New Developments in Thermal Dispersion Mass Flow Meters:
In-The-Field Compensation for Changes in Natural Gas Composition

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New Developments in Thermal Dispersion Mass Flow Meters: In-The-Field Compensation for Changes in Natural Gas Composition

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Introduction

The flow of natural gas in pipelines is often complicated by changes in the composition of the gas. The method described in this paper solves the problem of variable composition via a new four-temperature mass flow sensor. The new flow sensor feeds its measurements into the algorithms of an advanced mathematical model that includes gas properties in its calculations. The method described herein computes the properties of a specified pure gas or gas mixture to manage changes in gas composition, gas temperature, gas pressure, and outside temperature. This advance in thermal dispersion mass flow meters provides an immediate solution for natural gas applications, including distribution systems, flare gas produced in refineries, and flare gas produced in other applications, such as hydraulic fracturing.

Applications

Thermal dispersion mass flow meters measure the mass flow rate of pure gases and gas mixtures of known composition by sensing the heat that is convected from the surface of a heated velocity sensor immersed in the flow. Since it is the molecules of the gas, which bear its mass, that carry away the heat, thermal dispersion mass flow meters directly measure mass flow rate [1-6]. In addition to directly measuring mass flow rate, thermal dispersion mass flow meters have wide turn-down (more than 100:1), low pressure drop, and lower cost than most other technologies.

Since convective heat transfer depends on the properties of the gas (e.g., thermal conductivity, dynamic viscosity, and mass density), these properties must have known values. Traditionally, flow calibration of thermal mass flow meters is performed with the gas and the nominal temperature and pressure of the application. In cases where the specified gas mixture can not be used for flow calibration because of concerns for safety and expense, a surrogate gas mixture with similar heat transfer properties is used. Commonly, air or nitrogen is used as the surrogate gas and a correction factor based on the relationship between the properties of the surrogate gas and the gas properties of the specified pure gas or gas mixture

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is applied. Neither of these flow calibration options is optimal, particularly if temperature, pressure, or composition changes in the field.

When variations in temperature, pressure, and especially composition are encountered in the field, accuracy is adversely affected. In the past, correction factors have been applied to compensate for changes in temperature and pressure. But, compensating for changes in gas composition is much more difficult. Traditionally, changes in gas composition required returning the mass flow meter to the factory for flow recalibration. This wastes time, resources, and money [7].

This paper describes a new method for making in-the-field adjustments to thermal dispersion mass flow meters to account for changes in gas composition. A major application of this method is the measurement of the mass flow rate of natural gas in distribution systems. Once the gas composition is known, this method makes direct adjustments and essentially recalibrates the mass flow meter on site. This eliminates the need to return the mass flow meter to the factory for flow recalibration and avoids any errors associated with the use of a surrogate flow calibration gas.

In the field, when a change in composition is detected via periodic or quasi real-time gas sampling, the new method updates the mass flow meter and compensates for the compositional variation. Depending upon the intended application, periodic sampling is performed on an interval basis (e.g., daily, weekly, monthly etc.). Quasi real-time sampling, the preferred protocol, is performed with a tandem in-line gas composition sampling and analyzing system (typically based on gas chromatography). The outputs of the in-line analyzer are fed directly into the mass flow meter where compositional changes are processed instantaneously. The end result is improved mass flow measurement accuracy.

The new method of compositional compensation has direct application in the apportionment and custody transfer of natural gas in distribution systems. In situations where temperature, pressure, or composition are known to change, this new method delivers reliably accurate outputs of mass flow rate and totalized gas usage. This technology is also particularly valuable in the measurement of flare gas produced in refineries and in other applications, such as hydraulic fracturing.

In 2009, the EPA released the Mandatory Reporting of Greenhouse Gases Rule (40 CFR 98), which requires operations to measure and record the consumption of flare gas. All facilities emitting at or above 25,000 metric tons of CO_2 annually are required to report annual emissions. The most recent estimates indicate that there are over 5,500 facilities in the U.S. meeting this threshold. A typical accuracy of 5% is required by rule EPA 40 CFR 98, along with periodic flow calibration verification. The new compositional compensation method described in this paper provides a complete solution for these flare gas applications and enables facilities to be brought into full compliance with EPA 40 CFR 98 [8].

General Description

The new method for making in-the-field compositional adjustments to a thermal dispersion mass flow meter is based on two new developments - a breakthrough in thermal dispersion sensor technology and the development of an advanced mathematical model. When applied together, they provide previously unattainable accuracy in determining the heat carried away from the sensor via forced convection. This advanced mathematical model incorporates algorithms that calculate the properties of the gas.

The Graphical User Interface (GUI) facilitates creating gas mixtures from a library of over 100 pure gases. These mixtures are stored as files in a gas mixture library on the computer which is running the GUI. Up to three of these gas mixtures are stored in the flow meter's on board memory for immediate use. Once a new gas mixture is loaded into the flow meter, the updated gas properties are used in the advanced mathematical model and compositional adjustments are provided.

Advanced Flow Sensor

With the development of an advanced microprocessor-based thermal dispersion mass flow meter that uses four-temperature sensing elements in its flow sensor instead of the traditional two elements, in-the-field compositional adjustments became possible. This new sensor technology is capable of yielding a high accuracy heretofore unachievable in thermal dispersion mass flow meters [1, 2].

The outside temperature external to the flow sensor may be different than that of the flowing gas. For this reason, heat can be conducted in or out of the stems of the velocity sensor and the temperature sensor. Additionally, heat can be conducted from the hot velocity sensor to the cooler temperature sensor via their stems [1,2]. These phenomena are collectively called "stem conduction." Stem conduction is a large fraction of the total heat supplied to the velocity sensor. Left uncorrected, stem conduction constitutes a major source of error in measuring mass flow rate.

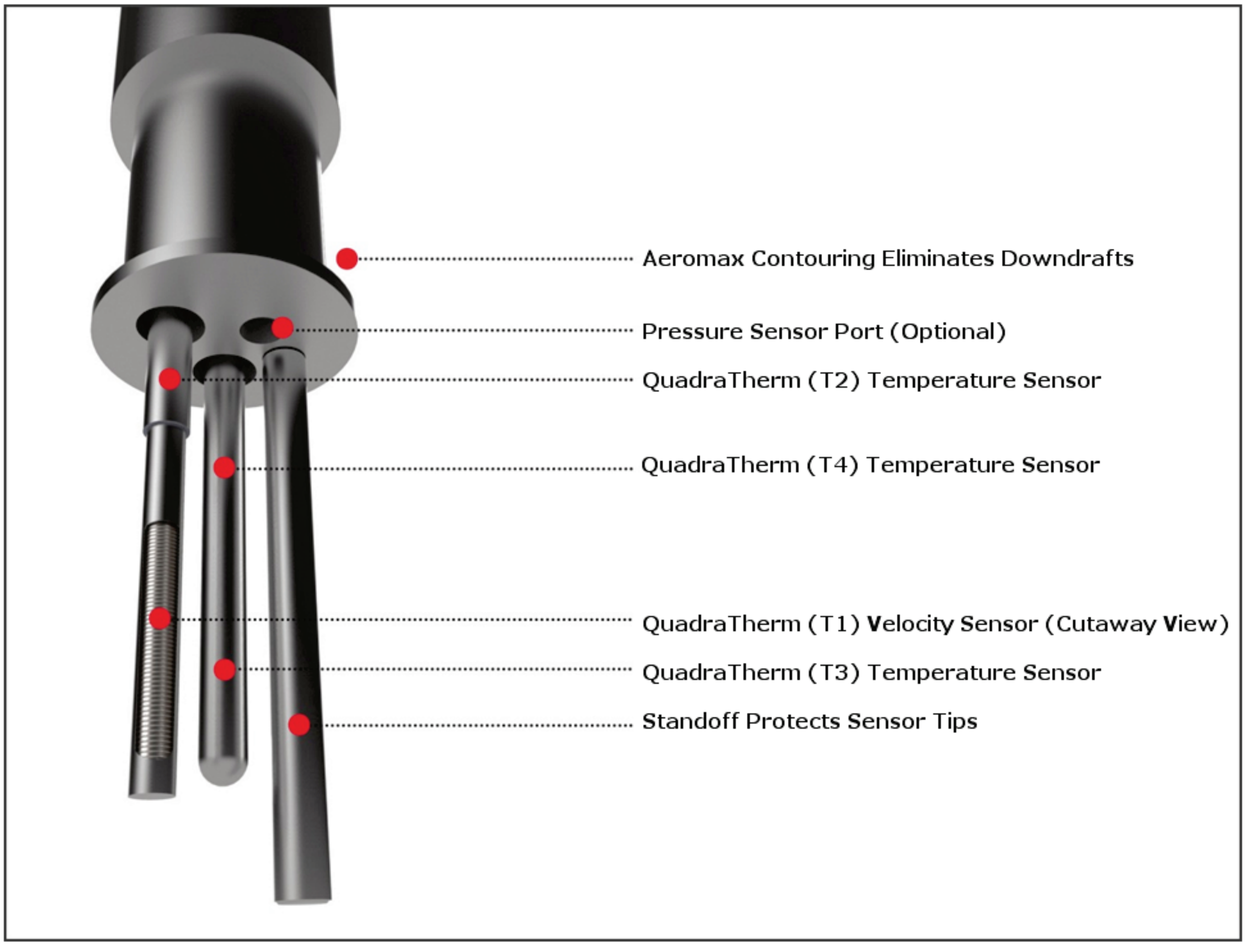

Figure 1 Advanced four-temperature flow sensor.

The four-temperature flow sensor design solves the stem conduction problem by employing a total of four platinum RTD temperature sensing elements. In this design, the velocity sensor and gas temperature sensor are present much like a standard thermal dispersion mass flow meter. In addition, two more RTDs are included, one above the velocity sensor and another above the gas temperature sensor. In operation, the two elements in each sensor act together as a heat-flux gauge that measures the fraction of heat conducted through the stem of the velocity sensor and the gas temperature sensor. The addition of these temperature sensing elements in the four-temperature flow sensor facilitates correction for stem conduction, whatever the cause.

A final improvement in this advanced flow sensor is the replacement of the traditional velocity sensor fabricated with potting cements or epoxies that are wet when mixed. These sensors pose potential long-term stability problems because the potting material can crack or otherwise degrade due to changes in

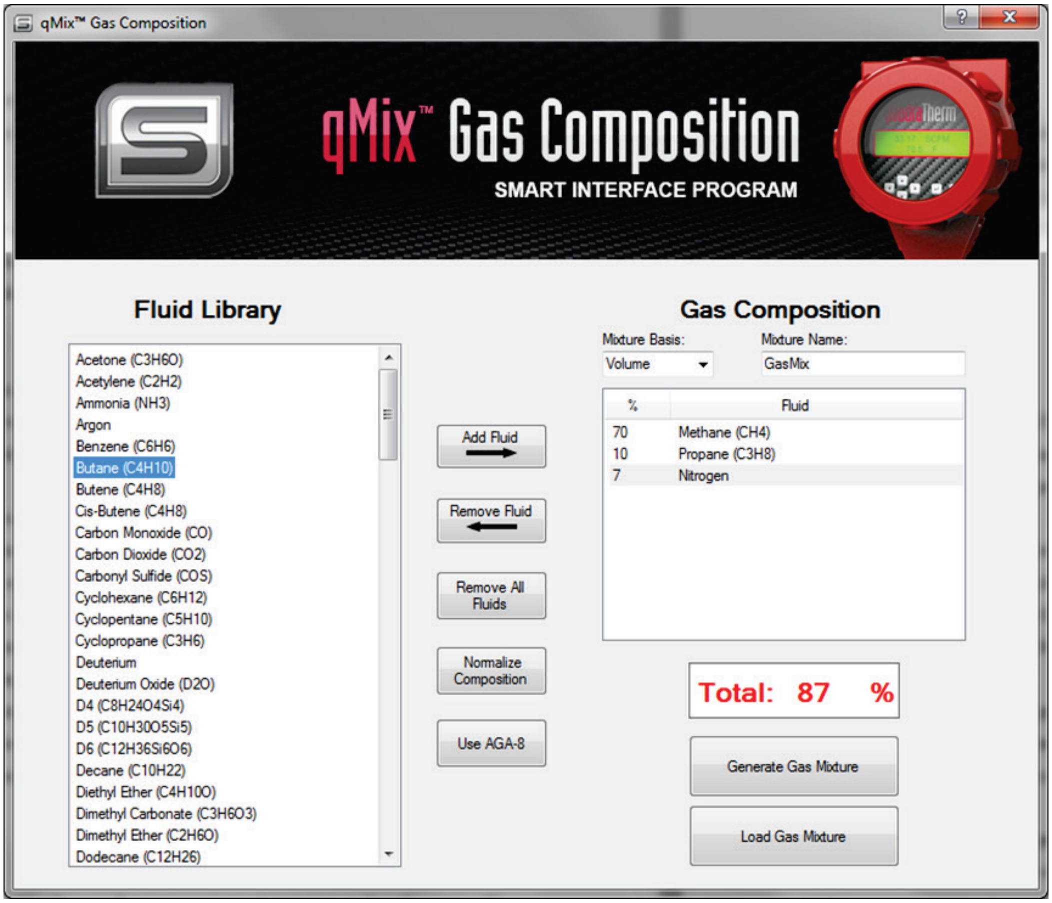

Figure 2 Gas composition graphical user interface.

temperature. Any change in the potting material causes a change in the "skin resistance" of the velocity sensor and thereby its stability. New "dry" sensor technology avoids the use of any potting materials and uses mating materials that have the same coefficient of thermal expansion. Filler materials are avoided by swaging the wire-wound velocity sensor into the sheath. These improvements serve to eliminate the skin resistance problem. Skin resistance and stem conduction are the two major factors that can degrade measurement accuracy. Both of these issues are accounted for in this advanced flow sensor design.

Advanced Mathematical Model

The advanced mathematical model operates the microprocessor-based system and provides the foundation for the new method described here for making in-the-field compositional compensation. In operation, the four-temperature microprocessor-based system measures the resistance of each of the four RTD sensors along with the current in the velocity sensor. The resistance values are converted to their four corresponding temperature values, and the current to the velocity sensor is converted to electrical power, or wattage. The four temperatures, the wattage, and the gas composition are the inputs to the system. The gas property algorithms calculate the updated properties of the gas (mass density, dynamic viscosity, thermal conductivity, and heat capacity). The system then computes the total mass flow rate (kg/s) in the pipe line – the desired output.

Graphical User Interface

The Graphical User Interface (GUI) shown in Figure 2 facilitates the selection of mixture components from a library of over 100 pure gases. A gas mixture is built by selecting each component and specifyinits compositional percentage. For compositions that do not total up to 100%, a normalizing function is applied. To improve accuracy in natural gas mixtures, the American Gas Association's AGA-8 standard can be selected for use in the calculation of gas properties. Calculations based on the AGA-8 program have been shown to offer more accurate results for mixtures containing hydrocarbons.

Once the desired composition is selected, the system calculates the properties of the gas mixture, which are then stored as a file in a gas mixture library on the local computer. The GUI manages the files stored in the local gas mixture library and enables loading any of these gas mixture files directly into the flow meter. Three gas mixtures are stored in the flow meter's on board memory at a time.

The Effect of Changes in Gas Properties

Thermal dispersion mass flow meters measure the heat carried away by convection from the surface of a heated velocity sensor immersed in the flow. Based on this principle, thermal dispersion mass flow meters are dependent on the gas properties of the specified mixture. These gas properties change with variations in temperature, pressure, and particularly composition and, in the absence of compensation, can result in significant errors in mass flow rate measurement [1, 7].

Table 1 shows the effect of variations in operating temperature and pressure on the requisite gas properties of methane. Changes in temperature have a major effect on the values of all of these properties. Variations in pressure have the most effect on mass density and have a lesser effect on the other properties, unless the change in pressure is very large. The advanced mathematical model accounts for all these property variations via the inputs for gas temperature, gas pressure, and outside temperature.

Table 1 Effects of temperature and pressure on the properties of methane

Temperature[a] (°F)	**Pressure (psia)**	**Mass Density (kg/m³)**	**Heat Capacity, c_p (J/kg·K)**	**Thermal Conductivity (W/m·K)**	**Dynamic Viscosity (Pa·s)**
-40	14.73	0.843871	1181.276	0.02558	0.000008885818
32	14.73	0.719125	1211.684	0.030599	0.000010254989
60	14.73	0.680092	1228.419	0.032667	0.000010768868
300	14.73	0.464471	1451.109	0.053636	0.000014800924
-40	100	5.867351	1219.852	0.026115	0.000008973767
32	100	4.950799	1236.221	0.031034	0.000010338721
60	100	4.670345	1249.524	0.033073	0.000010850394
300	100	3.159190	1459.093	0.053900	0.000014864407
-40	1500	150.4703	3093.999	0.054851	0.000016352041
32	1500	93.74452	1900.258	0.044705	0.000013832562
60	1500	83.72999	1752.614	0.044544	0.000013814388
300	1500	48.178886	1591.100	0.059210	0.000016285031

Note to Table 1: (a) The standard, ANSI Z132, has established 60°F and 14.73 psia as the base temperature and pressure to which all volumes are commonly referred. The new thermal dispersion mass flow sensor technology has an operational range of -40°F to 392°F.

Table 2 Effects of gas composition on the properties[a] of a natural gas mixture

Volumetric Concentration (percent methane/propane/nitrogen)	**Mass Density (kg/m³)**	**Heat Capacity, c_p (J/kg·K)**	**Thermal Conductivity (W/m·K)**	**Dynamic Viscosity (Pa·s)**
90 / 9 / 1	0.7927765	1150.4287	0.030473623	0.000010484
90 / 5 / 5	0.7651436	1138.6348	0.031131304	0.000010841
90 / 1 / 9	0.7375673	1126.0513	0.031808716	0.000011205
85 / 10 / 5	0.8249798	1108.7058	0.029993846	0.000010647
85 / 7.5 / 7.5	0.8076940	1100.8317	0.030394327	0.000010876
85 / 5 / 10	0.7904315	1092.6494	0.030801321	0.000011109
80 / 15 / 5	0.8849063	1082.8779	0.028905350	0.000010451
80 / 10 / 10	0.8502616	1066.8104	0.029672251	0.000010910
80 / 5 / 15	0.8157158	1049.5270	0.030467010	0.000011390

Note to Table 2: (a) Gas properties are calculated at 60°F and 14.73 psia.

Table 3 Effects of hydrogen on the properties[a] of a natural gas mixture

Volumetric Concentration (percent methane/nitrogen/hydrogen)	Mass Density (kg/m³)	Heat Capacity, c_p (J/kg·K)	Thermal Conductivity (W/m·K)	Dynamic Viscosity (Pa·s)
90 / 10 / 0	0.7306812	1122.7703	0.031979422	0.000011297
90 / 9 / 1	0.7196467	1139.8097	0.034254882	0.000011241
90 / 7 / 3	0.6975793	1175.5040	0.038601665	0.000011127
90 / 5 / 5	0.6755141	1213.5282	0.042697092	0.000011014
90 / 3 / 7	0.6534513	1254.1185	0.046555922	0.000010899
90 / 1 / 9	0.6313910	1297.5437	0.050199937	0.000010787
90 / 0 / 10	0.6203619	1320.4138	0.051942898	0.000010730

Note to Table 3: (a) Gas properties are calculated at 60°F and 14.73 psia.

Table 2 shows the effect of variations in composition on the properties of a simple natural gas mixture. For this example, three common natural gas components (methane, propane, and nitrogen) are applied in different volumetric concentrations. The same temperature and pressure conditions are applied in each data set. As shown, these compositional variations have a large effect on the property values of the gas mixture.

Table 3 shows a series of simple natural gas mixtures with increasing concentrations of hydrogen. The powerful effect that hydrogen has on natural gas mixtures can not be ignored. Tables 2 and 3 offer proof that even minor variations in the composition of a gas mixture can have a major effect on the properties of the mixture.

Comparison with Flow Calibration Data

Figure 3 compares experimental data points with the new method of gas composition compensation for six different gas mixtures: pure methane, two different natural gas mixtures, a flare gas mixture, and two digester gas mixtures. The graphs show the mass flow rate output of the mixture versus the wattage input. Each graph shows the experimental data points collected in the laboratory during flow calibration using the specified mixtures. The experimental data points are shown with the output curve calculated via the new compositional compensation method for the same gas mixtures. As evidenced by all six graphs, the curves produced via the new method closely match the experimental data.

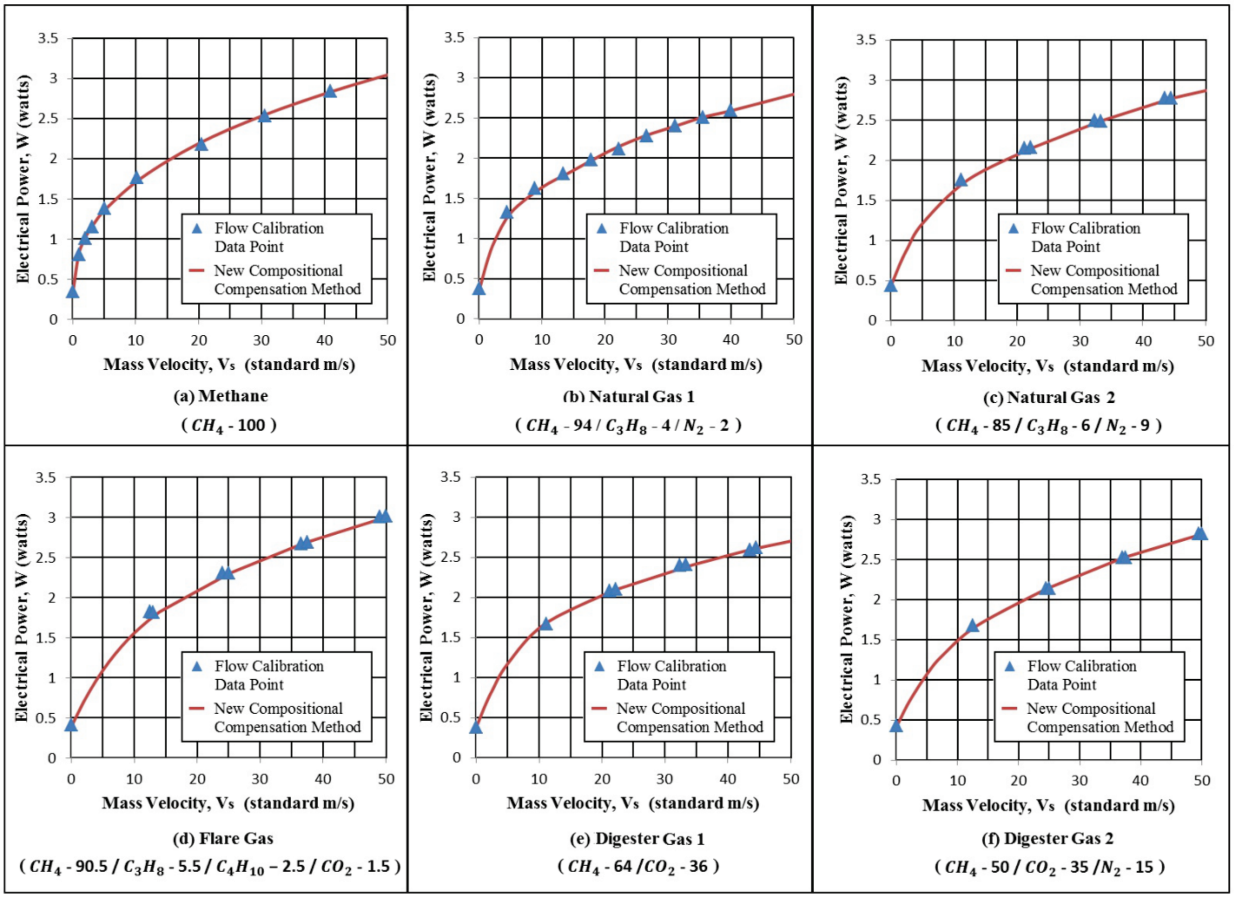

Figure 3 Comparison between flow calibration data points for the actual mixture and the new method for in-the-field gas compositional compensation. The compositions shown are in volumetric percentage concentration. The new compositional compensation method uses meter factors found via air flow calibration.

As shown in Figure 3, the new compositional compensation method offers a high accuracy solution to the problem of changing gas composition. The method avoids the inaccuracy of factory flow calibrations using surrogate gases and correction factors and is applicable in all but the most extreme compositions and conditions. The new method of compositional compensation facilitates improved performance in existing thermal mass flow applications and opens the door to a wide array of new applications.

Conclusion

All flow meters that measure mass flow rate, except coriolis meters, require knowledge of gas properties. Thermal dispersion mass flow meters require knowledge primarily of the thermal conductivity and viscosity of a pure gas or gas mixture and secondarily of the mass density and heat capacity. Volumetric multi-variable flow meters require knowledge primarily of mass density and secondarily of the viscosity of the gas to measure mass flow rate. These properties change not only with the temperature and pressure in the pipe line, but also with any changes in gas composition. If flow meters are flow calibrated in the factory with a surrogate gas or gas mixture and the composition of the gas changes in the field, then the accuracy of mass flow rate measurement is compromised. The flow of natural gas in applications such as distribution systems, flaring, and hydraulic fracturing often undergoes in-the-field changes in composition. Left uncorrected, errors in mass flow rate will occur.

The new technology presented here compensates for the changes in the composition of natural gas (and other pure gases and gas mixtures) and corrects this problem. This technology is based on a new four-temperature thermal dispersion mass flow meter that manages changes in gas temperature, gas pressure, and outside temperature. An advanced mathematical model based on this physical layer operates the on board system that also calculates the properties of natural gas mixtures in real time, thereby compensating for in-the-field compositional changes. The Graphical User Interface stores the properties of over 100 pure gases and facilitates building any natural gas or other mixture from these components. The end result: natural gas applications that formerly were unattainable are now possible.

The new method of in-the-field compositional compensation is proven to be accurate via comparison between the mass flow rate output computed by the mathematical model and experimental flow calibration data points obtained with six different gas mixtures.

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About the Authors

John G. Olin, Ph.D., is the founder and chairman of Sierra Instruments, Inc., located in Monterey, Calif. Dr. Olin received his bachelor's degree from Illinois Institute of Technology and his master's and Ph.D. from Stanford University, all in Mechanical Engineering. At Stanford, Dr. Olin specialized in fluid mechanics and heat transfer and used thermal flow meters in research pursuant to his doctoral dissertation. He founded Sierra Instruments in 1973 with the purpose of offering thermal mass flowmeters to solve industry's need for accurate, reliable flowmeters based on the thermal principle. Dr. Olin has a dozen patents and over 60 papers in the field.

Brian T. Estep currently serves as Senior Engineer at Sierra Instruments. Estep joined Sierra in 2012. Since then, he has become an integral member of the Engineering team and an R&D project leader. Estep's main areas of research interest are mass flow measurement (capillary, thermal dispersion, vortex), thermodynamic and transport properties of fluids, and the development of mathematical models for fluid dynamics. Brian Estep is a member of the Institute of Electrical and Electronics Engineers of the United States and the American Gas Association. He obtained a B.S. in Computer Science from the University of Texas at Austin in 2004 and has a strong educational background in Engineering Physics and Mathematics.