Configuration of Microcomputer-Based Instrumentation Systems Measuring Mass Consumption of Fuel Gas

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Abstract—The measurement of the mass consumption of fuel gas over a specified period of time is discussed in this paper. The various configurations of microcomputer-based instrumentation which may be used for this measurement are reviewed. Relationships expressing the overall measurement error as a function of the accuracies of the sensors used in each configuration are derived. On the basis of these relationships a method is developed for selecting the measurement configuration which presents the best cost to performance ratio. The use of this method is demonstrated by an application example.

I. Introduction

RECENTLY, increased emphasis has been given to the accurate measurement of the mass comsumption of fuel or natural gas in industrial plants. This has resulted in the development of microcomputer-based systems which can estimate the mass consumption on a continuous time basis. The calculations executed by these systems are based on algorithms recommended by organizations such as the American Gas Association (AGA) and the International Standards Organization (ISO). To execute these algorithmic calculations on a continuous time basis, input data must be provided by external sensors measuring physical variables such as volume flow rate, gas density, temperature, and absolute line pressure. When some of these variables do not vary significantly around an average value, an estimate of the mass consumption satisfying specific error requirements may be obtained by using average historical data of the variables. In this way the cost of the sensors is saved.

Cases of slightly varying gas flow conditions appear in a number of continuous process plants when they operate at constant throughputs. For example, in an oil refinery the volume flow rate and line pressure do not usually exceed ± 10 percent of an average value because of the existing regulatory control loops. Density seems to have wider variations which may be up to ± 30 percent around an average value. Temperature variations, however, are quite unpredictable and sometimes may be ± 50 percent around an average value.

Typical requirements for the relative error of the mass consumption estimation may vary from 0.2 to 6 percent. The selection of an error figure depends on the application. If the instrumentation system is used to charge gas sales to third parties, then the 0.2-percent figure is selected. If, however the system is used to determine monthly plant losses then the selection of an error limit depends on the impact the error has on the precise determination of the plant losses.

There are usually strong financial incentives in reducing the measurement error of mass consumption. For example, a ± 10 percent deviation of the actual gas density from an average value may result in an error of ± 100 kg per consumed ton of purchased gas. If a cost of \$0.18/kg is assumed there will be a loss or gain of \$18/ton. For a usual yearly consumption of 20 000 tons, the financial loss or illegal gain may be \$360 000. This is a significant figure and can be reduced if the microcomputer-based system is used to measure the gas density and perform the mass consumption calculations on a continuous time basis. If, in this last case, the relative error of the mass consumption is ± 2 percent then the absolute error per consumed ton of gas becomes 20 kg and the corresponding financial loss per year \$72 000.

Generally, there appears to be a lack of appropriate methodologies for rationally designing microcomputer-based systems which can estimate the mass consumption of fuel gas within specified error limits. To partially fill this gap a method is presented in this paper for selecting the algorithm, the number, and the type of sensors which optimize the cost to performance ratio of the system. The method makes use of relationships which have been obtained by analyzing the way the inherent errors of the sensors are propagated in the algorithmic computations.

II. Microcomputer-Based Instrumentation Systems for Mass Consumption Measurement

Any microcomputer-based system, which is designed to estimate the mass consumption of fuel gas according to the recommendations of the AGA and ISO organizations, will consist of:

a) a microcomputer programed to execute the recommended mathematical calculations,
b) interfacing circuits converting to binary form the

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values of the analog or pulse signals of external sensors,

c) a keyboard by means of which data are loaded in the system database and programs are modified,

d) a display unit which is used to monitor the system operation and output the results of the calculations, and

e) sensors measuring the gas volume flow rate, the absolute pressure, the gas density, and temperature.

The AGA and ISO recommendations assume the use of the orifice plate meters [7] for the volume flow rate measurement. The sensors that can be used for the pressure measurement may be of the diaphragm, bourdon tube, piezoelectric, or electrical type [7]. For the temperature measurement the three or four lead platinum resistance thermometers are used [7]. The most suitable instrument for the on-line measurement of the density of a flowing gas is the vibrating spool inertia-type meter [5]. It produces an electrical pulse signal the amplitude of which is constant but its period varies with the gas density, the line pressure, and the gas temperature.

The error of the mass measurement is mainly influenced by the errors of the used sensors, the variations of the nonmeasured variables and the sensitivity of the algorithm to these variations. The quantization, truncation, and roundoff errors introduced by the microcomputer can be reduced to levels which do not influence the most significant digits of the absolute error of the system. This can be done by properly selecting the word length of the analog to digital converter and by approximating the infinite series by an adequate number of terms. Also, errors which are introduced by such elements as multiplexers and sample and hold circuits can become negligible by properly selecting the sampling frequency to reduce the aliasing effect and by inserting filtering to reduce the high frequency noise components.

The simplified diagram of a system [3], [4] which is now in operation in a number of plants, is given in Fig. 1. The system uses the popular Motorola 6809 microprocessor and the reported processing error is below +0.001 percent of the estimated value of mass consumption.

III. Mass Consumption Estimation

The mass consumption over a specified period of time may be estimated from a number of samples of the mass flow rate. That is,

$$W = \sum_{i=1}^{n} q_i \cdot r \tag{1}$$

where q_i is the mass flow rate at the ith sampling instant, $1 \le i \le n$, expressed in kilograms per hour, r is the sampling period in hours, and W is the mass consumption in kilograms.

For calculating the rate of mass flow of a gass through an orifice is recommended by AGA [1]:

$$q_i = 0.07628 F_b F_{R_i} e_i (h_i g_i)^{0.5}. \tag{2}$$

In this equation, h_i is the differential pressure developed across the taps of the flange of the orifice plate at the ith sampling instant and is expressed in millibar, and g_i is the gas density expressed in kilograms per cubic meter. The factor F_b is used to compensate the disturbances caused in the gas flow by the orifice plate and is called the basic orifice factor. It is expressed in $\text{kg/h}\sqrt{\text{mbar} \cdot \text{kg/m}^3}$ and is given for an infinite Reynolds number by the empirical equation:

$$F_b = 0.5242 \frac{C_e d^2}{1 + 15J/10^6} \tag{3}$$

where d is the diameter in millimeters of the orifice bore, and C_e and J are functions of d and the internal diameter of the pipe D, which is also expressed in millimeters. These functions are

$$\begin{aligned} C_e = {} & 0.5993 + \frac{0.007}{D/25.44} + \left[0.364 + \frac{0.076}{\sqrt{D/25.44}}\right]\left(\frac{d}{D}\right)^4 \\ & + 0.4\left[1.6 - \frac{1}{D/25.44}\right]^5 \left[\left(0.07 + \frac{0.5}{D/25.44}\right) \right. \\ & \left. - \left(\frac{d}{D}\right)\right]^{2.5} - \left[0.009 + \frac{0.034}{D/25.44}\right]^{1.5} \\ & + \left[0.5 - \frac{d}{D}\right]^{1.5} + \left[\frac{65}{(D/25.44)^2} + 3\right]\left[\frac{d}{D} - 0.7\right]^{2.5} \end{aligned} \tag{4}$$

$$\begin{aligned} J = {} & \frac{530}{\sqrt{D/25.44}} + 830 + 9000\left(\frac{d}{D}\right)^2 - 5000\frac{d}{D} \\ & - 4200\left(\frac{d}{D}\right)^3. \end{aligned} \tag{5}$$

In any actual case of metering the Reynolds number has a finite value. The derivation of (3), however, was based on the assumption that the Reynolds number is infinite. The factor F_R which is called the Reynolds number factor, is applied to F_b to allow for this difference. F_R is dimensionless and its value at the ith sampling instant F_{R_i} is given by the equation

$$F_{R_i} = 1 + \frac{0.0103J(1 + 15J/10^6)}{359.041 C_e F_{R_{i-1}} (h_i g_i)^{0.5}}. \tag{6}$$

When gas flows through an orifice the change in velocity and pressure is accompanied by a change in specific weight. The expansion factor e_i is applied to F_b to allow for this change. It is also dimensionless and is given by the equation

$$e_i = 1 - \left(0.41 + 0.35\left(\frac{d}{D}\right)^4\right)\frac{h_i}{1300P_i}. \tag{7}$$

The relationship recommended by ISO [2] for calculating q_i is similar to (2). That is:

$$q_i = 0.0399 C_i E e_i d^2 (h_i g_i)^{0.5} \tag{8}$$

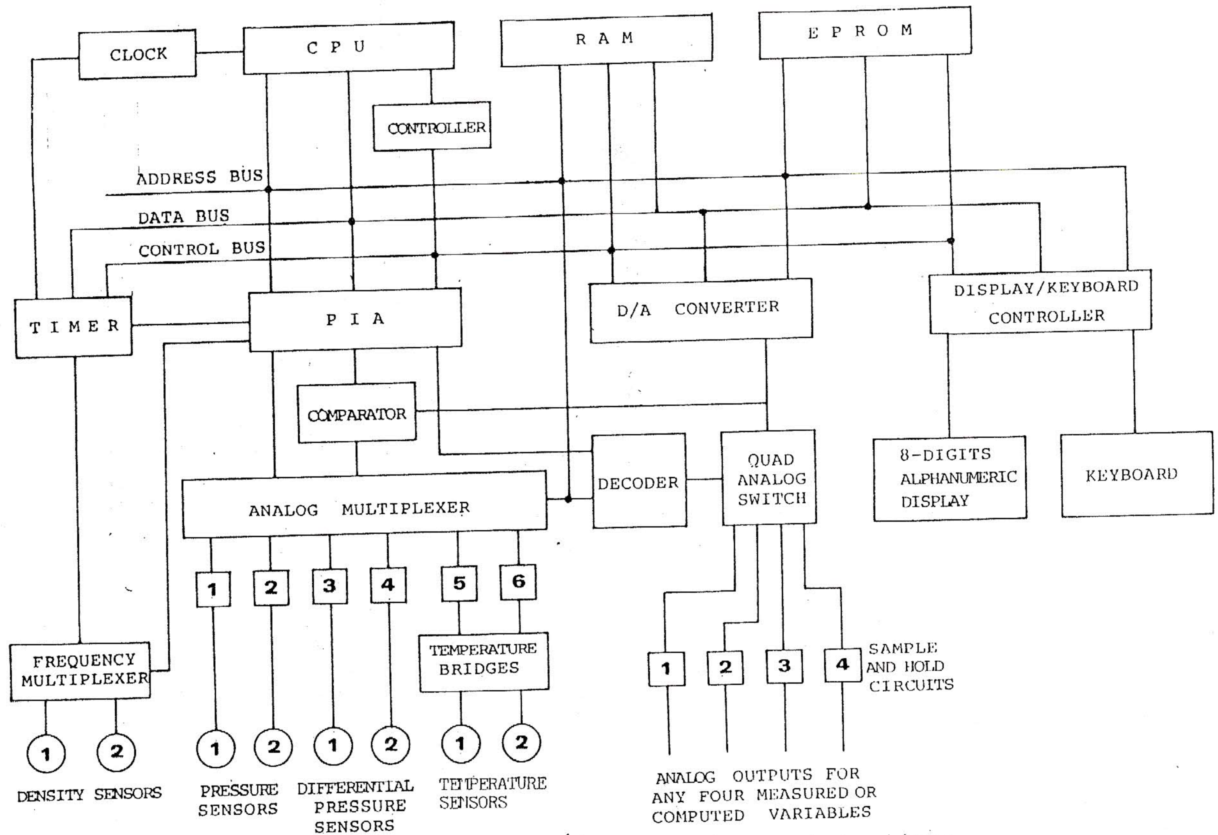

Fig. 1. Simplified schematic diagram of a microcomputer-based instrumentation system.

where e_i and d are the same quantities appearing in (2) and C_i and E are similar to F_{R_i} and F_b factors but they are computed from different empirical relationships. These relationships are

$$E = \frac{1}{\left(1 - \left(\frac{d}{D}\right)^4\right)^{0.5}} \tag{9}$$

$$C_i = C_0 + 0.003\left(\frac{d}{D}\right)^{2.5}\left(\frac{10^6}{R}\right)^{0.75} \tag{10}$$

where

$$C_0 = 0.5959 + 0.0312\left(\frac{d}{D}\right)^{2.1} - 0.1840\left(\frac{d}{D}\right)^8 + \left(0.09\left(\frac{d}{D}\right)^4\left(1 - \left(\frac{d}{D}\right)^4\right)^{-1}\right) \cdot \left(\frac{25.44}{D}\right) - 0.0337\left(\frac{d}{D}\right)^3\left(\frac{25.44}{D}\right) \tag{11}$$

$$R = \frac{14.14 E C_0 d^2 (h_i g_i)^{0.5}}{0.0103 D}. \tag{12}$$

IV. Error Analysis

If g_0, P_0, and h_0 are mean values of the g_i, P_i, and h_i variables, respectively, and s_{g_i}, s_{P_i}, and s_{h_i} are their standard deviations, then it is proved [6] that the standard deviation of the mass flow rate s_{q_i} is given by

$$s_{q_i} = \left(\frac{\partial q_i}{\partial g_i}\right)^2_{g_0, P_0, h_0} s^2_{g_i} + \left(\frac{\partial q_i}{\partial P_i}\right)^2_{g_0, P_0, h_0} s^2_{P_i} + \left(\frac{\partial q_i}{\partial h_i}\right)^2_{g_0, P_0, h_0} s^2_{h_i}. \tag{13}$$

Relationships for the partial derivatives may be derived by differentiating equation (2) or (8). All the partial derivatives are evaluated at $g_i = g_0$, $P_i = P_0$, $h_i = h_0$.

To evaluate s_{q_i} the standard deviations of g_i, P_i, and h_i must be known. If the variations of a variable are not monitored by a sensor, then the standard deviation of this variable can be evaluated by taking a limited number of independent measurements off line and over a specified period of time. If the variations are monitored by a sensor on a continuous time basis, then the specified error of the sensor may be used to ascribe a value to the standard deviation of this variable. Assuming that the variable is normally distributed and systematic errors have been eliminated, there will be a 95.4 percent probability [8] that

$$s_v = \frac{e_v}{2} \tag{14}$$

where s_v is the standard deviation of the variable and e_v is the absolute value of the upper bound of the sensor error. The e_v value is directly related to the accuracy specification of a sensor. This specification is expressed as a percentage of the operating range for sensors used to measure the P_i and h_i variables. The accuracy specification of the density sensor cannot be expressed in this form because of the sensor output dependence on the line absolute pressure and the gas temperature besides density. Its standard deviation, however, can be evaluated from the accuracy specifications of the sensors used for the measurement of the other variables. The mathematical relationships which describe the behavior of the density sensor are given in Table I. If we express the density variance in terms of the variances of the line pressure P_i, the gas temperature T_i, and the signal period t_2, replace the derived equation in (13), and assume that the t_2 variance is practically zero, we have

$$s_{qi}^2 = \left[\left(\frac{\partial q_i}{\partial g_i}\right)\left(\frac{\partial g_i}{\partial t_1}\right)\left(\frac{\partial t_1}{\partial T_i}\right)\right]^2_{g_0, P_0, h_0, T_0} s_{T_i}^2 + \left[\left(\frac{\partial q_i}{\partial g_i}\right)\left[\left(\frac{\partial g_i}{\partial t_1}\right)\left(\frac{\partial t_1}{\partial P_i}\right) + \left(\frac{\partial g_i}{\partial d_1}\right)\left(\frac{\partial d_1}{\partial P_i}\right)\right]\right. + \left.\left(\frac{\partial q_i}{\partial P_i}\right)\right]^2_{g_0, P_0, h_0, T_0} s_{P_i}^2 + \left(\frac{\partial q_i}{\partial h_i}\right)^2_{g_0, P_0, h_0, T_0} s_{h_i}^2. \quad (15)$$

For the computation of the partial derivatives the mean value of t_2 is also required. A mean value for t_2 is not however available during the design phase of the system. By using the equations of Table I and considering that for all the practical uses of the system it is $t_2 \geq t_1$ and $k = 1$, one can express t_2 as a function of P_i and g_i. That is

$$t_2 = \sqrt{\frac{[0.13P_i t_1^2(1 + d_0 g_i) + g_i] + \sqrt{[0.13P_i t_1^2(1 + d_0 g_i) + g_i]^2 - 0.52P_i d_0 g_i t_1^2}}{0.26P_i d_0}}.$$

The partial derivatives become independent of t_2 when it is replaced by its equivalent function.

In (1), each value of the mass flow rate q_i may be thought of having being selected at random from a population of measurements the standard deviation of which is s_q. Accordingly, the mass consumption W may be looked upon as one of many possible sums consisting of n terms of the form $q_i \cdot r$, the q_i variates of which are selected at random from n sets, each with the same deviation s_q. Then it will be

$$s_W^2 = n \cdot s_q^2 \cdot r^2. \quad (16)$$

If $s_q \cdot r << s_W$ the mass consumption will be normally distributed [9] and, therefore, it will be a 95.4-percent probability the estimation error to be

$$e_1 = 2s_W. \quad (17)$$

V. System Configuration

The designer of the instrumentation system is usually faced with the problem of finding the less expensive configuration by means of which the mass consumption can be measured with an error less than a specified upper limit. As the microcomputer is the basic component in any system configuration, the cost difference between any two configurations will depend entirely on the cost difference of their sensors and that associated with their interfacing circuits. Therefore, the problem of finding the less expensive configuration becomes a problem of finding the less expensive combination of sensors and interfacing circuits required to satisfy the specified limit. This can be done by evaluating the contributions of the variations of a variable or a combination of variables to the system error. Then, the individual contributions or the sum of the contributions of the cheapest sensors which result to an error greater than the specified, are found. To identify the cheapest combination of sensors the current relationships between the costs of the sensors and the associated with them interfacing circuits are considered. As an example we consider the system of Fig. 1. Then, we have

$$c_g > c_h > c_T > c_P \quad (18)$$

$$c_g > c'_h > c'_T > c'_P \quad (19)$$

$$c_g > c'_h + c'_T + c'_P \quad (20)$$

$$c'_h > c'_T + c'_P \quad (21)$$

where c_g is the sum of the costs of the density sensor, the multiplexer, and the timer. Each one of the c_h, c_T, and c_P quantities is the sum of the cost of the sensor used for the measurement of the h, T, or P variable, respectively, the cost of the input filter and the cost of the comparator. These figures are used to assess the cost of a configuration having only one of the three sensors. Each one of the c'_h, c'_T, and c'_P quantities corresponds to the cost of measuring the h, T, and P variables, respectively, when a combination of the h, T, and P sensors is used. This cost consists of the cost of the respective sensor, the cost of the input filter, and a fraction of the cost of the analog multiplexer and the comparator. It is assumed that the cost of the analog multiplexer is independent of the number of the used sensors.

Referring to (13), (15), and (16) one can easily derive that the contributions of the g, h, P, and T variables to the square of the system error are, respectively,

$$A = 4nr^2\left(\frac{\partial q_i}{\partial g_i}\right)^2_{g_0, P_0, h_0} \cdot s_{gi}^2 \quad (23)$$

$$B = 4nr^2\left(\frac{\partial q_i}{\partial h_i}\right)^2_{g_0, P_0, h_0} \cdot s_{hi}^2 \quad (24)$$

$$C = 4nr^2\left(\frac{\partial q_i}{\partial P_i}\right)^2_{g_0, P_0, h_0} \cdot s_{P_i}^2 \quad (25)$$

TABLE I
RELATIONSHIPS DESCRIBING THE BEHAVIOR OF THE DENSITY SENSOR

$$g_i = \frac{2d_1}{t_1}(t_2 - t_1)[1 + \frac{k}{2t_1}(t_2 - t_1)]$$

$$t_1 = t_0 + N_0(T_i - T_c) + Q_0(P_i - P_c)$$

$$d_1 = d_0[1 - \frac{10^6 \, g_i}{13.10^4 . P_i . t_2^2}]$$

T_c and P_c are the absolute temperature and pressure at which the density sensor was calibrated. They are expressed in ^oK and bar respectively.

T_i is the absolute temperature of the flowing gas in ^oK.

P_i is the absolute line pressure in bar, upstream of the orifice plate.

d_0 is a calibration constant of the spool in kg/m^3.

d_1 is the value of d_0 corrected at the flowing conditions of the gas

t_0 is the periodic time of spool in vacuum when $T_i=T_c$. It is expressed in secs.

N_0 is the temperature coefficient of the spool in secs/^oK.

k is a user defined calibration constant. It is set equal to one when a factory calibrated density sensor is provided. It is modified when the density sensor presents deviations from its initial calibration.

Q_0 is the pressure coefficient of spool in secs/bar.

t_2 is the period of the generated pulse signal in secs.

$$D = 4nr^2\left[\frac{\partial q_i}{\partial g_i}\left[\left(\frac{\partial q_i}{\partial t_1}\right)\left(\frac{\partial t_1}{\partial P_i}\right) + \left(\frac{\partial g_i}{\partial d_1}\right) \cdot \left(\frac{\partial d_1}{\partial P_i}\right)\right] + \left(\frac{\partial q_i}{\partial P_i}\right)\right]^2_{T_0, P_0} \cdot s^2_{P_i} \tag{26}$$

$$G = 4nr^2\left(\left(\frac{\partial q_i}{\partial g_i}\right)\left(\frac{\partial g_i}{\partial t_1}\right)\left(\frac{\partial t_1}{\partial T_i}\right)\right)^2_{T_0, P_0} \cdot s^2_{T_i}. \tag{27}$$

To obtain values for the g_0, P_0, h_0, s_{g_i}, s_{h_i}, and s_{T_i} quantities a number m of independent measurements of the g, P, T, and h variables are taken. The number m is obtained from the following relationship [6]:

$$m = \max\left[\frac{s^2_{g_i}}{s^2_{\bar{g}}}, \frac{s^2_{P_i}}{s^2_{\bar{P}}}, \frac{s^2_{T_i}}{s^2_{\bar{T}}}, \frac{s^2_{h_i}}{s^2_{\bar{h}}}\right] \tag{28}$$

where $s_{\bar{g}}$, $s_{\bar{P}}$, $s_{\bar{T}}$, and $s_{\bar{h}}$ are the standard deviations of the means of the g, P, h, and T variables. An initial estimate of m is obtained by arbitrarily selecting the standard deviation of the mean of a variable to be equal to 20 percent of its standard deviation. Equation (14) and the specified errors of the instruments measuring the variables are used to evaluate the standard deviations. To make sure that accurate estimates of the mean values have been obtained, the influence of the standard deviation of the mean of each variable to the system error is assessed. This is done by calculating and comparing with the specified system error the differences Δs_W between the s_W value at $g = g_0$, $P = P_0$, $h = h_0$, and $T = T_0$ and the s_W value at $g = g_0 \pm 2s_g$, $P = P_0 \pm 2s_P$, $h = h_0 \pm 2s_h$, and $T = T_0 \pm 2s_T$. If each difference is significantly less than this error then there will be no need to obtain a better estimate of each mean value. If, however, certain differences are of the same order of magnitude with the specified system error, then other values for the $s_{\bar{g}}$, $s_{\bar{P}}$, $s_{\bar{h}}$, and $s_{\bar{T}}$ standard deviations must be selected.

In the following an algorithmic procedure is presented for finding the cheapest combination of sensors. The procedure first checks the contributions of the cheapest combinations of sensors to the system error. These combinations are obtained from (18)–(21). If the contributions are not reduced by using sensors for the corresponding variables then the procedure proceeds to the next more expensive combination.

1. Set CN to 0.
2. Store the specified system error E.
3. Store g_0, P_0, h_0, T_0 s_{g_i}, s_{P_i}, s_{h_i}, s_{T_i}.
4. Store d, D, d_1, t_1, t_0, N_0, Q_0, e_P, e_h, e_T.
5. Compute $s'_P = e_P/2$, $s'_h = e_h/2$, $s'_T = e_T/2$ (e_P, e_h, e_T are the absolute errors of the sensors of the P, h, and T variables).
6. Compute $A_0 = A(s_{g_i})$, $B_0 = B(s_{P_i})$, $C_0 = C(s_{h_i})$, $D_0 = D(s_{P_i})$, $G_0 = (s_{T_i})$.
7. Compute $C_1 = C(s'_h)$, $D_1 = D(s'_P)$, $G_1 = G(s'_T)$.
8. Find $Z = \min(C_1, D_1, G_1)$.
9. Define functions $s_W = SQR(e_1^2/4)$, $s_q = SQR(e_1^2/4nr^2)$.
10. $K = E^2$.
11. If $A_0 \geq K$ and $B_0 < K$ and $D_0 < K$ and $G_0 < K$ then
    $e_1^2 = B_0 + D_0 + G_0$
    $CN = 1$ (only a density sensor is used)

else if $A_0 \geq K$ and $B_0 < K$ and $D_1 \geq K$ and $G_0 < K$ then
$e_1^2 = B_0 + D_0 + G_0$
$CN = 2$ (sensors for density and absolute pressure are used)
else if $A_0 \geq K$ and $B_0 < K$ and $D_0 < K$ and $G_0 \geq K$ then
$e_1^2 = B_0 + D_0 + G_1$
$CN = 3$ (sensors for density and gas temperature are used)
else if $A_0 \geq K$ and $B_0 < K$ and $D_0 \geq K$ and $G_0 \geq K$ then
$e_1^2 = B_0 + D_1 + G_1$
$CN = 4$ (sensors for density, absolute pressure and gas temperature)
else if $A_0 \geq K$ and $B_0 \geq K$ and $D_0 < K$ and $G_0 < K$ then
$e_1^2 = B_1 + D_0 + G_0$
$CN = 5$ (sensors for density and differential pressure are used)
else if $A_0 \geq K$ and $B_0 \geq K$ and $D_0 < K$ and $G_0 \geq K$ then
$e_1^2 = B_1 + D_0 + G_1$
$CN = 6$ (sensors for density, differential pressure, and gas temperature)
else if $A_0 \geq K$ and $B_0 \geq K$ and $D_0 \geq K$ and $G_0 < K$ then
$e_1^2 = B_1 + D_1 + G_0$
$CN = 7$ (sensors for density, differential pressure, and absolute pressure)
else if $A_0 \geq K$ and $B_0 \geq K$ and $D_0 \geq K$ and $G_0 \geq K$ then
$e_1^2 = B_1 + D_1 + G_1$
$CN = 8$ (sensors for all the four variables).

12. If $A_0 < K$ and $B_0 < K$ and $C_0 < K$ then
$e_1^2 = A_0 + B_0 + C_0$
$CN = 9$ (without external sensors)
else if $A_0 < K$ and $B_0 < K$ and $C_0 \geq K$ then
$e_1^2 = A_0 + B_0 + C_1$
$CN = 10$ (only a sensor for absolute pressure)
else if $A_0 < K$ and $B_0 \geq K$ and $C_0 < K$ then
$e_1^2 = A_0 + B_1 + C_0$
$CN = 11$ (only a sensor for differential pressure)
else if $A_0 < K$ and $B_0 \geq K$ and $C_0 \geq K$ then
$e_1^2 = A_0 + B_1 + C_1$
$CN = 12$ (sensors for differential pressure and absolute pressure).
13. Compute s_q and s_W.
14. If $s_q \cdot r < s_W/10$ and $e_1^2 \leq K$ then
end
else if $s_q \cdot r < s_W/10$ and $e_1^2 > K$ then
$K = E^2 - Z$
else if $s_q \cdot r > s_W/10$ and $e_1^2 \leq K$ then
$r = r - r/2$
else if $s_q \cdot r > s_W/10$ and $e_1^2 > K$ then
$r = r - r/2$
$K = E^2 - Z.$
15. Go to 6.

VI. An Application Example

In the vacuum pipestill unit of an oil refinery fuel gas is supplied through a pipe to the heater of the unit. The design specifications of the flow stream are given in Table II. To improve the precision of the mass balance calculations of the refinery the relative error of the measured normal daily mass consumption of the heater must be close to ± 0.2 percent. Due to externally induced disturbances, this normal everyday mass consumption computed does not remain constant to the theoretical consumption computed from the design specifications but varies around this value. From the data of Table II it is readily derived that the expected daily mass consumption, when the plant operates at the normal flow rate, is 56 000 kg/day. The 0.2 percent relative error of this quantity corresponds to an absolute error of 112 kg/day. This value is considered to be the upper limit of the error of any measured value of the normal consumption.

To find the less expensive configuration of a microcomputer system which is programmed to display the estimated mass consumption with a resolution of 1 kg, the explained in the previous section procedure is applied. According to this procedure, first 25 independent measurements of the g, P, T, and h variables are taken by using existing analog instruments of the refinery. These measurements are given in Table III. They have been collected over a period of 25 days during which the refinery throughput remained stable. Table IV shows the accuracies and the span of the operating range or the full scale value of the analog instruments. The same figures are valid for the sensors used in the microcomputer system. Since the values of Δs_W quantity, shown in Table V with a calculating accuracy of 10^{-3}, are in absolute value significantly less than the specified error there is no need to increase the number of measurements.

The application of the procedure resulted to the selec-

TABLE II
DESIGN SPECIFICATIONS OF THE GAS FLOW STREAM

Gas Temperature	70 °C
Line Pressure	3 bar
Pipe Diameter	205 mm
Bore Diameter of Orifice Plate	82 mm
Minimum Volume Flow Rate at 3 bar and 70°C	450 m^3/h
Normal Volume Flow Rate at 3 bar and 70°C	1460 m^3/h
Maximum Volume Flow Rate at 3bar and 70°C	1650 m^3/h

TABLE III
FUEL GAS SAMPLES

Sample Number	Pressure bar	Temperature °C	Density kg/m^3	Differential Pressure mbar
1	3.00	70	1.511	128
2	2.95	68	1.802	133
3	2.9	71	1.434	129
4	3.00	79	1.622	127
5	2.9	71	1.715	131
6	3.2	72	1.287	133
7	3.0	68	1.527	129
8	2.9	62	1.280	125
9	3.1	75	1.624	128
10	3.0	74	1.436	131
11	2.9	70	1.458	126
12	2.9	78	1.722	127
13	3.7	58	2.990	130
14	3.1	74	1.621	127
15	2.9	70	1.723	124
16	3.0	81	1.757	120
17	3.0	67	1.596	121
18	2.9	92	1.730	127
19	3.1	75	1.711	126
20	3.2	67	1.296	122
21	3.15	78	1.720	128
22	3.2	87	1.715	130
23	3.2	70	2.832	129
24	3.2	80	1.644	123
25	3.1	78	1.689	122
Mean Value	3.06	73.4	1.698	127.25
Variance	3.0625E-4	1	7.656E-3	12.24

TABLE IV
ACCURACIES OF ANALOG INSTRUMENTS

Measured Variable	Specified Accuracy	Span or Full Scale
Abs. Pressure	±0.6% of Span	6 bar
Gas Temperature	±2% of Full Scale	100 °C
Diff. Pressure	±0.5% of Span	330 mbar
Density	±5% of Full Scale	3.5 kg/m^3

tion of the fifth ($CN = 5$) system configuration which considers the use of a density sensor and a differential pressure sensor. The computed by the procedure A_0, B_0, C_0, D_0, B_1, C_1, and e_1 quantities for the AGA and ISO algorithms are given in Table VI. Referring to this table one can easily explain the reasons of selecting the fifth

TABLE V
CONTRIBUTIONS OF THE g, h, P, AND T VARIABLES IN KILOGRAMS

	A.G.A	I.S.O
g_0+2s_g	0.585	-1.57
g_0-2s_g	-2.304	1.74
P_0+2s_P	0.591	0.009
P_0-2s_P	0.579	-0.004
T_0+2s_T	0.000	-0.45
T_0-2s_T	0.000	0.000
h_0+2s_h	0.681	0.1
h_0-2s_h	0.49	-0.093

TABLE VI
COMPUTED Δs_W VALUES

Quantity	A.G.A	I.S.O
A_0	59715.235	60309.6
B_0	16081.165	16241.138
C_0	0.543	0.534
G_0	0.545	0.536
C_1	1.14	1.16
B_1	1083.9	1094.685
s_q	8.237	8.278
e_1	33.112	32.948
r	10 min	10 min
E^2	12544	

configuration. Since both algorithms have practically the same error the use of anyone of the two algorithms may be considered.

To check the correctness of these results a number of experiments were conducted with a system similar to the one shown in Fig. 1. This system has been installed on the considered refinery stream. The system has two independent channels which can accept any combination of external sensors and can be configured to compute the mass consumption of any two streams according to the AGA and ISO recommendations. The system can also accept recording facilities to monitor the time variations of the g, P, T, and h variables. In the first experiment the first channel of the system was configured according to the findings of the previous analysis. That is, a density sensor and a differential pressure sensor were connected to the system. The mean values of the h, P, and T variables which are shown in Table III were loaded in the database of the system. In the second channel, sensors for all the variables were used. The experimental setup is illustrated in Fig. 2. The variations of the g, P, h, and T variables were monitored for a number of days. The worst variations observed over a period of one day are illustrated in Fig. 3. The computed by each channel consumption at that day was according to the AGA recommendation:

$$W_1 = 55235 \text{ kg} \tag{29}$$

$$W_2 = 55214 \text{ kg}. \tag{30}$$

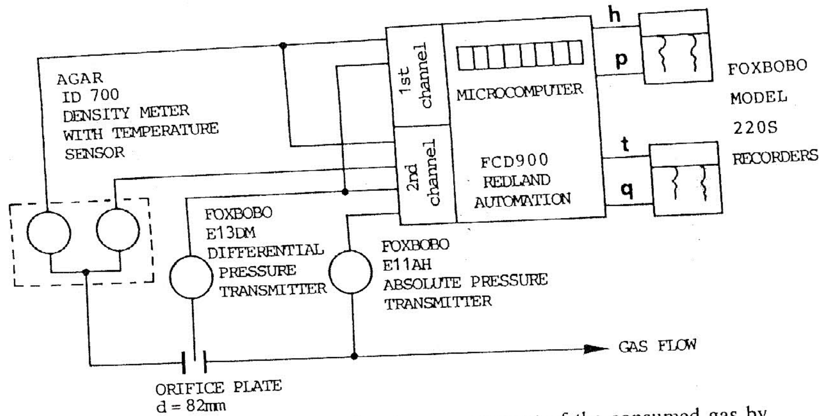

Fig. 2. Experimental setup for the measurement of the consumed gas by the heater.

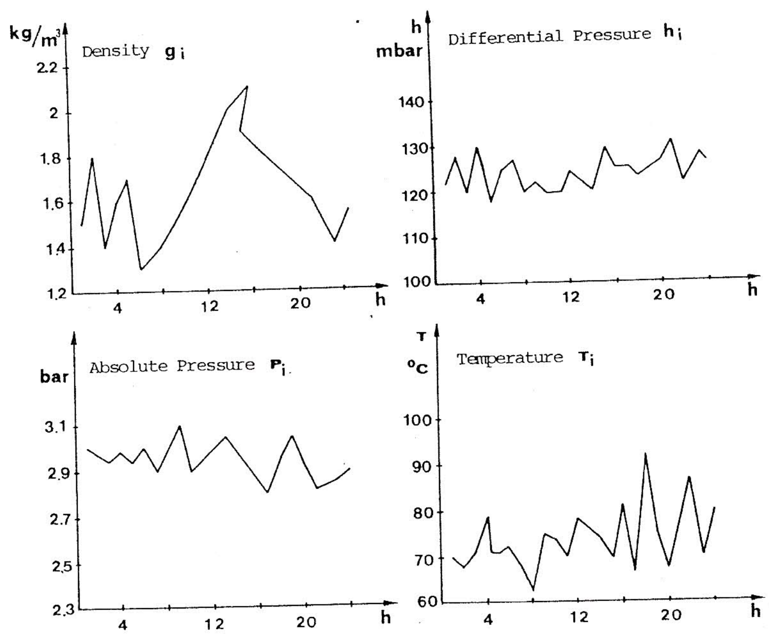

Fig. 3. Variations of the g, h, P, and T variables.

W_2 is the best possible estimate of the actual consumption. Its error can only be evaluated theoretically from (17), since the actually consumed quantity is never known. This error is negligible when it is compared to the error of W_1 with respect to W_2. Therefore, the absolute and relative error of W_1 is practically:

$$e_{1a} = 23 \text{ kg} \tag{31}$$

$$e_{1r} = 0.042 \text{ percent.} \tag{32}$$

This error is less than the specified error and therefore the initial selection of the system configuration seems to be correct.

Further, to demonstrate the effect of sudden and large variations of a variable on the system operation, the density sensor and the differential pressure were removed from the first channel and the following tests were conducted by speeding up the execution of the algorithm by a factor of 10. The mean value of each input variable was increased or decreased by 50 percent for an equivalent to a 10-h period. Then the daily mass consumption was compared with the consumption estimated when the actual mean value of the variable is used. Table VII provides the results of the conducted tests. It is noted that this large percentage variation of any variable results to a rather small percentage change in the mass consumption. This change, however, exceeds the 112-kg error limit. To continue measuring the mass consumption with the 0.2-percent relative error in the presence of such large variations which occur during the change of the plant operating conditions, new mean values must be loaded in the system database. Then, the estimation error will become again less than 0.2 percent, unless the statistics of the stream have changed drastically. In this case, which has a very low probability of occurrence, a new system configuration must be selected.

VII. Conclusions

The mass consumption of fuel gas in a process plant may be estimated with reasonable accuracy by microcom-

TABLE VII
SYSTEM RESPONSE TO +50-PERCENT VARIATIONS OF VARIABLES

Disturbed Variable by +50%	$W_{A.G.A}$	$W_{I.S.O}$	Relative Error for A.G.A	Relative Error for I.S.O
Density	62037	63153	10.37%	11.78%
Diff. Pressure	61796	63120	9.9%	11.72%
Absol. Pressure	56320	57240	0.19%	1.31%
Temperature	56349	56638	0.25%	0.25%
Disturbed Variable by -50%				
Density	48485	49399	14%	12.60%
Diff. Pressure	48796	49592	13.18%	12.22%
Absol. Pressure	55941	57236	0.475%	1.31%
Temperature	56575	56864	0.652%	0.65%

puter-based instrumentation systems. These systems consist of a microcomputer interfaced to external sensors by means of which the variations of the volume flow rate, absolute line pressure, temperature, and density of the flowing gas are monitored. The microcomputer is programmed to estimate the mass consumption according to the recommendations issued by the American Gas Association and the International Standards Organization. Depending on the desired estimation error, the instrumentation system may be configured to operate with external sensors for some of these variables and preset values for the other variables.

In this paper mathematical expressions are derived relating the estimation error of a certain system configuration with the errors of the used sensors. These expressions depend on the parameters of the equations used to estimate the mass consumption. They can be used by the system designer to assess the expected estimation error of the various system configurations. Then on the basis of this information the cheapest configuration which satisfies the desired accuracy may be realized. Adopting this approach, overspending on equipment which is not really needed may be avoided.

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