CENTRO DE INGENIERIA Y DESARROLLO INDUSTRIAL

CFE
COMISION FEDERAL DE ELECTRICIDAD

Central Termoeléctrica Salamanca

Proyecto Industrial Terminal

MEDICIÓN DEL FLUJO MÁSICO MEDIANTE UNA PLACA DE ORIFICIO

005395

PARA OBTENER LA ESPECILIDAD EN

“TECNÓLOGO EN MECATRÓNICA”

PRESENTA

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2007

1. RESUMEN

Los sistemas de medición de flujo de fluidos del tipo de presión diferencial son ampliamente usados en el sector industrial. En particular, las placas de orificio gozan de una ventaja comparativa importante: existe en la literatura una gran cantidad de información relacionada con el comportamiento de estos elementos, incluidas diferentes normas de referencia para el diseño, construcción, instalación y uso de los elementos de presión diferencial.

Aún cuando este tipo de instrumentos ha sido empleado desde principios del siglo XX en diversas industrias; hoy día, cerca de 25% del total de instrumentos para medición de flujo de fluidos instalados a nivel internacional son del tipo de presión diferencial. En particular, la industria del transporte de gas natural hace uso de una gran cantidad de placas de orificio para realizar la medición del gas que es transportado de un lugar a otro.

TEMA **Página**

3. ANTECEDENTES

En la Central Termoeléctrica de Salamanca, se produce energía eléctrica a través de la incineración de combustible líquido y/o gaseoso.

La medición del consumo del combustible líquido se hace a por medio de tanques de consumo diario, los cuales se llenan a cierta altura, de esos tanques se bombea el combustible a presión constante hacia las calderas y el consumo se calcula con la diferencia de volúmenes inicial y final del tanque.

Para el consumo de gas, la planta no cuenta con un sistema automático del cálculo de gas suministrado, tampoco con tanques de almacenamiento de gas que permitan tener un conocimiento más exacto del consumo, solo se cuentan con placas de orificio y medidores de presión diferencial, la medición se hace de manera visual y sólo una vez al día por lo que es necesario un procedimiento que permita conocer el consumo en tiempo real de gas, el cual es suministrado por PEMEX (Petróleos Mexicanos) de esta misma ciudad, y que, al no contar la Central Termoeléctrica con un sistema confiable de esta medición tiene que erogar lo que PEMEX le dice que ha consumido sin tener posibilidad de comprobación.

De esta inquietud ha surgido la presente propuesta para hacer un análisis del gas consumido por la Central Termoeléctrica que sea lo suficientemente confiable.

4. DEFINICION DEL TEMA

La presente solo trata de aplicar la Ecuación de Bernoulli para los sistemas de medición de la Central Termoeléctrica de Salamanca y así tener un sustento teórico del consumo que se tiene en la misma.

5. JUSTIFICACIÓN

La presente tiene como finalidad el determinar de manera teórica por medio de la Ecuación de Bernoulli el consumo de gas de la Central Termoeléctrica de Salamanca la cual se verá directamente beneficiada al contar con un sistema barato y eficiente de la medición y permitirá hacer sus propios cálculos de consumo y eficiencia así como la erogación que debe darse a PEMEX.

6. OBJETIVOS

Se desea linealizar la Ecuación de Bernoulli hasta obtener una constante multiplicada por la presión diferencial y así obtener el consumo instantáneo. Se encontró la relación de la constante pero no se podrá aplicar directamente por las razones que en las conclusiones se enuncian.

7. FUNDAMENTACIÓN

El principio de Bernoulli, también denominado ecuación de Bernoulli o Trinomio de Bernouilli, describe el comportamiento de un fluido moviéndose a lo largo de una línea de corriente. Fue expuesto por Daniel Bernoulli en su obra Hidrodinámica (1738) y expresa que en un fluido perfecto (sin viscosidad ni rozamiento) en régimen de circulación por un conducto cerrado, la energía que posee el fluido permanece constante a lo largo de su recorrido. La energía de un fluido en cualquier momento consta de tres componentes:

- Cinético: es la energía debida a la velocidad que posea el fluido.
- Potencial gravitacional: es la energía debido a la altitud que un fluido posea.
- Potencial Presión: es la energía que un fluido contiene debido a la presión que posee.

La siguiente ecuación conocida como "Ecuación de Bernoulli" (Trinomio de Bernouilli) consta de estos mismos términos.

$$\frac{v^2}{2g} + y + \frac{P}{\rho g} = cte$$

donde:

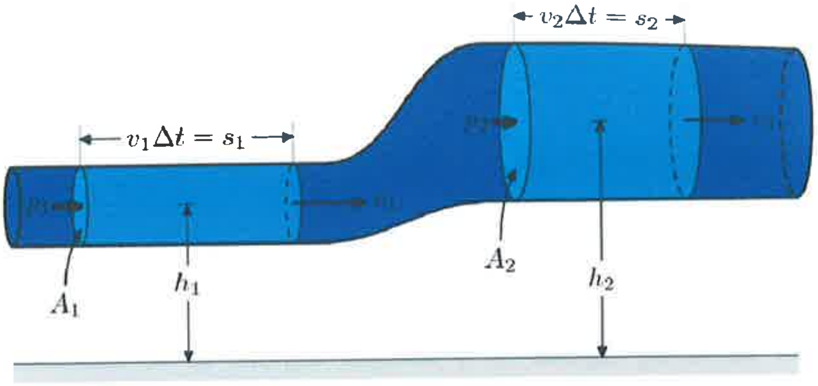
v = velocidad del fluido en la sección considerada.
g = aceleración de la gravedad
y = altura geométrica en la dirección de la gravedad
P = presión a lo largo de la línea de corriente
ρ = densidad del fluido

Para aplicar la ecuación se deben realizar los siguientes supuestos:

Viscosidad (fricción interna) = 0 Es decir que se aplica para un fluido perfecto.
Caudal constante
Fluido incompresible - ρ es constante
La ecuación se aplica a lo largo de una línea de corriente

Aunque el nombre de la ecuación se debe a Bernoulli, la forma arriba expuesta fue presentada en primer lugar por Leonhard Euler.

Un ejemplo de aplicación del principio lo encontramos en el Flujo de agua en tubería.



Evaluemos los cambios energéticos que ocurren en la porción de fluido señalada en color claro, cuando se desplaza a lo largo de la tubería. En la figura, se señala la situación inicial y se compara la situación final después de un tiempo Δt. Durante dicho intervalo de tiempo, la cara posterior s_2 se ha desplazado $v_2\Delta t$ y la cara anterior s_1 del elemento de fluido se ha desplazado $v_1\Delta t$ hacia la derecha.

El elemento de masa Δm se puede expresar como $\Delta m = rs_2v_2\Delta t = rs_1v_1\Delta t = r\Delta V$

Comparando la situación inicial en el instante t y la situación final en el instante $t + \Delta t$. Observamos que el elemento Δm incrementa su altura, desde la altura h_1 a la altura h_2

- La variación de energía potencial es $\Delta E_p = \Delta mgy_2 - \Delta mgy_1 = \rho\Delta V(y_2 - y_1)g$

El elemento Δm cambia su velocidad de v_1 a v_2.

- La variación de energía cinética es $\Delta E_k = \frac{1}{2}\Delta mv_2^2 - \frac{1}{2}\Delta mv_1^2 = \frac{1}{2}\rho\Delta V(v_2^2 - v_1^2)$

El resto del fluido ejerce fuerzas debidas a la presión sobre la porción de fluido considerado, sobre su cara anterior y sobre su cara posterior $P_1 = p_1s_1$ y $P_2 = p_2s_2$.

La fuerza P_1 se desplaza $\Delta x_1 = v_1\Delta t$. La fuerza y el desplazamiento son del mismo signo.

La fuerza P_2 se desplaza $\Delta x_2 = v_2\Delta t$. La fuerza y el desplazamiento son de signos contrarios.

- El trabajo de las fuerzas exteriores es $W_{ext} = P_1\Delta x_1 - P_2\Delta x_2 = (p_1 - p_2)\Delta V$

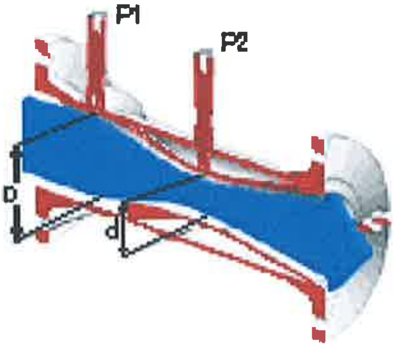
El teorema del trabajo-energía nos dice que el trabajo de las fuerzas exteriores que actúan sobre un sistema de partículas modifica la energía del sistema de partículas, es decir, la suma de las variaciones de la energía cinética y la energía potencial del sistema de partículas.

$$W_{ext} = E_f - E_i = (E_k + E_p)_f - (E_k + E_p)_i = \Delta E_k + \Delta E_p$$

Simplificando el término ΔV y reordenando los términos obtenemos la ecuación de Bernoulli.

$$p_1 + \rho g y_1 + \frac{1}{2}\rho v_1^2 = p_2 + \rho g y_2 + \frac{1}{2}\rho v_2^2$$

Efecto Venturi.



Cuando el desnivel es cero, la tubería es horizontal. Tenemos entonces, el denominado tubo de Venturi, cuya aplicación práctica es la medida de la velocidad del fluido en una tubería. El manómetro mide la diferencia de presión entre las dos ramas de la tubería.

La ecuación de continuidad se escribe:

$$v_1 s_1 = v_2 . s_2$$

Que nos dice que la velocidad del fluido en el tramo de la tubería que tiene menor sección es mayor que la velocidad del fluido en el tramo que tiene mayor sección. Si $s_1 > s_2$, se concluye que $v_1 < v_2$.

La en la ecuación de Bernoulli con $y_1 = y_2$

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2$$

Como la velocidad en el tramo de menor sección es mayor, la presión en dicho tramo es menor.

Si $v_1 < v_2$ se concluye que $p_1 > p_2$ El líquido manométrico desciende por el lado izquierdo y asciende por el derecho.

Podemos obtener las velocidades v_1 y v_2 en cada tramo de la tubería a partir de la lectura de la diferencia de presión $p_1 - p_2$ en el manómetro.

$$v_2 = s_1 \sqrt{\frac{2(p_1 - p_2)}{\rho(s_1^2 - s_2^2)}}$$

APLICACIONES DEL PRINCIPIO DE BERNOULLI

Chimenea

Las Chimeneas son altas para aprovechar que la velocidad del viento es más constante y elevada a mayores alturas. Cuanto más rápidamente sopla el viento sobre la boca de una chimenea, más baja es la presión y mayor es la diferencia de presión entre la base y la boca de la chimenea, en consecuencia, los gases de combustión se atraen mejor.

Tubería

La ecuación de Bernoulli y la ecuación de continuidad también nos dicen que si reducimos el área transversal de una tubería para que aumente la velocidad del fluido que pasa por ella, se reducirá la presión.

Sustentación de aviones

El efecto Bernoulli es también en parte el origen de la sustentación de los aviones. Gracias a la forma y orientación de los perfiles aerodinámicos, el ala es curva en su cara superior y esta angulada respecto a las líneas de corriente incidentes. Por ello, las líneas de corriente arriba del ala están mas juntas que abajo, por lo que la velocidad del aire es mayor y la presión es menor arriba del ala; al ser mayor la presión abajo del ala, se genera una fuerza neta hacia arriba llamada sustentación.

Carburador de automóvil

En un carburador de automóvil, la presión del aire que pasa a través del cuerpo del carburador, disminuye cuando pasa por un estrangulamiento. Al disminuir la presión, la gasolina fluye, se vaporiza y se mezcla con la corriente de aire.

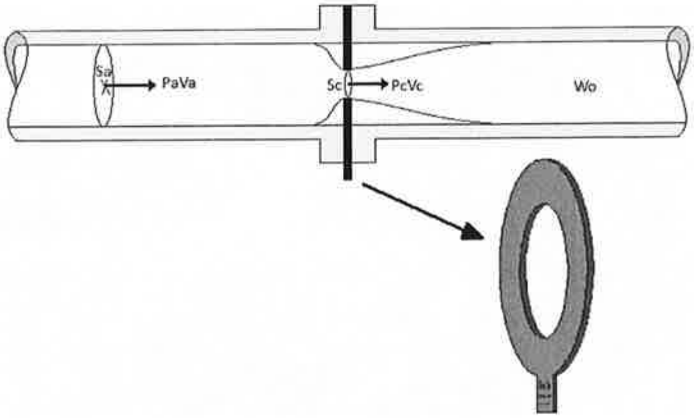
Flujo de fluido desde un tanque

La tasa de flujo está dada por la ecuación de Bernoulli.

8. PROCEDIMIENTO O MÉTODO

PRINCIPIO DE MEDICIÓN Y MENSURANDO

Como mensurando se considera el flujo másico, esto es la masa por unidad de tiempo que atraviesa una superficie dada como el mensurando. La medición de flujo másico por medio de elementos de presión diferencial se basa en las leyes de conservación de la masa y de la energía. Combinando ambas leyes es posible relacionar el flujo másico (o volumétrico) con la caída de presión que se presenta al pasar a través del elemento primario.



Para el principio del análisis consideramos la ecuación de los gases ideales al pasar por una placa de orificio.

$$\frac{\overrightarrow{V_a^2}}{2}+\frac{P_a}{\rho_o}=\frac{\overrightarrow{V_c^2}}{2}+\frac{P_c}{\rho_o}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Donde:

$\overrightarrow{V_a}$.—*Velocidad en el punto a*

P_a. —*Presión en el punto a*

$\overrightarrow{V_c}$.—*Velocidad en el punto c*

P_c.—*Presión en el punto c*

$\rho_o. -Densidad\ del\ gas$

$$S_a\overrightarrow{V_a} = S_c\overrightarrow{V_c}\text{..................................(2)}$$

Despejando Va de (2)

$$\overrightarrow{V_a} = \frac{S_c\overrightarrow{V_c}}{S_a}\text{..................................(3)}$$

De (1) obtenemos:

$$\frac{\overrightarrow{V_c^2}}{2} - \frac{\overrightarrow{V_a^2}}{2} = \frac{P_a}{\rho_o} - \frac{P_c}{\rho_o}\ \text{...................(4)}$$

Sustituyendo (3) en (4)

$$\overrightarrow{V_c^2} - \frac{S_c^2\overrightarrow{V_c^2}}{S_a^2} = 2\left(\frac{P_a - P_c}{\rho_o}\right)$$

$$\overrightarrow{V_c^2}\left[1 - \left(\frac{S_c}{S_a}\right)^2\right] = 2\left(\frac{P_a - P_c}{\rho_o}\right)$$

$$\overrightarrow{V_c} = \sqrt{\frac{2\left(\frac{P_a - P_c}{\rho_o}\right)}{1 - \left(\frac{S_c}{S_a}\right)^2}}$$

Haciendo

$$\beta = \frac{S_c}{S_a}$$

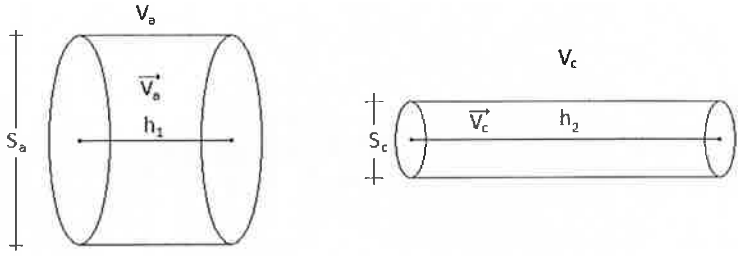
Y

$$E = \frac{1}{\sqrt{1-\beta^4}} \qquad (*)$$

Entonces:

$$\vec{V_c} = E\sqrt{2\left(\frac{P_a-P_c}{\rho_a}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Como el volumen desplazado del lado a es el mismo volumen desplazado del lado c entonces:



Donde:

Va.- Volumen en a

Vc.- Volumen en c

Sa.- Sección transversal en a

Sc.- Sección transversal en c

h_1.- desplazamiento del fluido en a

h_2.- desplazamiento del fluido en c

$\vec{V_a}$.- Velocidad del fluido en a

$\vec{V_c}$.- Velocidad del fluido en c

Como en los gases ideales:

$$V_a = V_c$$

Entonces podemos calcular cualquiera de los dos lados ya que la masa desplazada es igual en los dos lados, por tanto:

$$\vec{V_c} = \frac{h_2}{t}$$

(*) Se observa claramente que al sustituir β de la ecuación anterior en la fórmula debería quedar como β^2 pero en todos los libros de análisis termodinámico la toman como β^4 por lo que para este análisis se toma de esta manera

$$V_c = \left(\frac{S_c}{2}\right)^2 \pi \overrightarrow{V_c} t$$

$$\frac{V_c}{t} = \left(\frac{S_c}{2}\right)^2 \pi \overrightarrow{V_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Sustituyendo (5) en (6) la ecuación queda:

$$\frac{V_c}{t} = \left(\frac{S_c}{2}\right)^2 \pi E \sqrt{2\left(\frac{P_a - P_c}{\rho_o}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Como *2, S_c, π, E* y ρ_o Son constantes, entonces podemos escribirlas como una sola constante K, por tanto la ecuación nos queda como:

$$\boxed{\frac{V_c}{t} = K\sqrt{\Delta P} = Q_v} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

La ecuación se simplifica a una sola constante multiplicada por la raíz de la diferencial de presiones, y esto nos da un resultado en unidades de volumen entre tiempo.

Para encontrar la masa transferida, es necesario multiplicar esta ecuación por la densidad, lo cual, aplicándolo directamente en (7) quedaría como:

$$\boxed{\frac{V_c}{t}\rho_o = \left(\frac{S_c}{2}\right)^2 \pi E \sqrt{2\Delta P \rho_o}}$$

Por lo que de esta manera podemos encontrar la masa transferida (que es lo que mide el instrumento llamado másico).

LIMITACIONES

Para que estas ecuaciones funcionen se deben cumplir ciertas condiciones de energía de entalpía, por lo que ahora utilizamos las ecuaciones de los gases reales:

$$\frac{V_a^2}{2g} + L_{Z_a} + \underbrace{\frac{P_a}{\rho_a} + u_a}_{Entalpía\ H_a} = \frac{V_c^2}{2g} + L_{Z_c} + \underbrace{\frac{P_c}{\rho_c} + u_c}_{Entalpía\ H_c} + q + w_s$$

$$\frac{V_a^2}{2g} + L_{Z_a} + H_a = \frac{V_c^2}{2g} + L_{Z_c} + H_c + q + w_s$$

$$H_a - H_c = \frac{V_c^2}{2g} + L_{z_c} + q + w_s - \frac{V_a^2}{2g} - L_{z_a}$$

Si no hay elevación del tubo, entonces podemos despreciar el calor y el trabajo provocados por la gravedad, por tanto:

$$H_a - H_c = \frac{1}{2g}(V_c^2 - V_a^2) + \underbrace{L_{z_c} - L_{z_a}}_{L_{z_c} = L_{z_a}} + \underbrace{q + w_s}_{=0}$$

Y la ecuación nos queda:

$$H_a - H_c = \frac{1}{2g}(V_c^2 - V_a^2)$$

Con estas consideraciones podemos aplicar las leyes de los gases ideales:

$$PV^k = constante$$

Despejando V:

$$V = \frac{1}{P^{\frac{1}{k}}} = P^{-\frac{1}{k}}$$

$$H_a - H_c = V_a \int_{P_a}^{P_c} VdP = V_a \int_{P_a}^{P_c} P^{-\frac{1}{k}} dP$$

$$= V_a \left[\frac{P^{-\frac{1}{k}+1}}{-\frac{1}{k}+1} \right]_{P_a}^{P_c} = \frac{k}{k-1} V_a \left[P_a^{\frac{k-1}{k}} - P_c^{\frac{k-1}{k}} \right]$$

$$\boxed{H_a - H_c = \frac{k}{k-1} V_a P_a^{\frac{k-1}{k}} \left[1 - \left(\frac{P_c}{P_a} \right)^{\frac{k-1}{k}} \right]}$$

Esta ecuación nos dice que mientras las condiciones del tubo sean horizontales la entalpía siempre será negativa.

MEDICIÓN POR PLACA DE ORIFICIO DE GAS NATURAL

Y OTROS FLUIDOS HIDROCARBUROS RELACIONADOS

ALCANCE

TIPOS DE MEDICIÓN

Estas especificaciones estándar están limitadas por los dos tipos siguientes de medidas de placa de orificio:

- Placas de orificio localizadas en céntricamente de las medidas de aguas abajo y aguas arriba.
- Placas de orificio con orificios circulares localizadas concéntricamente en las medidas del tubo teniendo aguas arriba y aguas abajo.

TIPOS EQUIPOS DE MEDICIÓN.

Este Manual cubre las medidas de gas natural y otros fluidos asociados con la producción, procesamiento, transportación y distribución de gas natural por medio de la placa de orificio del elemento primario y los métodos del cálculo de flujo. Este manual no cubre con los equipos usados en la medición y determinación de las presiones, temperaturas y otras variables, con el conocimiento de las mediciones exactas de los elementos de flujo o fluido en una tubería. Esto publicado por la Asociación Americana de Gas (AGA), el Instituto Americano del Petróleo y otras posiblemente usadas en esta guía.

CAMPO DE APLICACIÓN

Este manual es aplicado al gas natural, gas líquido, e hidrocarburos asociados gaseosos y líquidos, también para sustancias mezcladas o contaminadas con hidrocarburos o sustancias que no son hidrocarburos.

SÍMBOLOS.

Los símbolos técnicos son usados generalmente para reflejar la aplicación de la medición de flujo de fluidos. Estos símbolos son variables que se usan para generar una correlación entre las distintas variables para publicaciones en varios campos de la industria y la tecnología.

$Q_v = Volúmen\ de\ Flujo\ con\ condiciones\ base$

$F_n = Factor\ básico\ del\ orificio$

$C_d = Factor\ del\ Número\ de\ Reynolds$

$Y_1 = Factor\ de\ Expansión$

$F_{pb} = Factor\ base\ de\ Presión$

$F_{tb} = Factor\ base\ de\ temperatura$

$F_{tf} = Factor\ del\ flujo\ de\ temperatura$

$F_g = Factor\ de\ densidad\ relativa\ de\ los\ gases\ reales$

$F_{pv} = Factor\ de\ supercompresibilidad$

$R_d = Número\ de\ Reynolds$

FACTOR BASICO DEL ORIFICIO

La ecuación del factor básico del orificio es la siguiente:

$$F_n = 338.196ED^2\beta^2$$

La constante numérica combina varias sustituciones y unidades de multiplicación de factores. Este valor depende directamente de los números de Reynolds tanto de la tubería como de la placa de orificio y provienen de una interpolación del comportamiento de la relación de varios valores diferentes entre d y D, se trata de linealizar la ecuación lo más posible.

FACTOR DEL NÚMERO DE REYNOLDS

El factor del número de Reynolds C_d se introduce en cualquier caso real de medición, el número de Reynolds tiene un valor finito, el valor del número de Reynolds es definido por:

$$C_d = 1 + \frac{E}{R_d}$$

Esta ecuación está determinada para diferentes mezclas de gas natural, pero, la constante de Reynolds R_d está determinada para condiciones de presión estática, por lo que es necesario hacer iteraciones, con las condiciones reales para encontrar una constante más real y apegada al proceso, la forma en que se realizarán estas iteraciones se explicará más adelante.

FACTOR DE EXPANSIÓN

El factor de expansión Y_1 está en función de la razón β, la razón de presión diferencial estática y la razón de calor específico (también llamado el exponente isotrópico ó la relación de la capacidad calorífica). La ecuación del factor de expansión se define de la siguiente manera:

$$Y_1 = 1 - \frac{[0.333 + 1.145(\beta^2 + 0.7\beta^5 + 12\beta^{13})]\Delta Pc_v}{P_a c_p}$$

Donde

$$c_v = Calor\ específico\ a\ volúmen\ constante$$

$$c_p = Calor\ específico\ a\ presión\ constante$$

FACTOR BASE DE PRESIÓN

El factor base de presión se aplica para normalizar la presión con respecto la presión absoluta 14.73 libras por pulgada cuadrada, y es calculada con respecto a 14.73 (presión base absoluta) y se representa como:

$$F_{pb} = \frac{14.73}{P_b}$$

Donde:

P_b = La presión base (o normalizada) en libras por pulgada cuadrada.

FACTOR BASE DE TEMPERATURA

El factor base de temperatura es aplicado cuando la temperatura está por debajo de los 60°F y es calculada a partir de la comparación de las condiciones estándar de temperatura en grados Rankin a 519.67°R. Para usar este factor hay que sustituir la temperatura estándar por T_b en la siguiente ecuación:

$$F_{tb} = \frac{T_b}{519.67}$$

Donde:

T_b = Es la temperatura estándar en grados Rankin

FACTOR DEL FLUJO DE TEMPERATURA

El factor del flujo de temperatura F_{tf} se requiere para cambiar estandarizar la temperatura cuando la temperatura del flujo es menor de 60°F y es determinada por dividir 519.67°R entre la temperatura del flujo en °R y al resultado sacarle raíz cuadrada, y se representa por la siguiente ecuación

$$F_{tf} = \sqrt{\frac{519.67}{T_f}}$$

FACTOR DE DENSIDAD RELATIVA

El factor densidad relativa para comparar la densidad relativa igual a 1.0 de un gas ideal con la densidad relativa de un gas real y a ese cociente sacarle raíz cuadrada, la fórmula que lo define es la siguiente:

$$F_g = \sqrt{\frac{1}{G}}$$

Donde:

G = Gravedad específica del gas

FACTOR DE SUPERCOMPRESIBILIDAD

El factor de supercompresibilidad se puede calcular a partir de la siguiente ecuación:

$$F_{pv} = \sqrt{1 + \frac{P_f \cdot 3.444 \times 10^5 \cdot 10^{1.785G}}{T_f^{3.825}}}$$

Esta ecuación fue extraída del manual de la tabla número 50 del Foxboro.

Cálculo para determinar el valor de K en la fórmula del consumo de gas en la unidad 1 C. T. Salamanca.

Datos generales para la medición del gas (constantes):

$D = Diámetro\ interno\ de\ la\ tubería = 13.25\ in$

$d = Diámetro\ del\ orificio\ de\ la\ placa = 9.516\ in$

$Red = Número\ de\ Reynolds = 3{,}500{,}000$

$\beta = \frac{d}{D} = 0.71818$

$T_b = Temperatura\ absoluta\ condiciones\ estandar = 518.67\,°R$

$P_b = Presión\ absoluta\ condiciones\ estandar = 14.696\ psi$

$T_f = Temperatura\ absoluta\ del\ fluido = 3°C = 497.07\,°R$

$G = Gravedad\ específica\ del\ gas = 0.6025$

$P_f = Presión\ manométrica\ promedio\ en\ Salamanca = 38.1466\ psi$

$h_w = \Delta P = Presión\ diferencial\ del\ fluido\ en\ columna\ de\ agua = 100\ in\ H_2O$

$Y_1 = Factor\ de\ dilatación\ tabla\ 43\ Foxboro = 0.9643$

Fórmulas:

$F_{pb} = \frac{14.73}{P_b}$ ………………… (8)

$F_{tb} = \frac{T_b}{520}$ …………………….. (9)

$F_{tb} = \sqrt{\frac{520}{T_f}}$ …………………. (10)

$F_g = \sqrt{\frac{1}{G}}$ ……………………… (11)

$F_{pv} = \sqrt{1 + \frac{P_f \cdot 3.444 \times 10^5 \cdot 10^{1.785G}}{T_f^{3.825}}} = 1.03725$ ……………………. (12)

$Q_v = F_n C_d Y_1 F_{pb} F_{tb} F_{tf} F_g F_{pv} \left(P_f h_w\right)^{\frac{1}{2}}$ ……………………………….. (13)

$F_n = 338.196 E D^2 \beta^2$ …………………………………………………….. (14)

$C_d = F_c + F_{sl}$ ………………………………………………………………. (15)

$F_c = 0.5961 + 0.0291\beta^2 - 0.2290\beta^8 - \left(0.0433 + 0.712e^{-\frac{8.5}{D}} - 0.1145e^{-\frac{6}{D}}\right)\left[1 - 0.23\left(\frac{19000\beta}{R_{ed}}\right)^{0.8}\right]\frac{\beta^4}{1-\beta^4} - 0.0116\left[\frac{2}{D(1-\beta)} - 0.52\left(\frac{2}{D(1-\beta)}\right)^{1.3}\right]\beta^{1.1}\left[1 - 0.14\left(\frac{19000\beta}{R_{ed}}\right)^{0.8}\right]$

……………………………………(16)

$F_{sl} = 0.0005111\left(\frac{1000000\beta}{R_{ed}}\right)^{0.7} + \left[0.021 + 0.0049\left(\frac{19000\beta}{R_{ed}}\right)^{0.8}\right]\beta^4\left(\frac{100000\beta}{R_{ed}}\right)^{0.35}$

………….. (17)

a) Después de calcular Q_v usar $R_{ed} = 3.32449Q_v$

b) Sustituir la nueva R_{ed} en (16) y (17)

c) Repetir los paso a) y b) de tres a cinco iteraciones hasta que converja

d) Obtener $K = \frac{Q_v}{\sqrt{h_w}}$

9. RESULTADOS

Las fórmulas anteriores fueron introducidas y calculadas desde Excel, dando el siguiente resultado para una presión diferencial de 100 in H_2O que es la recomendada por el fabricante en la hoja de especificación Bailey:

Qv4= 102,649.3063 m³/h	**K= 10,264.93**

Ya en aplicación real se hicieron pruebas de mediciones para calcular el consumo de gas a diferentes condiciones de consumo y estos fueron los resultados de la unidad 1.

UNIDAD 1

Hora	11:40	12:00	12:20	12:40	13:00	13:20
Quemadores	4	4	7	7	7	7
Integrador de flujo	27,983	27,986	27,995	28,002	28,010	28,018
Temperatura °C	4.02°C	4.21°C	4.26°C	4.27°C	4.33°C	4.49°C
Másico	100,657.88	100,660.58	100,667.64	100,672.60	100,679.90	100,684.82
Presión de gas a quemadores	1.06	1.06	1.11	1.11	1.33	1.33
Flujo	8.62	8.41	14.95	15.86	16.92	17.83

Al aplicar estas condiciones y los ΔP proporcionados por el personal de LAPEM se obtuvieron las siguientes constantes K para cada evento.

Hora	11:40	12:00	12:20	12:40	13:00	13:20
ΔP	139.83	139.69	139.31	139.31	140.77	140.56
T °R	498.09	498.28	498.33	498.34	498.40	498.56
K	10,248.76	10,246.32	10,245.27	10,245.53	10,244.67	10,242.60
Qv	120,964.98	120,935.79	120,923.51	120,926.58	121,548.46	121,434.25
Flujo(Másico)	100,657.88	100,660.58	100,672.60	100,672.70	100,679.90	100,684.82

Y obtenemos los siguientes resultados estadísticos

	Media	□
K	10,245.53	2.02217617
Qv	121,122.26	288.543505
Flujo(Másico)	100,671.41	10.5388628

10. CONCLUSIONES

Se observa una alta desviación estándar del flujo calculado a partir de la hoja de cálculo con respecto a la K y a la lectura del másico, esto puede ser atribuible, entre otras cosas, a que la placa de orificio se encuentra en la tubería en posición vertical y la ecuación fue formulada para una tubería en posición horizontal, esto provoca trabajo por gravedad el cual debe ser considerado en las fórmulas.

La fórmula debe replantearse considerando la altura a la que se encuentra la tubería para poder considerar la diferencia en energía potencial y anexarlo a la fórmula para su mejor análisis.

Por otra parte, sería conveniente ver la posibilidad de reubicar la placa, para facilitar las fórmulas y evitar los trabajos por gravedad.

Otra conclusión sería la de reducir el tamaño del orificio, esto con la finalidad de aumentar el efecto de diferencial de presión, diferencial de temperatura y el de disminuir la β para poder tener mediciones más precisas.

Estuve investigando acerca del sistema Telepelm XP y tiene la posibilidad de, que si ya se conocen las variables de presión y temperatura, introducir la fórmula dentro del sistema el cual se podría mostrar en pantallas como una variable más y así poder ver su comportamiento en una curva, y el área bajo esa curva es el consumo.

También se sugiere tener la posibilidad de obtener la medición de la densidad del gas suministrado por PEMEX, ya que la variación de temperaturas durante el día hace que factores como la gravedad específica, se vean fuertemente involucrados y esas variables también deben ser monitoreadas para una mejor resolución del consumo.

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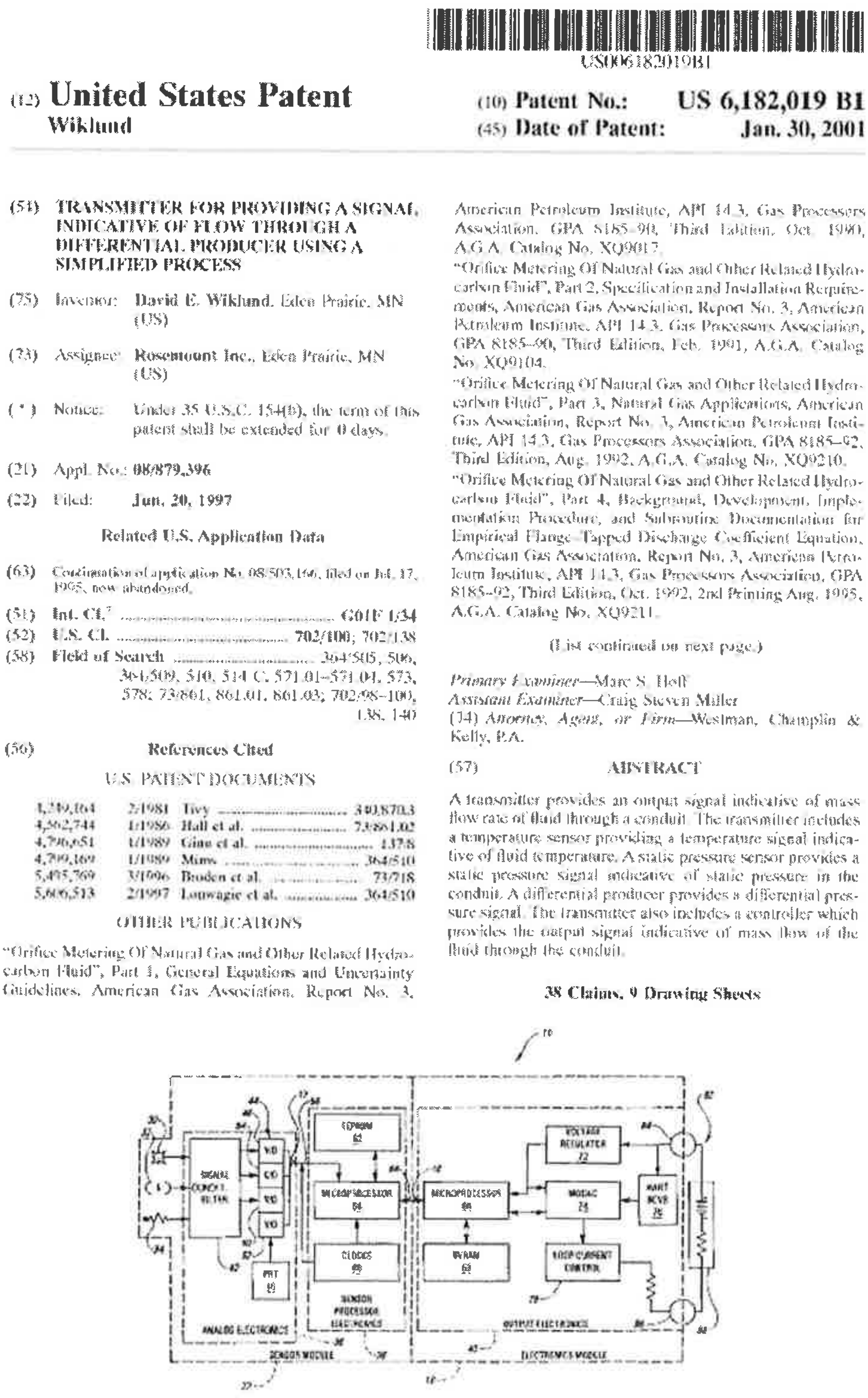
12. ANEXO 1



US006182019B1

(12) **United States Patent**
Wiklund

(10) **Patent No.: US 6,182,019 B1**
(45) **Date of Patent: Jan. 30, 2001**

(54) **TRANSMITTER FOR PROVIDING A SIGNAL INDICATIVE OF FLOW THROUGH A DIFFERENTIAL PRODUCER USING A SIMPLIFIED PROCESS**

(75) Inventor: **David E. Wiklund**, Eden Prairie, MN (US)

(73) Assignee: **Rosemount Inc.**, Eden Prairie, MN (US)

(*) Notice: Under 35 U.S.C. 154(b), the term of this patent shall be extended for 0 days.

(21) Appl. No.: **08/879,396**

(22) Filed: **Jun. 20, 1997**

Related U.S. Application Data

(63) Continuation of application No. 08/503,166, filed on Jul. 17, 1995, now abandoned.

(51) **Int. Cl.**^{7} **G01F 1/34**
(52) **U.S. Cl.** **702/100**; 702/138
(58) **Field of Search** .... 364/505, 506, 364/509, 510, 514 C, 571.01–571.04, 573, 578; 73/861, 861.01, 861.03; 702/98–100, 138, 140

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Primary Examiner—Marc S. Hoff
Assistant Examiner—Craig Steven Miller
(74) *Attorney, Agent, or Firm*—Westman, Champlin & Kelly, P.A.

(57) **ABSTRACT**

A transmitter provides an output signal indicative of mass flow rate of fluid through a conduit. The transmitter includes a temperature sensor providing a temperature signal indicative of fluid temperature. A static pressure sensor provides a static pressure signal indicative of static pressure in the conduit. A differential producer provides a differential pressure signal. The transmitter also includes a controller which provides the output signal indicative of mass flow of the fluid through the conduit.

38 Claims, 9 Drawing Sheets

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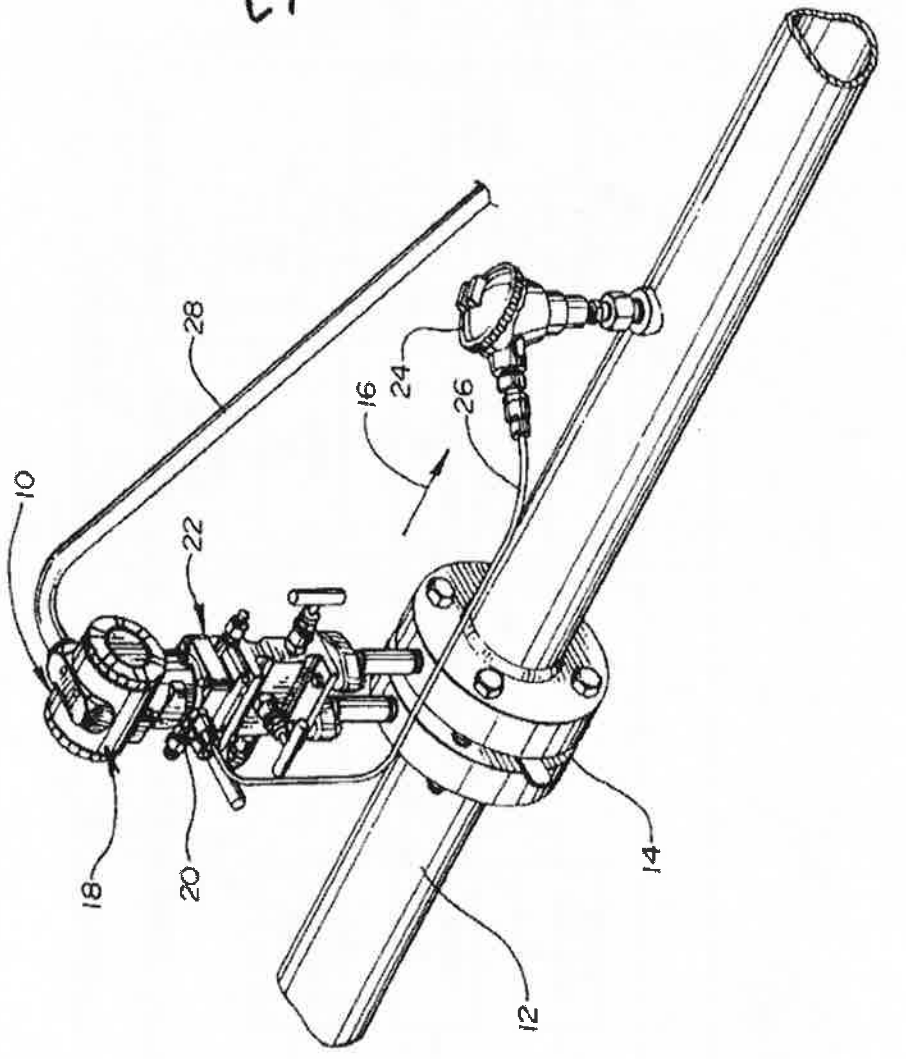


Fig. 1

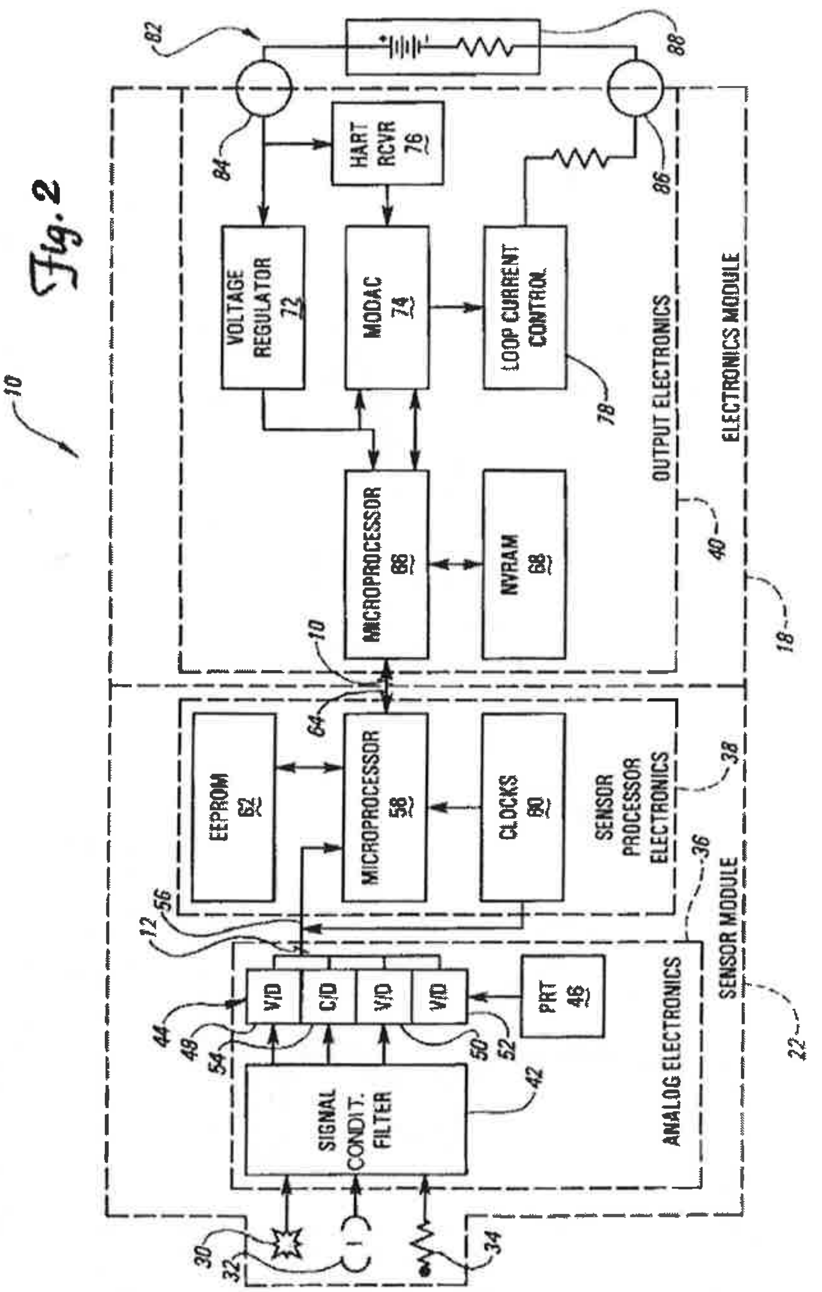


Fig. 2

10
82
88
84
86
HART RCVR 76
VOLTAGE REGULATOR 72
MODAC 74
LOOP CURRENT CONTROL
78
MICROPROCESSOR 66
NVRAM 68
OUTPUT ELECTRONICS
40
ELECTRONICS MODULE
18
10
64
EEPROM 62
MICROPROCESSOR 58
CLOCKS 60
SENSOR PROCESSOR ELECTRONICS
38
36
SENSOR MODULE
22
12
56
V/D
C/D
V/D
V/D
PRT 46
ANALOG ELECTRONICS
44
49
54
50
52
SIGNAL CONDIT. FILTER
42
30
32
34

Fig. 3A

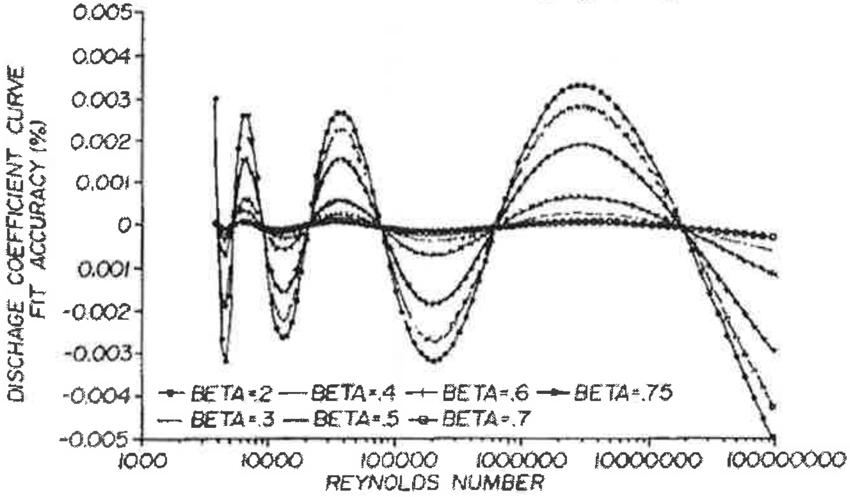

0.005
0.004
0.003
0.002
0.001
0
0.001
-0.002
-0.003
-0.004
-0.005
DISCHAGE COEFFICIENT CURVE FIT ACCURACY (%)
BETA=.2
BETA=.4
BETA=.6
BETA=.75
BETA=.3
BETA=.5
BETA=.7
1000
10000
100000
1000000
10000000
100000000
REYNOLDS NUMBER

Fig. 3B

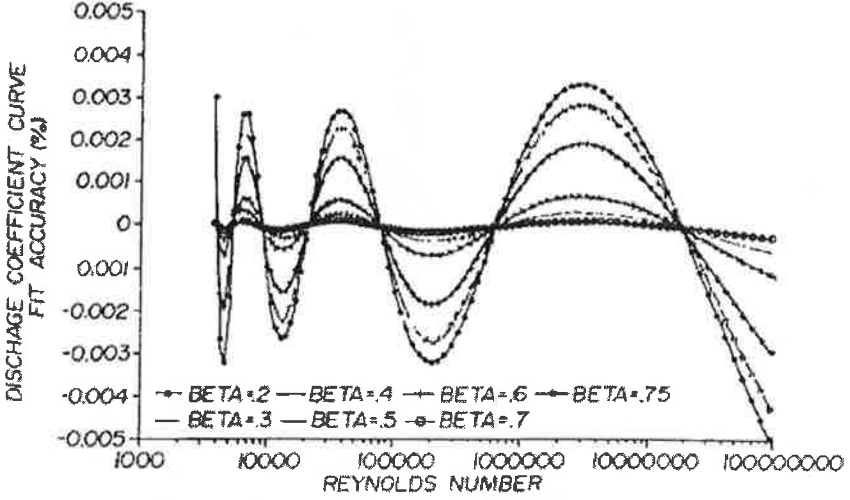

0.005
0.004
0.003
0.002
0.001
0
0.001
-0.002
-0.003
-0.004
-0.005
DISCHAGE COEFFICIENT CURVE FIT ACCURACY (%)
BETA=.2
BETA=.4
BETA=.6
BETA=.75
BETA=.3
BETA=.5
BETA=.7
1000
10000
100000
1000000
10000000
100000000
REYNOLDS NUMBER

Fig.3C

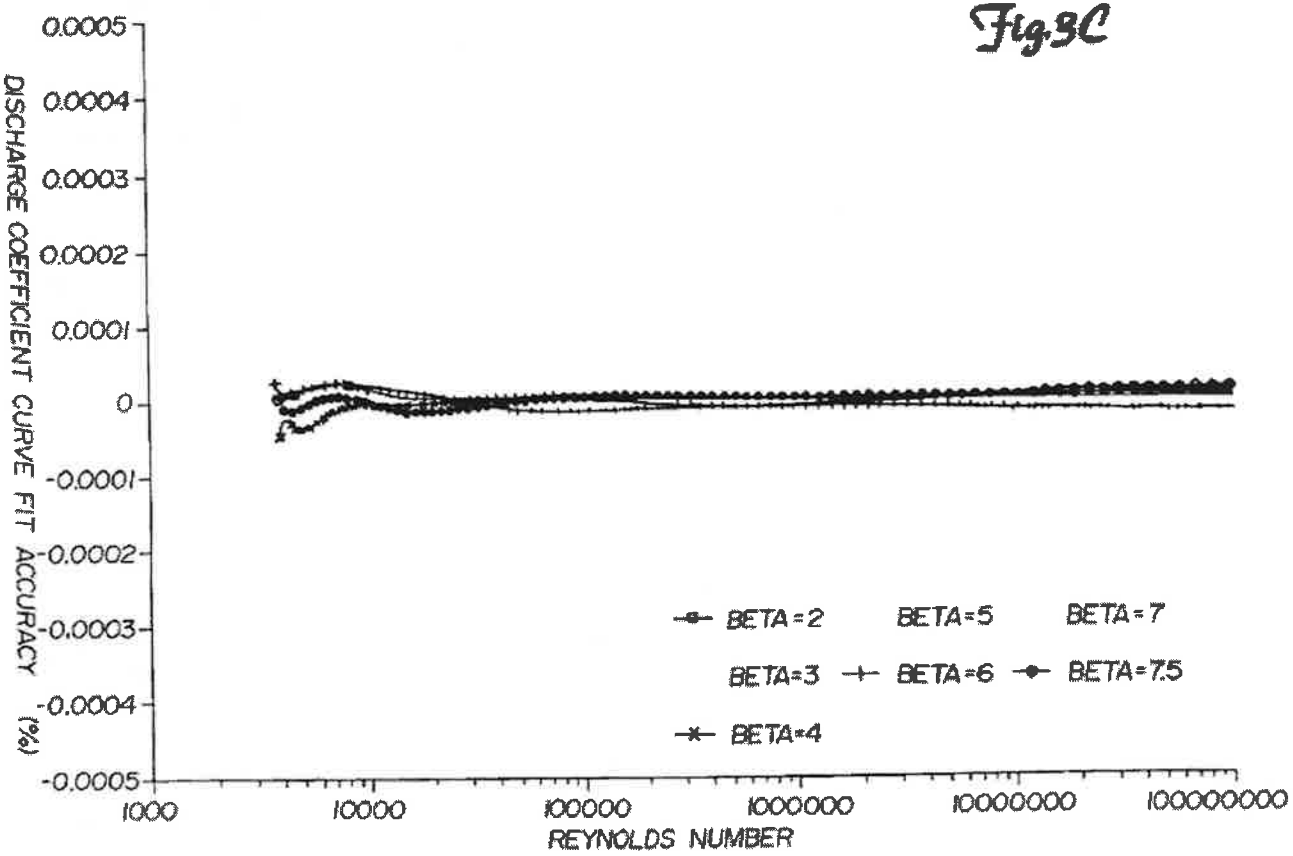

0.0005
0.0004
0.0003
0.0002
0.0001
0
-0.0001
-0.0002
-0.0003
-0.0004
-0.0005
DISCHARGE COEFFICIENT CURVE FIT ACCURACY (%)
1000
10000
100000
1000000
10000000
100000000
REYNOLDS NUMBER
BETA=2
BETA=3
BETA=4
BETA=5
BETA=6
BETA=7
BETA=7.5

Fig. 4A

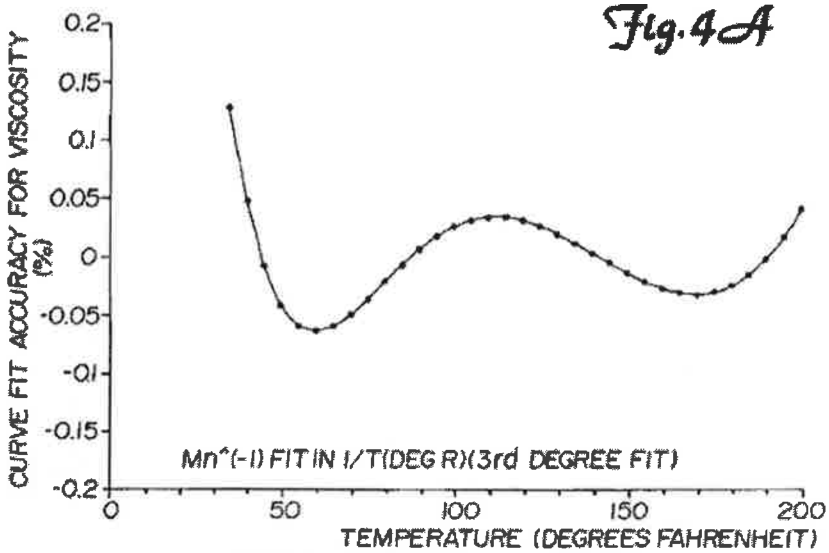
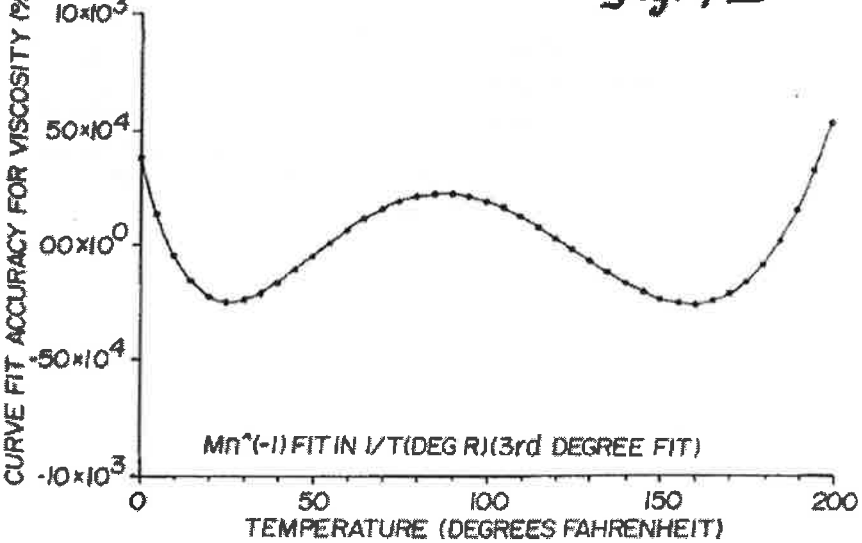

CURVE FIT ACCURACY FOR VISCOSITY (%)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Mn^(-1) FIT IN 1/T(DEG R)(3rd DEGREE FIT)
0
50
100
150
200
TEMPERATURE (DEGREES FAHRENHEIT)

Fig. 4B


CURVE FIT ACCURACY FOR VISCOSITY (%)
10×10^{3}
50×10^{4}
00×10^{0}
-50×10^{4}
-10×10^{3}
Mn^(-1) FIT IN 1/T(DEG R)(3rd DEGREE FIT)
0
50
100
150
200
TEMPERATURE (DEGREES FAHRENHEIT)

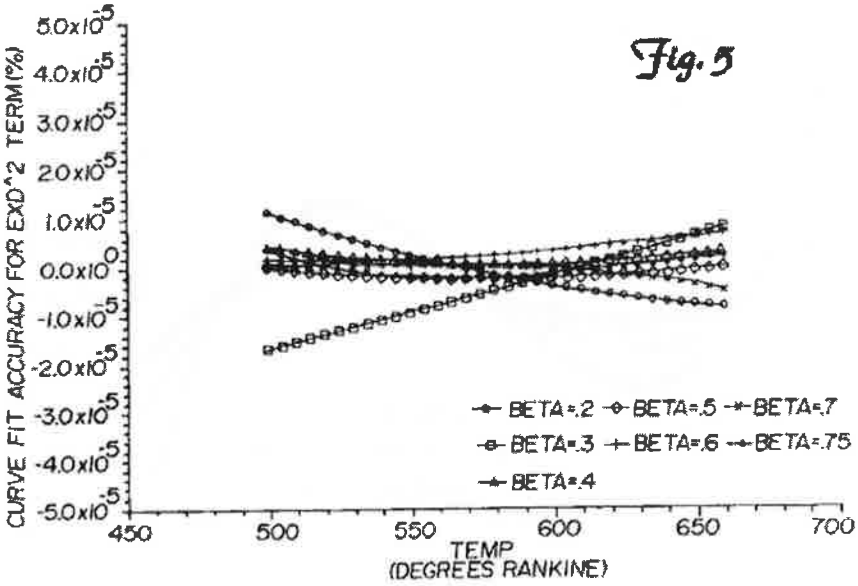


Fig. 5

CURVE FIT ACCURACY FOR EXD^2 TERM (%)
5.0x10⁻⁵
4.0x10⁻⁵
3.0x10⁻⁵
2.0x10⁻⁵
1.0x10⁻⁵
0.0x10⁰
-1.0x10⁻⁵
-2.0x10⁻⁵
-3.0x10⁻⁵
-4.0x10⁻⁵
-5.0x10⁻⁵
450
500
550
600
650
700
TEMP
(DEGREES RANKINE)
BETA=.2
BETA=.5
BETA=.7
BETA=.3
BETA=.6
BETA=.75
BETA=.4

Fig. 6

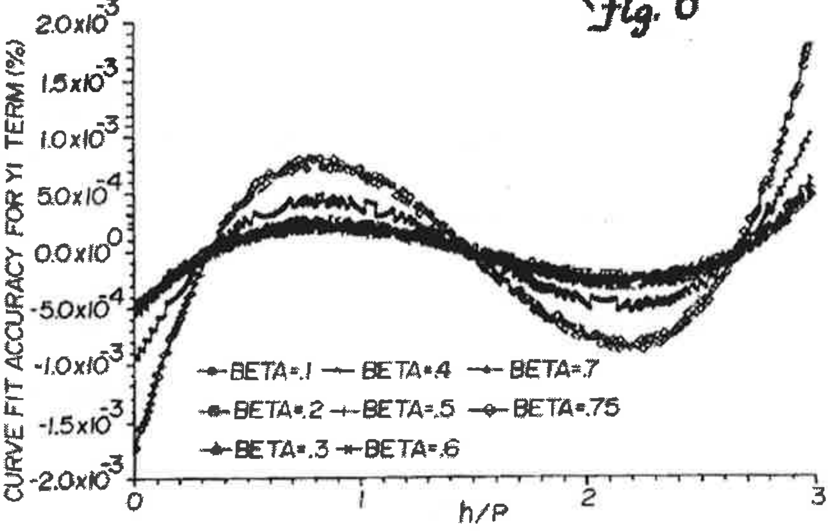

CURVE FIT ACCURACY FOR YI TERM (%)
2.0×10^{-3}
1.5×10^{-3}
1.0×10^{-3}
5.0×10^{-4}
0.0×10^{0}
-5.0×10^{-4}
-1.0×10^{-3}
-1.5×10^{-3}
-2.0×10^{-3}
0
1
2
3
h/P
BETA=.1
BETA=.2
BETA=.3
BETA=.4
BETA=.5
BETA=.6
BETA=.7
BETA=.75

Fig. 7A

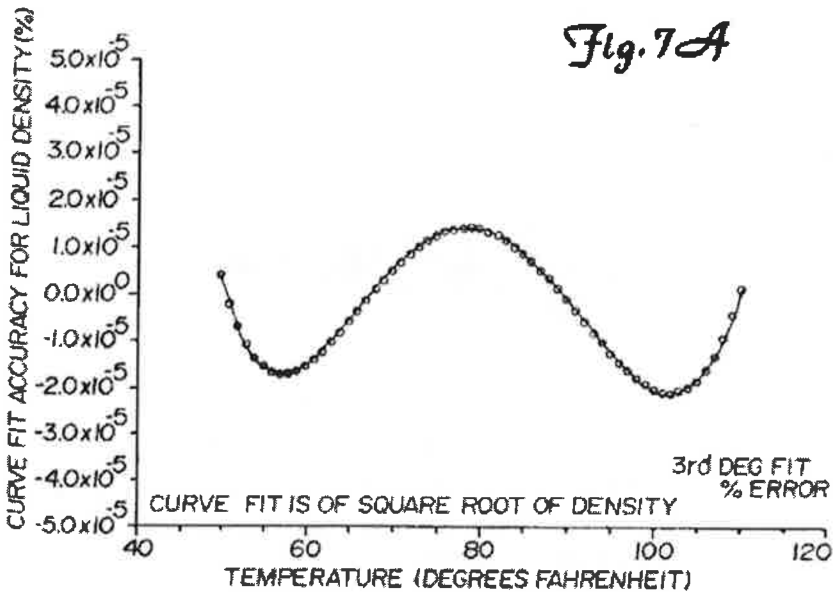

CURVE FIT ACCURACY FOR LIQUID DENSITY (%)
5.0x10^{-5}
4.0x10^{-5}
3.0x10^{-5}
2.0x10^{-5}
1.0x10^{-5}
0.0x10^{0}
-1.0x10^{-5}
-2.0x10^{-5}
-3.0x10^{-5}
-4.0x10^{-5}
-5.0x10^{-5}
3rd DEG FIT
% ERROR
CURVE FIT IS OF SQUARE ROOT OF DENSITY
40
60
80
100
120
TEMPERATURE (DEGREES FAHRENHEIT)

Fig. 7B

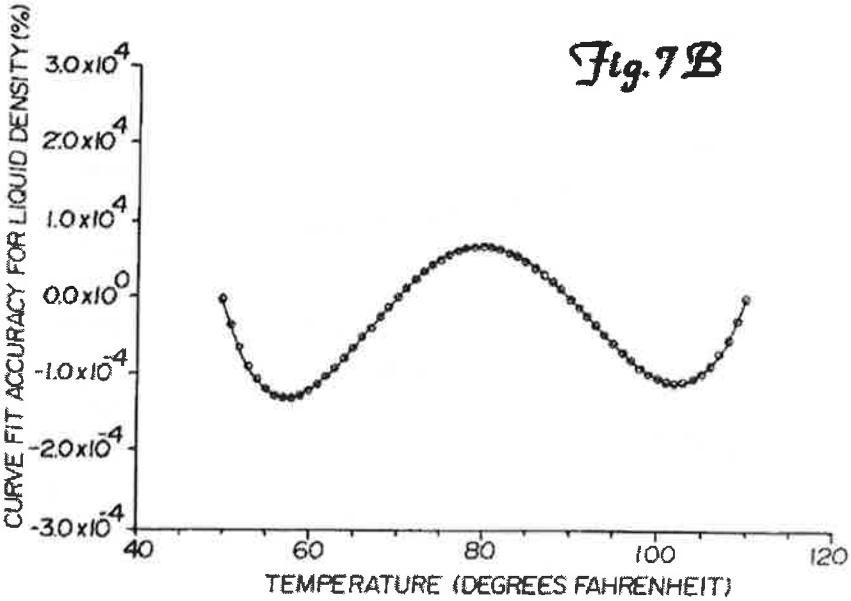

CURVE FIT ACCURACY FOR LIQUID DENSITY (%)
3.0x10^{4}
2.0x10^{4}
1.0x10^{4}
0.0x10^{0}
-1.0x10^{-4}
-2.0x10^{-4}
-3.0x10^{-4}
40
60
80
100
120
TEMPERATURE (DEGREES FAHRENHEIT)

Fig. 8A

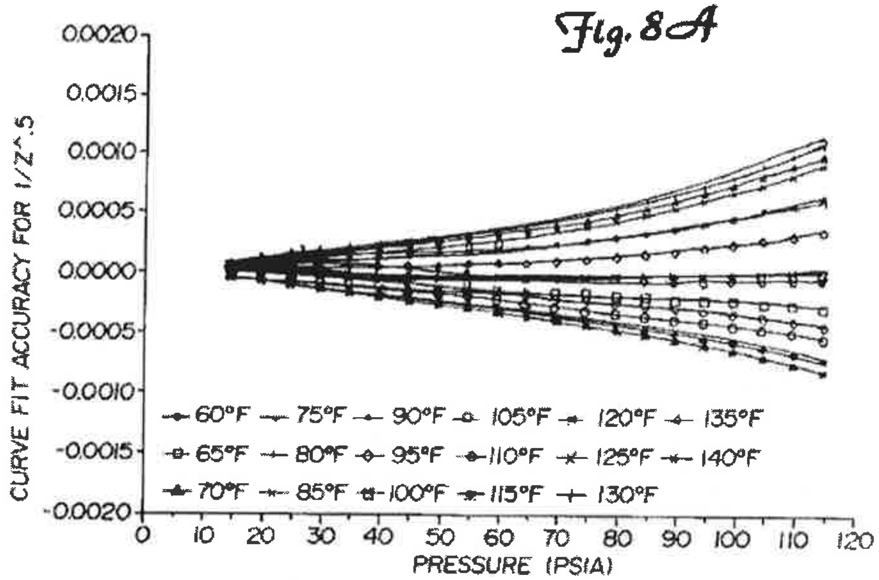
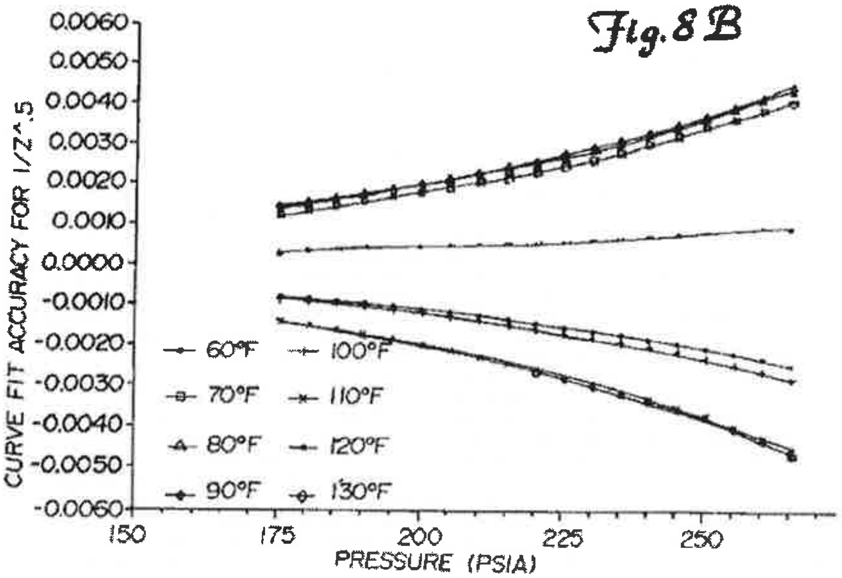

0.0020
0.0015
0.0010
0.0005
0.0000
-0.0005
-0.0010
-0.0015
-0.0020
CURVE FIT ACCURACY FOR 1/Z^.5
60°F
75°F
90°F
105°F
120°F
135°F
65°F
80°F
95°F
110°F
125°F
140°F
70°F
85°F
100°F
115°F
130°F
0
10
20
30
40
50
60
70
80
90
100
110
120
PRESSURE (PSIA)

Fig. 8B


0.0060
0.0050
0.0040
0.0030
0.0020
0.0010
0.0000
-0.0010
-0.0020
-0.0030
-0.0040
-0.0050
-0.0060
CURVE FIT ACCURACY FOR 1/Z^.5
60°F
100°F
70°F
110°F
80°F
120°F
90°F
130°F
150
175
200
225
250
PRESSURE (PSIA)

TRANSMITTER FOR PROVIDING A SIGNAL INDICATIVE OF FLOW THROUGH A DIFFERENTIAL PRODUCER USING A SIMPLIFIED PROCESS

This is a continuation of application Ser. No. 08/503,166, filed Jul. 17, 1995 now abandoned.

REFERENCE TO CO-PENDING APPLICATION

Reference is made to co-pending U.S. patent application Ser. No. 08/258,262, filed Jun. 9, 1994 now U.S. Pat. No. 5,606,513 entitled DIFFERENTIAL PRESSURE MEASUREMENT ARRANGEMENT UTILIZING DUAL TRANSMITTERS, and assigned to the same assignee as the present application, and to the U.S. patent applications referenced therein.

BACKGROUND OF THE INVENTION

The present invention deals with a transmitter in the process control industry. More particularly, the present invention deals with a simplified process, used in a transmitter, for providing an output signal indicative of flow through a differential producer.

Transmitters which sense various characteristics of fluid flowing through a conduit are known. Such transmitters typically sense and measure differential pressure, line pressure (or static pressure) and temperature of the process fluid. Such transmitters are typically mounted in the field of a refinery, or other process control industry installation. The field mounted transmitters are subject to significant constraints on power consumption. Such transmitters commonly provide an output in the form of a current representative of the variable being sensed. The magnitude of the current varies between 4–20 mA as a function of the sensed process variable. Therefore, the current available to operate the transmitter is less than 4 mA.

One way in which flow computation is done in industries such as the process control industry and the petroleum industry is through the use of dedicated flow computers. Such devices either use separate pressure, differential pressure and temperature transmitters or have sensing mechanisms housed in large enclosures. These devices are generally large and consume more power than 4 mA. Additionally, they are often limited to use in specialized applications such as the monitoring of hydrocarbons for custody transfer or at wellheads to monitor the output of gas or oil wells.

Another way in which flow computation is done is through the use of local control systems, often called programmable loop controllers (PLC). PLC's typically receive inputs from separate pressure, differential pressure and temperature transmitters and compute the flow based on these inputs. Such devices are often performing additional local control tasks such as the calculation of other variables required in the control of the plant or the monitoring of process variables for alarm purposes. The calculation of flow in these devices requires programming by the user.

A third way in which flow computation is done is through the use of large computers which control entire plants, often called distributed control systems (DCS). DCS's typically perform a wide range of tasks ranging from receiving inputs from field-based transmitters to computing the intermediate process variables such as flow or level, to sending positioning signals to final control elements such as valves, to performing the monitoring and alarm functions within the plant. Because of the wide range of tasks required and the typically high cost of DCS input/output capability, memory and computational time, it is common to do a flow computation that is not compensated for all of the effects due to changing process conditions.

One common means of measuring flow rate in the process control industry is to measure the pressure drop across a fixed restriction in the pipe, often referred to as a differential producer or primary element. The general equation for calculating flow rate through a differential producer can be written as:

$$Q=NC_dEY_1d^2\sqrt{\rho h} \qquad \text{Equation 1}$$

where:

Q=Mass flow rate (mass/unit time)

N=Units conversion factor (units vary)

C_d=Discharge coefficient (dimensionless)

E=Velocity of approach factor (dimensionless)

Y_1=Gas expansion factor (dimensionless)

d=Bore of differential producer (length)

ρ=Fluid density (mass/unit volume)

h=Differential pressure (force/unit area)

Of the terms in this expression, only the units conversion factor, which is a constant, is simple to calculate. The other terms are expressed by equations that range from relatively simple to very complex. Some of the expressions contain many terms and require the raising of numbers to non-integer powers. This is a computationally intensive operation.

In addition, it is desirable to have the transmitter operate compatibly with as many types of differential producers as possible. Implementing all of the calculations and equations needed for the conventional flow equation in order to determine flow based on the output of one differential producer (much less a plurality of different types of differential producers) requires computations which can only be reasonably performed by a processor which has a high calculation speed and which is quite powerful. Operation of such a processor results in increased power consumption and memory requirements in the transmitter. This is highly undesirable given the 4 mA power constraint on conventional transmitters. Therefore, current transmitter-based microprocessors, given the above power and memory constraints, simply do not have the capability of performing the calculations in any reasonable time period.

There has been some work done in obtaining a simplified discharge coefficient equation. However, this is only one small part of the flow equation. Even assuming the discharge coefficient is extremely simplified, implementing the flow equation accurately is still very difficult given the constraints on current transmitter-based microprocessors.

Other attempts have been made to simplify the entire flow equation. However, in order to make the flow equation simple enough that it can be implemented in transmitter-based microprocessors, the simplified flow equations are simply not very accurate. For example, some such simplified flow equations do not account for the discharge coefficient. Others do not account for compressibility, or viscosity effects.

Therefore, common transmitter-based microprocessors which are powered by the 4–20 mA loop simply do not accurately calculate flow. Rather, they provide outputs indicative of differential pressure across the orifice plate, static line pressure, and temperature. These variables are provided to a flow computer in a control room as mentioned above, which, in turn, calculates flow. This is a significant processing burden on the flow computer.

SUMMARY OF THE INVENTION

A transmitter provides an output signal indicative of mass flow rate of fluid through a conduit. The transmitter includes a temperature sensor providing a temperature signal indicative of fluid temperature. A static pressure sensor provides a static pressure signal indicative of static pressure in the conduit. A differential producer provides a differential pressure signal. The transmitter also includes a controller which provides the output signal indicative of mass flow of the fluid through the conduit based on a plurality of simplified equations.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a transmitter according to the present invention connected to a pipe which conducts fluid therethrough.

FIG. 2 is a block diagram, in partial schematic form of the transmitter according to the present invention.

FIGS. 3A–3C graphically illustrate curve fit accuracy for the discharge coefficient used by the system according to the present invention.

FIGS. 4A and 4B graphically illustrate curve fit accuracy of viscosity used according to the present invention.

FIG. 5 illustrates the curve fit accuracy of the term Ed^2 used according to the present invention.

FIG. 6 graphically illustrates the curve fit accuracy of the gas expansion factor used according to the present invention.

FIGS. 7A and 7B graphically illustrate the curve fit accuracy of fluid density for liquid used according to the present invention.

FIGS. 8A and 8B graphically illustrate curve fit accuracy of fluid density for gas used according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is an illustration of a transmitter **10** according to the present invention. Transmitter **10** is coupled to a pipe **12** through pipe fitting or flange **14**. Pipe **12** conducts flow of a fluid, either a gas or a liquid, in the direction indicated by arrow **16**.

Transmitter **10** includes transmitter electronics module **18** and sensor module **22** which collectively house a transmitter more fully illustrated at FIG. 2. Transmitter electronics module **18** also preferably includes a boss **20** for accepting an input from a resistive temperature device (RTD), preferably a 100 ohm RTD which is typically inserted directly into the pipe or into a thermowell which is inserted into the pipe to measure the fluid temperature. The wires from the RTD are connected to one side of a terminal block in a temperature sensor housing **24**. To the other side of the terminal block are connected wires which run through an electrical conduit **26** and are coupled to boss **20**.

Sensor module **22** includes a differential pressure sensor and an absolute pressure sensor. The differential pressure sensor and absolute pressure sensor provide pressure signals to conditioning and digitizing circuitry, and to a linearizing and compensating circuit. The compensated, linearized and digitized signals are provided to the electronics module **18**. The electronics module **18** in transmitter **10** provides an output signal indicative of process conditions of the process fluid flowing through pipe **12** to a remote location, by a 4–20 mA two-wire loop preferably formed using twisted pair conductors, through flexible conduit **28**. In the preferred embodiment, transmitter **10** provides signals which are indicative of the three process variables (temperature, static pressure, and differential pressure) according to the HART® or Fieldbus Standards. Further, in accordance with the present invention, transmitter **10** also provides an output signal indicative of flow. The method of determining flow according to the present invention is significantly simplified over prior methods allowing the microprocessor in the electronics module of transmitter **10** to calculate flow without exceeding the power constraints on the microprocessor, and at acceptably fast update times.

FIG. 2 is a more detailed block diagram of sensor module **22** and electronics module **18** of transmitter **10**. Sensor module **22** includes a strain gauge pressure sensor **30**, differential pressure sensor **32** and temperature sensor **34**. Strain gauge sensor **30** senses the line pressure (or static pressure) of fluid flowing through conduit **12**. Differential pressure sensor **32** is preferably formed as a metal cell capacitance-based differential pressure sensor which senses the differential pressure across an orifice in conduit **12**. Temperature sensor **34**, as discussed above, is preferably a 100 ohm RTD sensor which senses a process temperature of fluid in pipe **12**. While, in FIG. 1, sensor **34** and sensor housing **24** are shown downstream of transmitter **10**, this is but one preferred embodiment, and any suitable placement of temperature sensor **34** is contemplated.

Sensor module **22** also preferably includes an analog electronics portion **36**, and a sensor processor electronics portion **38**. Electronics module **18** includes output electronics portion **40**. Analog electronics portion **36** in sensor module **22** includes signal conditioning and power supply filtering circuitry **42**, analog-to-digital (A/D) circuitry **44**, and PRT **46**. The analog signals received from sensors **30**, **32** and **34** are provided to analog signal conditioning and power supply filtering circuitry **42**. The analog signals are conditioned (such as amplified) and the conditioned analog signals are provided to A/D converter circuitry **44**.

In a preferred embodiment, A/D converter circuitry **44** includes a plurality of voltage-to-digital converters, or capacitance-to-digital converters, or both (as appropriate) which digitize the analog input signals. Such converters are preferably constructed according to the teachings of U.S. Pat. Nos. 4,878,012; 5,083,091; 5,119,033 and 5,155,455; assigned to the same assignee as the present invention, and hereby incorporated by reference. In the embodiment shown in FIG. 2, three voltage-to-digital converters **48**, **50** and **52**, and one capacitance-to-digital converter **54** are shown. The voltage-to-digital converters **48** and **50** are used to convert the signals from sensors **30** and **34** into digital signals. The capacitance-to-digital converter **54** is used to convert the signal from capacitive pressure sensor **32** to a digital signal.

PRT **46** is preferably formed as a low cost, silicon-based PRT positioned proximate pressure sensors **30** and **32**. PRT **46** provides a temperature signal indicative of the temperature proximate sensors **30** and **32**. This temperature signal is provided to voltage-to-digital converter **52** where it is digitized. This digitized signal is then used to compensate the differential and line pressure signals for temperature variations. Analog signal conditioning and power supply filtering circuitry **42**, the A/D converters **44** and PRT **46** are all preferably physically located proximate to, or on, a single circuit board housed in transmitter **10**.

Once the analog signals are digitized by A/D converters **44**, the digitized signals are provided to sensor processor electronics portion **38** as four respective sixteen bit wide outputs on any suitable connection or bus **56**.

Sensor processor electronics portion **38** preferably includes a microprocessor **58**, clock circuitry **60** and memory (preferably electrically erasable programmable read only memory, EEPROM) **62**. Microprocessor **58** compensates and linearizes the process variables received from analog electronics portion **36** for various sources of errors and non-linearity. For instance, during manufacture of transmitter **10**, pressure sensors **30** and **32** are individually characterized over temperature and pressure ranges, and appropriate correction constants are determined. These correction constants are stored in EEPROM **62**. During operation of transmitter **10**, the constants in EEPROM **62** are retrieved by microprocessor **58** and are used by microprocessor **58** in calculating polynomials which are, in turn, used to compensate the digitized differential pressure and static pressure signals.

Clock circuitry **60** is provided in sensor processor electronics portion **38** and provides clock signals to microprocessor **58**, A/D circuits **44** and to other electronics as appropriate, in order to accomplish the desired operations. It should also be noted that the functionality of portions **36** and **38** can be combined into a single integrated circuit chip through application specific integrated circuit (ASIC) technology.

After the analog signals from sensors **30**, **32** and **34** are digitized, compensated and corrected, the process variable signals are provided over a serial peripheral interface (SPI) bus **64** to output electronics portion **40** in electronics module **18**. SPI bus **64** preferably includes power signals, two hand shaking signals and the three signals necessary for typical SPI signaling.

Output electronics module **40** preferably includes microprocessor **66**, non-volatile memory **68**, voltage regulator **72**, modulator circuit **74**, HART® protocol receiver **76** and loop current controller **78**. In addition, output electronics portion **40** may optionally be coupled to a battery back-up circuit which provides battery power to the output electronics in case of failure of the power provided over the two-wire loop.

Microprocessor **66** receives the digitized, compensated process variables over SPI bus **64**. In response, and as will be described in greater detail later in this specification, microprocessor **66** calculates the mass flow of fluid flowing through pipe **12** based on the process variables received over bus **64**. This information is stored in non-volatile memory **68** which, preferably, is suitable for storing up to 35 days worth of mass flow data.

When requested, microprocessor **66** configures output electronics **40** to provide the mass flow data stored in non-volatile memory **68** over two-wire loop **82**. Therefore, output electronics **40** is coupled at positive and negative terminals **84** and **86** to loop **82** which includes controller **88** (modeled as a power supply and a resistor). In the preferred embodiment, output electronics **40** communicates over two-wire loop **82** according to a HART® communications protocol, wherein controller **88** is configured as a master and transmitter **10** is configured as a slave. Other communications protocols common to the process control industry may be used, with appropriate modifications to the code used with microprocessor **66** and to the encoding circuitry. Communication using the HART® protocol is accomplished by utilizing HART® receiver **76**. HART® receiver **76** extracts digital signals received over loop **82** from controller **88** and provides the digital signals to circuit **74** which, in turn, demodulates the signals according to the HART® protocol and provides them to microprocessor **66**.

Circuit **74** receives digital signals (which are to be sent over loop **82**) from microprocessor **66**. Circuit **74** converts

the digital signals into analog signals, modulates them for transmission, and provides the modulated signals to circuit **76**. Circuit **74** preferably includes a Bell **22** compatible modem. The loop current control circuit **78** receives an analog voltage signal from a D/A converter in circuit **74**. In response, loop current control circuit **78** provides a 4–20 mA output representative of the particular information being transmitted by microprocessor **66** over loop **82** (such as one of the process variables, or the calculated flow).

Also, voltage regulator **72** preferably provides 3.5 volts and other suitable reference voltages to output electronics circuitry **40**, sensor processor electronics **38**, and analog electronics **36**.

In order to calculate flow through a differential producer (such as an orifice plate) information is required about three things. Information is required about the process conditions, about the geometry of the differential producer and about the physical properties of the fluid. Information about the process conditions is obtained from sensor signals, such as the signals from sensors **30**, **32** and **34**. Information regarding the geometry of the differential producer and the physical properties of the fluid are provided by the user.

Flow through a differential producer is conventionally calculated by utilizing the equation set out as Equation 1 above. Flow is typically calculated in mass units, but can be expressed in volumetric units if required. The choice of units determines the value of the units conversion factor, N.

The discharge coefficient, C_d, is a dimensionless, empirical factor which corrects theoretical flow for the influence of the velocity profile of the fluid in the pipe, the assumption of zero energy loss in the pipe, and the location of pressure taps. C_d is related to the geometry of the differential producer and can be expressed as a seemingly simple relationship in the following form:

$$C_d = C_\infty + \frac{b}{R_{e_D}^n} \qquad \text{Equation 2}$$

where the Reynolds number

$$R_{e_D} = \frac{KQ}{\mu D};$$

C_∞=the discharge coefficient at infinite Reynolds number;

b=a known Reynolds number correction term;

n=a known exponent term; and

μ=the fluid viscosity

This relationship varies for different types of differential producers, the location of the pressure taps on such producers, and the beta ratio. Typical equations defining C_d and the other above terms have a wide range of complexity and are set out in Table 1. The calculation for C_d associated with an orifice plate-type differential producer is the most common in the industry.

The velocity of approach factor, E, is a geometrical term and relates the fluid velocity in the throat of the differential producer to that in the remainder of the pipe. The velocity of approach factor is a function of temperature as follows:

$$E = \frac{1}{\sqrt{1-\beta^4}} \qquad \text{Equation 3}$$

where, for an orifice meter,

$$\beta = \frac{d_r[1+\alpha_1(T-T_r)]}{D_r[1+\alpha_2(T-T_r)]} \qquad \text{Equation 4}$$

d_r=orifice diameter at reference temperature T_r;

D_r=meter tube diameter at reference temperature T_r;

α_1=thermal expansion coefficient of the orifice plate; and

α_2=thermal expansion coefficient of a meter tube.

The gas expansion factor Y_1 is a dimensionless factor which is related to geometry, the physical properties of the fluid and the process conditions. The gas expansion factor accounts for density changes as the fluid passes through a differential producer. The gas expansion factor for primary elements with abrupt changes in diameter, such as orifice meters, is given by the following empirical relationship:

$$Y_1 = 1-(0.41+0.35\beta^4)\frac{h}{27.73PK} \qquad \text{Equation 5}$$

where h=differential pressure in inches of water at 68° F.;

P=upstream pressure in psia; and

K=isentropic exponent of the gas.

The adiabatic gas expansion factor for contoured elements is described as follows:

$$Y_1 = \left[\frac{(1-\beta^4)(K/(K-1))(P_2/P_1)^{2/K}(1-(P_2/P_1)^{(K-1)/K})}{(1-\beta^4(P_2/P_1)^{2/K})(1-P_2/P_1)}\right]^{1/2} \qquad \text{Equation 6}$$

where

$$\frac{P_2}{P_1} = 1-\frac{h}{27.73P} \qquad \text{Equation 7}$$

K=isentropic exponent of the gas.

The value of Y_1 is 1.0 for liquids.

The bore of the differential producer, d, is related to geometry and is a function of temperature as follows:

$$d=d_r[1+\alpha_1(T-T_r)] \qquad \text{Equation 8}$$

The differential pressure factor, h, is measured by a conventional differential pressure sensor.

The fluid density factor ρ is described in mass per unit volume and is a physical property of the fluid. For typical process control applications, the density of liquids is a function of temperature only. It can be described by expressions such as the PTB equation for the density of water.

$$\rho=A+BT+CT^2+DT^3+ET^4+FT^5 \qquad \text{Equation 9}$$

where A–F are constants, or a generic expression given by the American Institute of Chemical Engineers (AIChE):

$$\rho = \frac{aM}{b^{[1+(1-T/c)^d]}} \qquad \text{Equation 10}$$

Where a–d are fluid dependent constants and M is the molecular weight.

Gas density is a function of absolute pressure and absolute temperature given by the real gas law:

$$\rho = \frac{P}{nZR_uT} \qquad \text{Equation 11}$$

where Z the compressibility factor;

R_u=universal gas constant; and

n=number of moles.

Gas density and compressibility factors are calculated using equations of state. Some equations of state, such as AGA8, the ASME steam equation and MBWR, are useful for single fluids or a restricted number of fluids. Others, such as Redlich-Kwong or AIChE equations of state are generic in nature and can be used for a large number of fluids. The AIChE equation is as follows:

$$\rho = M\left[-\frac{1}{2B} - \frac{1}{2}\left[\frac{1}{B^2} + 4\frac{P}{BRT}\right]^{1/2}\right] \qquad \text{Equation 12}$$

where

$$B = a + \frac{b}{T} + \frac{c}{T^3} + \frac{d}{T^8} + \frac{e}{T^9} \qquad \text{Equation 13}$$

where a–e are fluid dependent constants; and

M=the molecular weight of the fluid.

Implementing the flow calculation using equations 1–13 set out above would yield a highly accurate result. However, the constraints of power consumption, calculation speed and memory requirements make the implementation of the full equations beyond the capability of currently available transmitter based microprocessors. Therefore, the transmitter of the present invention calculates flow based on a number of simplified equations, while retaining a high degree of accuracy in the flow calculation.

The dependencies related to the discharge coefficient are as follows:

C_d (β, Re_D);

Re_D (Q, μ) where μ is the viscosity of the fluid; and

μ (T)

Using the AIChE equation for liquids:

$$\mu=\exp[a+b/T+c\ln(T)+dT^e] \qquad \text{Equation 14}$$

and, using AIChE equation for gases:

$$\mu = \frac{aT^b}{1+c/T+d/T^2} \qquad \text{Equation 15}$$

According to the present invention, the discharge coefficient C_d equation is simplified by approximating μ^{-1} by a polynomial in T or 1/T. Preferably, this approximation is done using a third degree polynomial equation. Also, C_d is approximated using a sixth degree polynomial equation in

$$\frac{1}{\sqrt{R_{eD}}}$$

or

$$\frac{1}{Ln(R_{eD})}$$

It has been observed that better accuracy is obtained using the polynomial for C_d with the term

$$\frac{1}{Ln(R_{eD})}$$

being the independent variable, but this also increases the calculation time. Therefore, this can be used, or the other polynomial can be used, depending upon the degree of accuracy desired.

FIGS. 3A, 3B and 3C are examples of curve fit accuracy of the discharge coefficient using the above equations. FIG. 3A is a graph of the discharge coefficient curve fit error versus the Reynolds number for an ASME flange tap orifice meter having a diameter in excess of 2.3 inches. This graph was obtained by doing a sixth degree fit in

$$\frac{1}{\sqrt{R_{eD}}}$$

as follows:

$$C_d = b_0 + \frac{1}{\sqrt{R_{eD}}}\left(b_1 + \frac{1}{\sqrt{R_{eD}}}\left(b_2 + \frac{1}{\sqrt{R_{eD}}}\left(b_3 + \frac{1}{\sqrt{R_{eD}}}\left(b_4 + \frac{1}{\sqrt{R_{eD}}}\left(b_5 + \frac{b_6}{\sqrt{R_{eD}}}\right)\right)\right)\right)\right) \quad \text{Equation 16}$$

and using an approximation of viscosity as follows:

$$\mu^{-1} = a_0 + \frac{1}{T}\left(a_1 + \frac{1}{T}\left(a_2 + a_3\frac{1}{T}\right)\right) \quad \text{Equation 17}$$

FIG. 3B graphically illustrates the discharge coefficient curve fit error plotted against Reynolds number for an ASME corner tap orifice meter using a sixth degree fit in

$$\frac{1}{\sqrt{R_{eD}}}$$

FIG. 3C graphically illustrates the discharge coefficient curve fit error against Reynolds number for an ASME long radius nozzle using the sixth degree fit in

$$\frac{1}{\sqrt{R_{eD}}}$$

FIGS. 3A–3C illustrate that the curve fit approach approximates the discharge coefficient C_d to better than +/−0.005%. Similar results are obtained for other differential producers.

FIGS. 4A and 4B are examples of curve fit accuracy obtained for viscosity. FIG. 4A graphically illustrates curve fit accuracy for viscosity versus temperature using a third degree polynomial fit in 1/T. FIG. 4B illustrates the curve fit accuracy for viscosity versus temperature using a third degree polynomial fit in 1/T. FIG. 4A is based on water and FIG. 4B is calculated for air. It is seen that the curve fit approach approximates the viscosity of air to better than +/−0.001% and the viscosity of water to better than +/−0.2%. A polynomial fit of a higher degree in 1/T, such as 4 or 5, would improve the accuracy of the fit for water. Because the discharge coefficient, C_d, is weakly dependent on Reynolds number and, thus, viscosity, the accuracy provided using a third degree polynomial fit in 1/T is acceptable and the added computational complexity of a higher degree polynomial approximation is not necessary. Similar results are obtained for other liquids and gases.

The dependencies related to the velocity of approach factor, E, and the bore of the differential producer, d, are as follows:

$E(T)$, and $d^2(T)$

The method of the present invention simplifies the Ed^2 calculation by grouping E and d^2 together and approximating the product of Ed^2 by a polynomial in T or 1/T. This polynomial is preferably a second degree polynomial.

FIG. 5 is an example of the curve fit accuracy of the Ed^2 term. FIG. 5 graphically illustrates the accuracy of this term plotted against temperature using a second degree polynomial in T as follows:

$$Ed^2 = c_0 + \frac{1}{T}\left(c_1 + \frac{1}{T}c_2\right) \quad \text{Equation 18}$$

FIG. 5 illustrates that the curve fit approach approximates the Ed^2 term to better than +/−0.00002%.

The dependencies of the gas expansion factor, Y_1, are as follows:

$Y_1(h, K, \beta)$ gas and

$Y_1(T)$

Simplifying the gas expansion factor calculation is accomplished by ignoring the dependency on T. The Y_1 term is approximated using a polynomial equation in h/P where h is the differential pressure and P is the static pressure. Preferably, this polynomial is a second degree polynomial. For an orifice, a linear relationship exists between Y_1, and h/P.

FIG. 6 is an example of curve fit accuracy of Y_1 versus temperature using a second degree polynomial fit in h/P as follows:

$$Y_1 = d_0 + \frac{h}{P}\left(d_1 + \frac{h}{P}d_2\right) \quad \text{Equation 19}$$

The curve is illustrated for a contoured element differential producer. FIG. 6 illustrates that the term Y_1 for contoured elements is accurate, using the system according to the present invention, to better than +/−0.002% for all beta ratios. Accuracy is better than +/−0.0005% for beta ratios less than 0.6. Similar results are obtained for the square edged orifice.

Dependencies related to the fluid density for liquid and gas are as follows:

$\rho_{l,g}(T)$; and

$\rho_{G,S} = f(P,T)$, specifically $\rho_{G,S} = \left(\frac{P}{RT}\right)\frac{1}{Z}$

The fluid density calculation for liquid is simplified according to the present invention by providing two levels of curve fit. The term $\sqrt{\rho_{liq}}$ is approximated by a polynomial in T or 1/T. Preferably, this is a third degree polynomial and is provided as a default equation for a lower accuracy fit as follows:

$$\sqrt{\rho} = c_0 + \frac{1}{T}\left[c_1 + \frac{1}{T}\left(c_2 + \frac{1}{T}c_3\right)\right] \qquad \text{Equation 20}$$

The same term is also preferably approximated by a polynomial in 1/T using a fifth degree polynomial as a higher accuracy fit for broader operating ranges of temperature.

Simplifying the calculation for fluid density for gas is accomplished by, again providing two levels of curve fit. Fitting a curve to $1/\sqrt{Z}$ and not $\rho_{G,S}$ improves the curve fit accuracy, reduces calculation time, and improves the simplified flow equation accuracy. According to the present invention, the term $1/\sqrt{Z}$ is approximated by a polynomial in P and 1/T. In the preferred embodiment, the default polynomial is a 3×2 polynomial and is used for a lower accuracy fit. However, the term $1/\sqrt{Z}$ can also be approximated by a polynomial in P and 1/T using an 8×6 polynomial for higher accuracy fits, and for broader operating ranges of both P and T. The preferred simplified equation for fluid density for all gases is as follows:

$$\sqrt{\rho} = \left[\frac{144M_r}{R}\right]^{\frac{1}{2}}\left[\frac{P}{T}\right]^{\frac{1}{2}}\Big[(f_0 + Pf_1 + P^2f_2 + P^3f_3) + \frac{1}{T}(f_4 + Pf_5 + P^2f_6 + P^3f_7) + \frac{1}{T^2}(f_8 + Pf_9 + P^2f_{10} + P^3f_{11})\Big] \qquad \text{Equation 21}$$

FIG. 7A graphically illustrates an example of curve fit accuracy for $\sqrt{\rho_{liq}}$ for water versus temperature using the third degree polynomial fit in 1/T. FIG. 7B graphically illustrates curve fit accuracy density of acrylonitrile versus temperature. In both cases, the temperature range is 50° F. to 110° F. FIGS. 7A and 7B illustrate that the curve fit approach approximates $\sqrt{\rho_{liq}}$ to better than +/−0.0002% for these two liquids and the selected temperature range. Similar results are obtained for other liquids and other temperature ranges.

FIGS. 8A and 8B illustrate examples of curve fit accuracy for $1/\sqrt{Z}$ for two fluids and pressure temperature ranges. FIG. 8A illustrates the curve fit accuracy using the 3×2 polynomial fit for carbon dioxide gas. The pressure and temperature ranges are 15 psia to 115 psia and 60° F. to 140° F. The results show that the curve fit approach accurately approximates $1/\sqrt{Z}$ to better than +/−0.0015%. FIG. 8B illustrates the curve fit accuracy using the 3×2 polynomial fit for ethylene gas. The pressure and temperature ranges are 75 psia to 265 psia and 60° F. to 140° F. The results show that the curve fit approach accurately approximates $1/\sqrt{Z}$ to better then +/−0.005%. As these results indicate, the accuracy of the curve fit approximation varies, as the fluid is changed and as the operating ranges of pressure and/or temperature change. When the operating ranges of pressure and/or temperature result in unacceptable approximations by using a 3×2 polynomial, an 8×6 polynomial will improve the results to levels similar to those indicated in FIGS. 8A and 8B.

In sum, the classic flow calculation given by Equation 1 above, is simplified according to the present invention as follows:

$$Q = N[C_d][Ed^2][Y_1][\sqrt{\rho}]\sqrt{h} \qquad \text{Equation 22}$$

For gases this equation can be rewritten as:

$$Q = KN[C_d][Ed^2][Y_1]\left[\frac{1}{\sqrt{Z}}\right]\sqrt{\frac{hP}{T}}$$

where

$$K = \sqrt{\frac{144M}{R}}$$

M=molecular weight of the gas;

R=gas constant; and

P, h, T are in units of psia, inches of water and degrees Rankine, respectively. For liquids, the equation can be rewritten as:

$$Q = N[C_d][Ed^2][Y_1][\sqrt{\rho}]\sqrt{h}$$

where the bracketed terms are curve fit approximations. By simplifying the flow equation as set out above, the transmitter based microprocessor **66** is capable of updating the flow calculation each time it receives updated sensor information by bus **64**. In the event that one or more of the curve fit approximations have not been completely calculated the previous value is used in the flow calculation.

The effect of variations in the process variables has a direct affect on the flow calculation by virtue of their appearance in the flow equation. They have a smaller effect on the curve fit terms. Thus, by using the newly updated process variable information and the most recently calculated curve fit approximations, the result is a flow calculation that is both fast and accurate. Having newly calculated flow terms at such an expedient update rate allows transmitter **10** to exploit fast digital communication protocols.

Also, by simplifying the flow calculation as set out above, microprocessor **66** performs the same calculations regardless of the type of differential producer used, regardless of the beta ratio used, and regardless of whether the user requires a simplified or fully compensated flow.

It should also be noted that the curve fit coefficients are easily calculable by the user using known techniques. These coefficients are simply stored in memory associated with microprocessor **66** and used in performing the desired calculations.

These simplifications allow transmitter **10** to actually calculate flow in a highly accurate manner. Rather than requiring the transmitter to simply transmit the process variables back to a control room, and have a flow computer in the control room or installation calculate flow, the transmitter according to the present invention is capable of not only providing the process variables, but also providing a flow calculation to the control room. This relieves the processing overhead on the flow computer or other processor in the control room, yet does not over burden the transmitter-based microprocessor, or require the transmitter-based microprocessor to use energy which exceeds that available to it.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

What is claimed is:

1. A loop powered transmitter for providing an output signal indicative of mass flow rate of fluid through a conduit, the transmitter comprising:

a temperature receiving circuit configured to receive a temperature signal indicative of fluid temperature,

a static pressure sensor providing a static pressure signal indicative of static pressure in the conduit;

a differential pressure sensor providing a differential pressure signal;

a microcomputing circuit, coupled to the temperature receiving circuit, the static pressure sensor, and the differential pressure sensor, to receive the temperature signal, the static pressure signal and the differential pressure signal, and providing an output signal indicative of flow of the fluid through the conduit;

wherein the microcomputing circuit calculates flow, Q, according to an equation having multiplicands generally of the form:

$$Q = NC_d[Ed^2]Y_1[\sqrt{\rho}]\sqrt{h}$$

wherein the microcomputing circuit is configured such that at least two of the multiplicands are each approximated as a function of at least one of the temperature, the static pressure, and differential pressure.

2. The transmitter of claim 1 wherein the microcomputing circuit includes:

a first microprocessor coupled to the temperature sensor, static pressure sensor and differential pressure sensor, and corrects the static pressure signal, differential pressure signal and temperature signal for non-linearities and provides corrected output signals; and

a second microprocessor, coupled to the first microprocessor, for calculating flow based on the corrected output signals.

3. The transmitter of claim 1 and further comprising:

a housing enclosing a portion of the transmitter, and

a temperature sensor disposed substantially within the housing and coupled to the temperature receiving circuit, sensing the temperature of the fluid and providing the temperature signal.

4. The transmitter of claim 1 and further comprising:

a housing enclosing a portion of the transmitter, and

a temperature sensor disposed substantially outside the housing and coupled to the temperature receiving circuit, sensing the temperature of the fluid and providing the temperature signal.

5. The transmitter of claim 1 wherein the transmitter comprises a two wire transmitter.

6. A process control transmitter coupled to a conduit conducting a fluid therethrough, the transmitter comprising:

a first pressure sensor sensing line pressure in the conduit and providing a line pressure signal indicative of the line pressure;

a second pressure sensor sensing differential pressure across an orifice in the conduit and providing a differential pressure signal indicative of the differential pressure;

a temperature receiving circuit configured to receive a temperature signal indicative of a temperature of the fluid;

a microcomputing circuit, coupled to the first and second pressure sensors and the temperature receiving circuit and powered over a loop, calculating flow of the fluid through the conduit based on the line pressure signal, the differential pressure signal and the temperature signal and providing an output signal indicative of the flow;

wherein the microcomputing circuit calculates flow, Q, according to an equation having multiplicands generally of the form:

$$Q = NC_d[Ed^2]Y_1[\sqrt{\rho}]\sqrt{h}$$

and

wherein the microcomputing circuit is configured such that at least two of the multiplicands are each approximated as a function of at least one of the temperature, the static pressure, and the differential pressure.

7. The transmitter of claim 6 wherein the microcomputing circuit calculates flow based on an approximation of C_d according to a polynomial equation having the form:

$$C_d = \sum_{i=0}^{6}\left[\frac{1}{\sqrt{R_{eD}}}\right]^i b_i.$$

8. The transmitter of claim 7 wherein C_d is calculated as:

$$C_d = b_0 + \frac{1}{\sqrt{R_{eD}}}\left(b_1 + \frac{1}{\sqrt{R_{eD}}}\left(b_2 + \frac{1}{\sqrt{R_{eD}}}\left(b_3 + \frac{1}{\sqrt{R_{eD}}}\left(b_4 + \frac{1}{\sqrt{R_{eD}}}\left(b_5 + \frac{b_6}{\sqrt{R_{eD}}}\right)\right)\right)\right)\right)$$

9. The transmitter of claim 6 wherein the microcomputing circuit calculates flow based on an approximation of Ed^2 according to a polynomial equation having the form:

$$Ed^2 = \sum_{i=0}^{2} c_i\left(\frac{1}{T}\right)^i.$$

10. The transmitter of claim 9 where Ed^2 is calculated as:

$$Ed^2 = c_0 + \frac{1}{T}\left(c_1 + \frac{1}{T}c_2\right)$$

11. The transmitter of claim 6 wherein the microcomputing circuit calculates flow based on an approximation of Y_1 according to a polynomial equation having the form:

$$Y_1 = \sum_{i=0}^{2}\left(\frac{h}{P}\right)^i a_i.$$

12. The transmitter of claim 11 wherein Y_1 is calculated as:

$$Y_1 = a_0 + \frac{h}{P}\left(a_1 + \frac{h}{P}a_2\right)$$

13. The transmitter of claim 6 wherein the microcomputing circuit calculates flow based on an of ρ for liquid according to a polynomial equation having the form:

$$\sqrt{\rho} = \sum_{j=0}^{n}\left(\frac{1}{T}\right)^{j} c_j$$

14. The transmitter of claim 13 wherein ρ for liquid is calculated as:

$$\sqrt{\rho} = c_0 + \frac{1}{T}\left(c_1 + \frac{1}{T}\left(c_2 + c_3\frac{1}{T}\right)\right)$$

15. The transmitter of claim 6 wherein ρ for a gas is calculated substantially as:

$$\sqrt{\rho} = \left[\frac{144M_w}{R}\right]^{.5}\left[\frac{P}{T}\right]^{.5}\sum_{i=0}^{n}\sum_{j=0}^{m} P^{i}\left(\frac{1}{T}\right)^{j} f_{ij}$$

16. The transmitter of claim 15 wherein ρ for gas is calculated as:

$$\sqrt{\rho} = \left[\frac{144M_w}{R}\right]^{.5}\left[\frac{P}{T}\right]^{.5}\left[f_{00} + Pf_{10} + P^2f_{20} + f_{30}P^3 + \frac{1}{T}\left(f_{01} + Pf_{11} + P^2f_{21} + f_{31}P^3 + \frac{1}{T}\left(f_{02} + Pf_{12} + P^2f_{22} + f_{32}P^3\right)\right)\right].$$

17. The transmitter of claim 16 wherein C_d is calculated as:

$$C_d = b_0 + \frac{1}{\ln(R_{eD})}\left(b_1 + \frac{1}{\ln(R_{eD})}\left(b_2 + \frac{1}{\ln(R_{eD})}\left(b_3 + \frac{1}{\ln(R_{eD})}\left(b_4 + \frac{1}{\ln(R_{eD})}\left(b_5 + \frac{b_6}{\ln(R_{eD})}\right)\right)\right)\right)\right).$$

18. The transmitter of claim 6 wherein C_d is calculated using an equation generally in the form:

$$C_d = \sum_{i=0}^{n}\left(\frac{1}{\ln(R_{eD})}\right)^{i} b_i$$

19. The transmitter of claim 6 wherein the term Ed^2Y_1 is calculated using an equation substantially in the form:

$$Ed^2Y_1 = a_0 + \frac{1}{T}\left(a_1 + \frac{a_2}{T}\right) + \frac{h}{P}\left(a_3 + \frac{1}{T}\left(a_4 + \frac{a_5}{T}\right) + \frac{h}{P}\left(a_6 + \frac{1}{T}\left(a_7 + \frac{a_8}{T}\right)\right)\right)$$

20. The transmitter of claim 6 wherein the microcomputing circuit is configured to calculate flow based on a plurality of polynomial equations using polynomial curve fits, each of the approximated multiplicands being approximated with a polynomial equation having at least one of the temperature, the static pressure and the differential pressure, Reynolds number as an independent variable.

21. The transmitter of claim 6 wherein the loop comprises a two-wire loop.

22. A method of providing an indication of flow of fluid through a conduit using a process control transmitter powered by a control loop, comprising:

sensing static pressure and providing a static pressure signal indicative of the static pressure;

sensing differential pressure and providing a differential pressure signal indicative of the differential pressure;

receiving a temperature signal indicative of a temperature of the fluid;

calculating flow of the fluid through the conduit based on the static pressure signal, the differential pressure signal and the temperature signal and providing an output signal indicative of the flow

wherein calculating comprises calculating flow, Q, according to an equation having multiplicands generally of the form:

$$Q = NC_dEd^2Y_1\sqrt{\rho}\sqrt{h}$$

wherein the microcomputing circuit is configured such that at least two of the multiplicands are each approximated as a function of at least one of the temperature, the static pressure and the differential pressure.

23. The method of claim 22 wherein calculating comprises:

calculating flow based on at least one polynomial equation using a polynomial curve fit with at least one of temperature, static pressure and differential pressure being an independent variable in the polynomial equation.

24. The transmitter of claim 23 wherein calculating comprises:

calculating flow based on a plurality of polynomial equations using polynomial curve fits to approximate a plurality of C_d, E, d^2, Y_1, and ρ with at least one of the temperature, the static pressure and the differential pressure being an independent variable in the polynomial equations.

25. The method of claim 22 wherein calculating comprises:

calculating flow based on an approximation of C_d according to a polynomial equation having the form:

$$C_d = \sum_{i=0}^{n}\left(\frac{1}{\sqrt{R_{eD}}}\right)^{i} b_i$$

26. The transmitter of claim 25 wherein C_d is calculated substantially as:

$$C_d = b_0 + \frac{1}{\sqrt{R_{eD}}}\left(b_1 + \frac{1}{\sqrt{R_{eD}}}\left(b_2 + \frac{1}{\sqrt{R_{eD}}}\left(b_3 + \frac{1}{\sqrt{R_{eD}}}\left(b_4 + \frac{1}{\sqrt{R_{eD}}}\left(b_5 + \frac{b_6}{\sqrt{R_{eD}}}\right)\right)\right)\right)\right)$$

27. The method of claim 22 wherein calculating comprises:

calculating flow based on an approximation of Ed^2 according to a polynomial equation having the form:

$$Ed^2 = \sum_{i=0}^{n} c_i\left(\frac{1}{T}\right)^{i}$$

28. The transmitter of claim **27** where Ed^2 is calculated substantially as.

$$Ed^2 = e_0 + \lambda(e_1 + \lambda e_2).$$

29. The method of claim **22** wherein calculating comprises:

calculating flow based on an approximation of Y_1 according to a polynomial equation having the form:

$$Ed^2 = e_0 + \lambda(e_1 + \lambda e_2).$$

30. The transmitter of claim **29** wherein Y_1 is calculated substantially as:

$$Y_1 = d_0 + \frac{h}{P}\left(d_1 + \frac{h}{P}d_2\right)$$

31. The method of claim **22** wherein calculating comprises:

calculating flow based on an approximation of ρ for liquids according to a polynomial equation having the form:

$$\sqrt{\rho} = \sum_{i=0}^{k}\left(\frac{1}{T}\right)^i c_i.$$

32. The transmitter of claim **31** wherein ρ for liquid is calculated substantially as:

$$\sqrt{\rho} = c_0 + \frac{1}{T}\left(c_1 + \frac{1}{T}\left(c_2 + c_3\frac{1}{T}\right)\right)$$

33. The transmitter of claim **31** wherein ρ for gas is calculated substantially as:

$$\sqrt{\rho} = \left[\frac{144M_w}{R}\right]^{\frac{1}{2}}\left[\frac{P}{T}\right]^{\frac{1}{2}}\left[f_{00} + P(f_{10} + P(f_{20} + f_{30}P)) + \frac{1}{T}(f_{01} + P(f_{11} + P(f_{21} + f_{31}P))) + \frac{1}{T}(f_{02} + P(f_{12} + P(f_{22} + f_{32}P)))\right]$$

34. The method of claim **22** wherein calculating comprises:

calculating flow based on an approximation of ρ for gases according to a polynomial equation having the form:

$$\sqrt{\rho} = \left[\frac{144M_w}{R}\right]^{\frac{1}{2}}\left[\frac{P}{T}\right]^{\frac{1}{2}}\sum_{i=0}^{n}\sum_{j=0}^{m}P^i\left(\frac{1}{T}\right)^j f_{ij}$$

35. The method of claim **22** and further comprising:

powering the process control transmitter over a 4–20 mA loop.

36. A method of providing an indication of flow of fluid through a conduit using a process control transmitter powered over a control loop, comprising:

- sensing static pressure and differential pressure and providing pressure signals indicative of the static and differential pressure;
- receiving a temperature signal indicative of a temperature of the fluid;
- calculating flow of the fluid through the conduit based on the pressure signals and the temperature signal and providing an output signal indicative of the flow,
- wherein calculating flow comprises calculating flow, Q, according to an equation having multiplicands generally of the form:

$$Q = N[C_d][Ed^2][Y_1][\sqrt{\rho}][\sqrt{h}]$$

- wherein at least two of the multiplicands are each approximated as a function of at least one of the temperature, the static pressure, and the differential pressure.

37. The method of claim **36** wherein the multiplicands are each approximated using a polynomial equation having at least one of the temperature, the static pressure, Reynolds number and the differential pressure as an independent variable.

38. The method of claim **38** and further comprising:

powering the process control transmitter over a 4–20 mA loop.

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