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A novel gas divider using nonlinear laminar flow

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ABSTRACT

Gas dividers are important in emissions measurement since they continuously and accurately mix two gases to create a known gas concentration that is needed in the multi-point calibration of gas analyzers. A novel gas divider was designed using nonlinear laminar flow induced from the density change along the capillary channels due to the high-pressure drop (relative to the inlet gas pressure). The minor losses from entrance and exit effects can be ignored due to the high pressure loss from Hagen-Poiseuille's law relative to the minor losses. Small diameter wires inside of a tube were used to create capillary channels through which gas could flow. The gas divider, using nonlinear laminar flow, showed lower measurement uncertainty at high (90%) dilution levels than using linear laminar flow due to the higher-pressure drop at the same volumetric flow rates. Experiments showed the expected gas concentration from using the gas divider to be within 2% of the measured gas concentrations.

1. Introduction

Gas dividers are widely used in environmental pollution control, such as automotive and exhaust plumes for the calibrating of gas analyzers used in the measurement of emissions from different pollution emitters. The gas analyzers require multi-point calibration via a gas divider that accurately and continuously mixes two gases at known concentrations. Gas dividers require accurate regulation and measurement of the flow rate from each gas stream.

Some of the commonly used techniques for flow measurement with gas dividers are volumetric pumps, critical orifices, thermal mass-flow controllers, and capillary tubes [1,2]. A study by Wright and Murdoch [3] investigated four different commercially available gas dividers. The four gas dividers used were thermal mass flow controllers, capillaries, positive-displacement pumps (varying stroke frequency), and positive-displacement pumps (varying the number of pumps), respectively. Sherman et al. [4] developed a gas divider based on mass flow technology that achieved residual errors of less than 1% of point for most of the tested analyzer ranges.

When using capillary tubes, the small diameter of the capillary generates the laminar flow inside the gas divider. The internal laminar flow follows the Hagen-Poiseuille law and the flow rate increases linearly as the pressure drop across the capillary channel increases. For larger flow rates, multiple capillary tubes of the same diameter are arranged in parallel. Therefore, to have a higher flow rate while still maintaining laminar flow, the gas divider requires more capillary tubes [5]. These laminar flow meters are common in industry to measure the flow rate of clean gases. Authors [6,7] have studied the use of a concentric annular duct instead of capillary tube bundles to generate linear laminar flow. Priestman and Boucher [8] showed that the range of other flow meter types could be extended by using a laminar by-pass resistance.

The objective of this study was to develop a novel gas divider using a compressible fluid with a high-pressure drop (with respect to the inlet gas pressure) that created nonlinear laminar flow. A gas divider was designed, constructed, calibrated using a reference flow meter, and experimentally verified using an emissions analyzer. In addition, equations were developed that demonstrate the behavior of the non-linear laminar flow and propagation of error analysis was performed on the gas divider when using nonlinear or linear laminar flow channels.

2. Theory

For a gas divider, diluting one gas concentration (by volume) to lower gas concentrations (by volume) requires the mixing of two gas streams. The first gas stream has a gas concentration (by volume) for a specific gas species, called the component gas, and the remainder of that gas stream is another gas species, called the balance gas. The second gas stream consists of only the balance gas. The exit concentration (by volume) of the component gas is dependent on the volumetric flow rates of the gas streams and the inlet concentration (by volume) of the component gas species, as shown in Eq. (1). When diluting a gas with a low concentration ($<1\%$), the variation in the densities between the two gas streams and the outlet can be neglected as shown in Eq. (2).

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Nomenclature

A	Cross sectional area
d	Diameter of capillary channels
d_h	Hydraulic diameter of the capillary channels
d_t	Inside diameter of the tube
d_w	Wire diameter
Γ	Wetted perimeter
K_i	Entrance loss coefficient
K_e	Exit loss coefficient
L	Length of the capillary channels
L_e	Entrance length
$\dot{m}$	Mass flow rate
n	Number of capillary channels
P	Pressure in the capillary channels
P_i	Inlet pressure of the capillary channels
P_o	Outlet pressure of the capillary channels
$P_{o,cal}$	Outlet pressure during calibration of the capillary channels
Q	Volumetric flow rate
Q_o	Outlet volumetric flowrate
$Q_{o,corr}$	Corrected outlet volumetric flowrate
$Q_{o,1}$	Outlet volumetric flowrate of tube 1
$Q_{o,2}$	Outlet volumetric flowrate of tube 2
R	Gas constant
Re_D	Reynolds number based on the hydraulic diameter
T	Temperature of the gas in the capillary channels
V_i	Inlet gas velocity
V_o	Outlet gas velocity
x	Length along the capillary channels
Y_o	Gas divider outlet gas concentration, by volume
Y_1	Gas divider inlet gas concentration, by volume
α	Calibration constant for the capillary channels
β	Calibration constant for the capillary channels
ΔP	Pressure drop from the inlet to the outlet of the capillary channels
ΔP_{loss}	Pressure loss associated with the entrance and exit effects
ΔP_m	Maximum pressure drop from the inlet to the outlet of the capillary channels
μ	Gas viscosity
μ_{cal}	Gas viscosity of the calibration gas
$\rho_{o,1}$	Outlet gas density of tube 1
$\rho_{o,2}$	Outlet gas density of tube 2

$$Y_o = Y_1 \frac{Q_{o,1}}{\left(\frac{\rho_{o,1}Q_{o,1}+\rho_{o,2}Q_{o,2}}{\rho_o}\right)} \quad (1)$$

$$Y_o = Y_1 \frac{Q_{o,1}}{Q_{o,1} + Q_{o,2}} \quad (2)$$

The mass flow rate (Eq. (3)) through a tube is a function of density and the volumetric flow rate. Hagen-Poiseuille's law, Eq. (4), applies to laminar flow for a constant cross sectional area and relates the pressure drop over a small length to the volumetric flow rate. Eq. (5) applies the ideal gas law and Eqs. (4) to (3). The mass flow rate is constant through the tube, and by assuming isothermal conditions throughout the length of the tube, Eq. (5), can be integrated from the inlet to the outlet of the tube and results in Eq. (6). Eq. (7) shows the volumetric flow rate at the outlet was developed using Eqs. (3) and (6).

By substituting Eqs. (8) and (9) gives an expression for the outlet volumetric flow as a second-order polynomial of the pressure drop. Neglecting the second order term in Eq. (9) due to the small pressure drop compared to the outlet pressure, results in Eq. (10), which is the form of the Hagen-Poiseuille's law used in other studies with capillaries [5–8]. Calculations in this study use Eq. (9) due to the high-pressure drops relative to the outlet pressure.

$$\dot{m} = \rho Q \quad (3)$$

$$Q = -\frac{n\pi d^4}{128\mu}\frac{dP}{dx} \quad (4)$$

$$\dot{m} = -\frac{P}{RT}\frac{n\pi d^4}{128\mu}\frac{dP}{dx} \quad (5)$$

$$\dot{m} = -\frac{n\pi d^4}{128\mu RTL}\frac{P_o^2 - P_i^2}{2} \quad (6)$$

$$Q_o = \frac{n\pi d^4}{128\mu L}\left(\frac{\Delta P}{2}\right)\left(\frac{P_i}{P_o}+1\right) \quad (7)$$

$$P_i = \Delta P + P_o \quad (8)$$

$$Q_o = \frac{n\pi d^4}{128\mu L}\left(\frac{(\Delta P)^2}{2P_o}+\Delta P\right) \quad (9)$$

$$Q_o = \frac{n\pi d^4}{128\mu L}\Delta P \quad (10)$$

3. Experimental setup

The gas divider system (Fig. 1) consisted of three inlet gas flow measurement sections that allowed three gases to be mixed. Each flow measurement section consisted of a needle valve (to regulate the inlet pressure), an inlet pressure gauge, and the laminar flow tube. The outlet of each flow measurement section connected to a manifold, with a pressure gauge, and then the flow traveled through a flow meter. The pressure gauges measured gage pressure and had a range of 0–400 kPa with an accuracy of 0.5% of full scale. The flow meter was a variable area style flow meter with a range of 1.0×10^{-5} – 8.3×10^{-5} m^3/s and an accuracy of 5% of full scale. Three different gas bottle mixtures of air (20.5% O_2/79.5% N_2), NO (1533 ppm NO/balance N_2), and N_2 (99.999% pure) were used for the experiments. The air and NO gas bottle concentrations were accurate to within 0.1% and 1%, respectively.

Common methods in industry of creating laminar flow channels

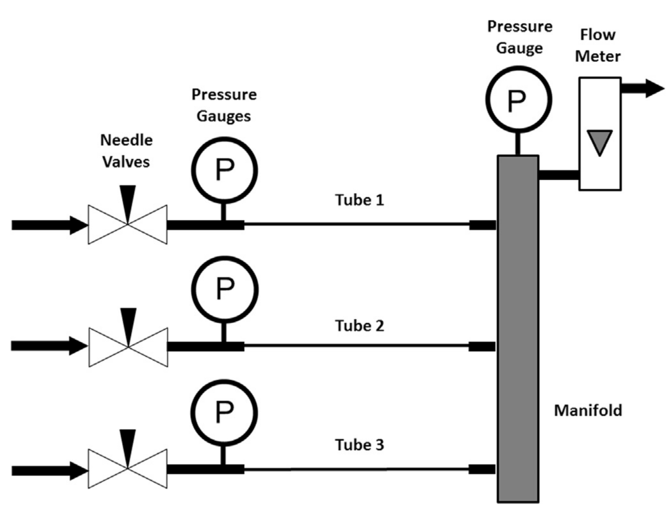

Fig. 1. Gas divider system.