JOURNAL OF ENGINEERING RESEARCH

UNIVERSITY OF LAGOS
IN DEED AND IN TRUTH

ISSN: 0795 - 2333

September, 2011

JER-16, No. 3

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**Faculty of Engineering,
University of Lagos, Akoka
Yaba, Lagos State
Nigeria.**

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ISSN: 0795-2333
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c/o Faculty of Engineering,
University of Lagos, Akoka
Yaba, Lagos State
Nigeria.

Publisher:
The Faculty of Engineering, University of Lagos, Lagos, Nigeria.
Under the University of Lagos Book Policy.

Subscription Rates:

(including postage by surface mail)

		Within Nigeria	Outside Nigeria
Individuals	annual	₦3,500.00	US$350
	single copy	₦1,000.00	US$100
Institutions	annual	₦7,500.00	US$750
	single copy	₦2,000.00	US$200

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September 2011. JER-16, No. 3

CONTENTS

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

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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%

1.0 INTRODUCTION

There is a need to take samples of flue gas iso-kinetically to obtain an accurate concentration of particulate matter in a flue gas stream. Iso-kinetic 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. A 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).

2.0 THEORETICAL DEVELOPMENT

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

$$V = K_p\sqrt{\frac{Th}{sP}} \qquad (1)$$

Where

h	Pitot tube pressure reading
K_p	Calibration factor of the Pitot tube
P	Static Pressure of gas in the duct
s	relative density of the gas in the duct
T	Absolute temperature of the gas in the duct

The volumetric gas flow rate, Q , measured at duct conditions which should be withdrawn through a sampling nozzle of cross-sectional area, a at isokinetic sampling conditions is given by

$$Q = aV \qquad (2)$$

If Q_f is the volumetric flow rate obtained by correcting to flow meter conditions then

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

where

P_f Static Pressure of in Flow meter

T_f Absolute temperature of gas at the flowmeter

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

$$Q_f = K_f\sqrt{\frac{T_f H}{s_f P_f}} \qquad (4)$$

where

K_f Calibration factor of the flow meter

s_f relative density of the gas at the flowmeter

H Pressure drop across the flowmeter

For isokinetic sampling

$$Q_f = Q_f' \qquad (5)$$

By substituting equations 1, 2, 3 and 4 into equation 5 and rearranging the equations, Equation 6 is obtained

$$H = \left[\frac{K_p a}{K_f}\right]^2 \frac{T_f}{T}\frac{P}{P_f}\frac{s_f}{s}h \qquad (6)$$

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.

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

$$H = \left[\frac{K_p a}{K_f}\right]^2 \frac{T_f}{T}\frac{P}{P_f}h \qquad (7)$$

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^{-4}, 6.19 x 10^{-4}, 4.65 x 10^{-4}, 3.10 x 10^{-4} and 2.17 x 10^{-4} m^2 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

$$K_f = A_k + B_k Z^{-1} \qquad (8)$$

where

$$Z = \frac{Q_0\mu_0}{\mu_f} = Q_f\frac{\mu_0}{\mu_f}\frac{T_0}{T_f}\frac{P_f}{P_0} \qquad (9)$$

Where

P_0 Pressure at NTP

Q_0 Volumetric gas flow rate flowing through the flowmeter corrected to N.T.P.

T_0 Temperature at NTP

ρ_0 Gas density at NTP

μ_f Viscosity of the gas at the flowmeter

μ_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 Regression Coefficients A_k and B_k)(Hawskley et al.,1961;Akinola, 1985

Type of Flow meter	A_k(x 10^4)	B_k(x 10^4)
Cyclone with Nozzle A	5.752	7.289
Cyclone with Nozzle B	5.771	7.152
Cyclone with Nozzle C	5.832	6.729
Cyclone with Nozzle D	5.919	6.145
Cyclone with Nozzle E	6.355	13.898
Orifice Plate	9,895	17.511

As an aid to calculating Z, Hawskley et al (1961) and Akinola (1985) derived the following relationship between μ_0/μ_f and T_f.

$$\mu_0/\mu_f = 0.184129 + (22392/T_f) \qquad (10)$$

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; Hyde , 2006).

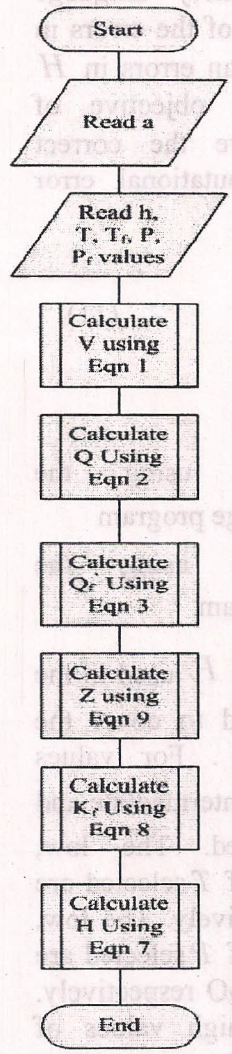

Figure 1: Flowchart used in Calculating H at Isokinetic Sampling Conditions

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 and underflow in the microprocessor's memory.

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 H itself. This is because the objective of computing H is to achieve the correct sampling velocity. The computational error E_{cp} is defined as

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

where

$V_s(ALP)$ V_s calculated using the Assembly language program

$V_s(FORT)$ V_s Calculated using the 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$_2$O respectively. The low, intermediate and high values of T_f selected are 323K, 523K and 823K respectively and The low, intermediate and high values of P_f selected are 932.4, 1036.8 and 1142.3 cmH$_2$O respectively.

The values of h used in the trial calculations were also selected to cover the ranges obtained in practice. 5 values of h equally spaced in the possible range were selected for each nozzle. More values of h were selected because in practice the values of H are 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$_2$0.

For Nozzle B the values of h selected are 0.140625, 0.21875, 0.296875, 0.37500 and 0.453125 cmH$_2$0.

For Nozzle C the values of h selected are 0.28125, 0.4375, 0.59375 and 0.7500 and 0.90625 cmH$_2$0.

For Nozzle D the values of h selected are 0.5625, 0.8750, 1.1875, 1.500 and 1.8125cmH$_2$0.

For Nozzle E the values of h selected are 1.125, 1.750, 2.375, 3.000 and 3.625 cmH$_2$0.

4.0 RESULTS AND DISCUSSION

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 h are 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_{cp} 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 Table 2. Again examinations of Figure . 3 shows that there is no clearly defined 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 P while 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 $h$used 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^{-4}, 6.19 x 10^{-4}, 4.65 x 10^{-4}, 3.10 x 10^{-4} and 2.17 x 10^{-4} 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 temperatures, pressures and velocities considered.

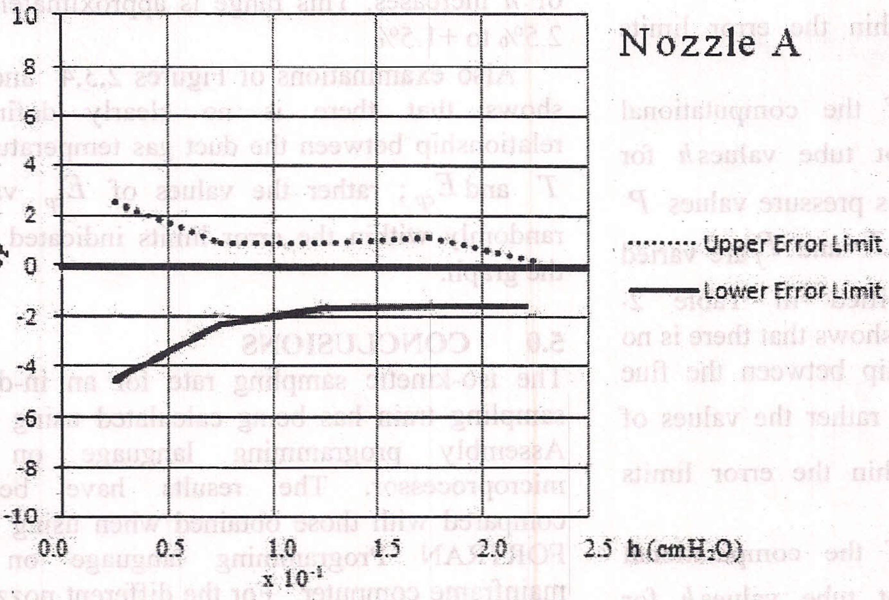

Figure 2: Graph of E_{cp} against h for constant values of T

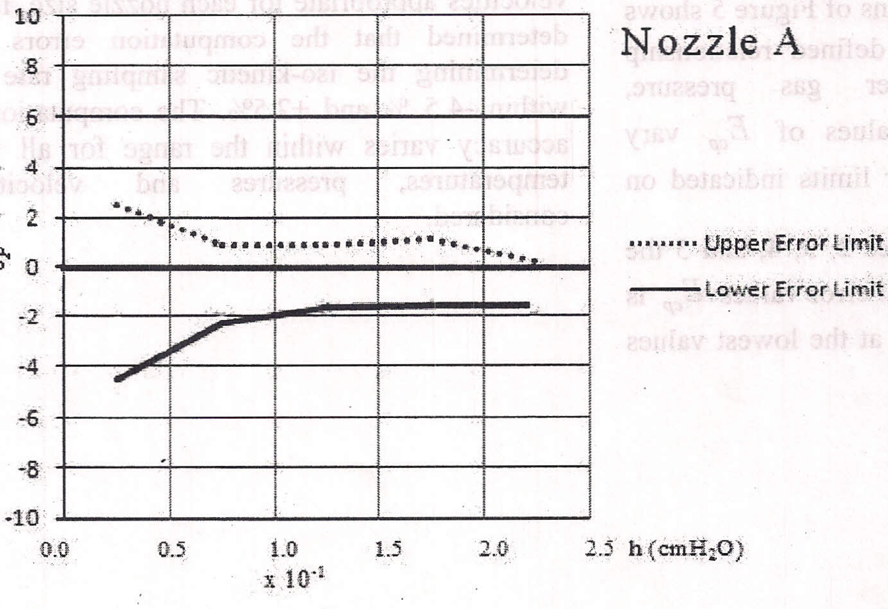

Figure 3: Graph of E_{cp} against h for constant values of T_f

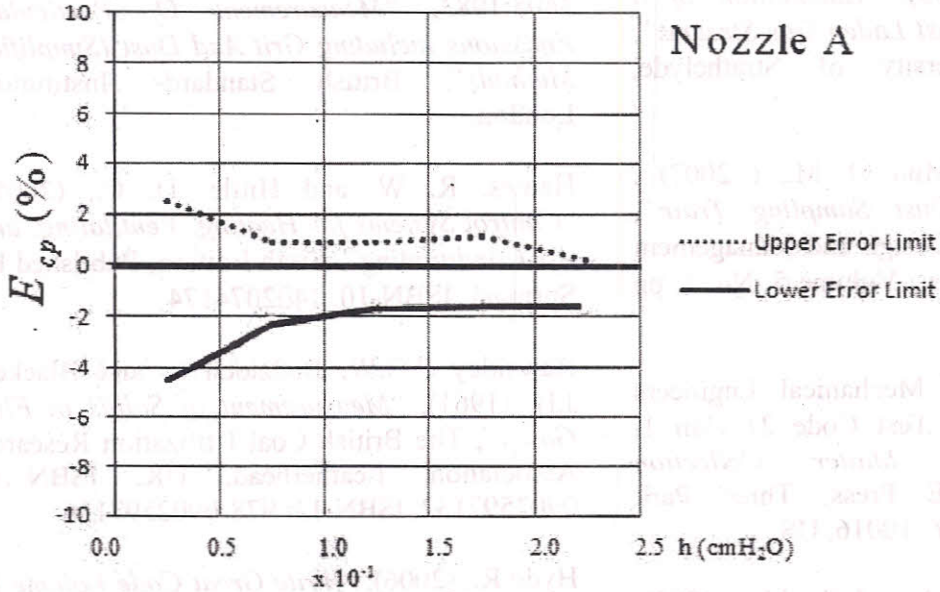

Figure 4: Graph of E_{cp} against h for constant values of P

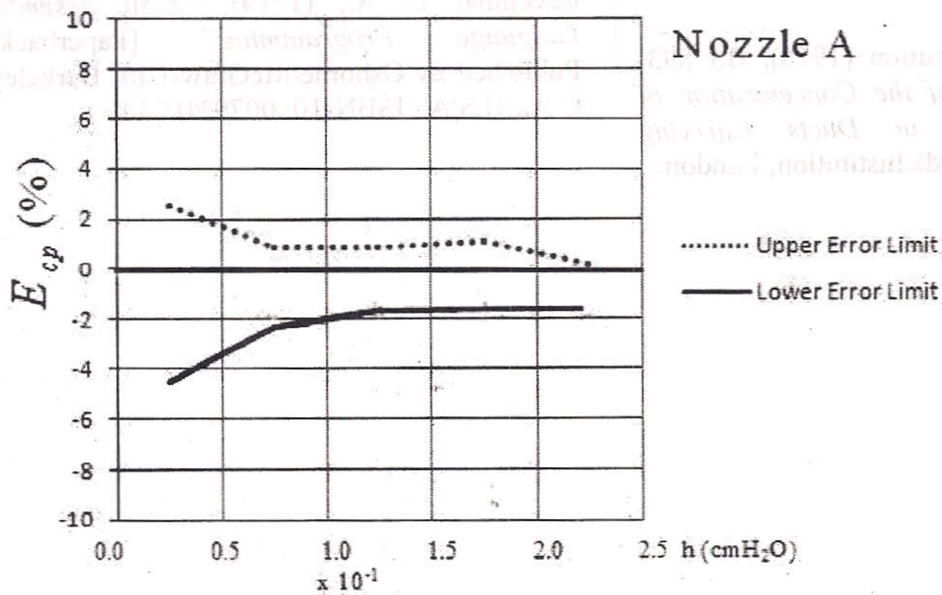

Figure 5: Graph of E_{cp} against h for constant values of P_f

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