specified in Table 2. Again examinations of Figure 5 shows that there is no clearly defined relationship between the flowmeter gas pressure,  $P_f$  and  $E_{cp}$ ; rather the values of  $E_{cp}$  vary randomly within the error limits indicated on the graph.

Examinations of Figures 2, 3, 4, and 5 the values of the computational error values  $E_{cp}$  is greatest (-4.5% to +2.5%) at the lowest values

of hused but then reduces rapidly as the value of h increases. This range is approximately -2.5% to +1.5%

Also examinations of Figures 2,3,4 and 5 shows that there is no clearly defined relationship between the duct gas temperature, T and  $E_{cp}$ ; rather the values of  $E_{cp}$  vary randomly within the error limits indicated on the graph.

### 5.0 CONCLUSIONS

The iso-kinetic sampling rate for an in-duct sampling train has being calculated using the Assembly programming language on a microprocessor. The results have being compared with those obtained when using the FORTRAN Programming language on a mainframe computer. For the different nozzles sizes used (9.29 x 10<sup>-4</sup>, 6.19 x 10<sup>-4</sup>, 4.65 x 10<sup>-4</sup>,  $3.10 \times 10^{-4}$  and  $2.17 \times 10^{-4} \text{ m}^2$ ) and for temperatures range 323K - 823K, pressure range 932 cm  $H_20 - 1143$  cm  $H_20$  and for velocities appropriate for each nozzle size, it is determined that the computation errors in determining the iso-kinetic sampling rate is within -4.5 % and +2.5%. The computational accuracy varies within the range for all the velocities temperatures, pressures and considered.

Figure 3: Graph of  $E_{\phi}$  against *h* for constant values o

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Nozzle A di within vinobast vary A

...... Upper Error Limit Taoulay rodio odt olidw - Lower Error Limit 2.5 h (cmH2O) not of the com (02Hm2O)

Nozzle A

······· Upper Error Limit - Lower Error Limit

10



101 x or the different nozzles Figure 2: Graph of  $E_{cp}$  against h for constant values of  $T_{cp}$  and  $T_{cp}$  against h for constant values of  $T_{cp}$ 10 8 6 00 (%) 4 2 4° 0 EN -2 -4 -6 -8 -10 2.5  $h(cmH_2O)$ 0.0 0.5 1.0 1.5 2.0 x 10<sup>-1</sup>





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Nozzle A

------ Upper Error Limit ------ Lower Error Limit

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------ Upper Error Limit



Figure 4: Graph of  $E_{cp}$  against h for constant values of P





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