Portable LTCC gas viscometer for determining Wobbe number

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Abstract

This work presents the continued development of an autonomous portable system for measuring the Wobbe number (calorific content) of gases for the purpose of determining the quality of natural gas. Past research has shown the Wobbe number can be determined if the dynamic viscosity is known. The sensor described here operates on this principle and is essentially a gas viscometer. The sensing components are integrated into single low temperature co-fired ceramic (LTCC) device making the sensor compact and low cost. The sensor was placed within a compact enclosure with data acquisition electronics and was connected to a PC from which a LabVIEW program controls the sensors operation and records the data. It is an evolution of previous work where the sensor concept was proven using a non-integrated system. Preliminary results show the sensor could operate autonomously and was stable when measuring the viscosity of air.

Keywords: LTCC; Portable; Sensor; Viscometer; Natural Gas;

Nomenclature

P	Pressure (Pa)
t	Time (s)
τ	Time Constant (s)
Q	Volumetric flow rate ($m^3\ s^{-1}$)
μ	Dynamic Viscosity (Pa s)
k	Stiffness (Pa m^{-1})

1. Introduction

In terms of fossil fuels natural gas is regarded as a clean and efficient source of energy that will continue to be viable into the foreseeable future. However, these characteristics are solely dependent on the precise control of the combustion of this gas, which is effectively control of the oxidant to fuel ratio during ignition. A further complication to this problem is that, although natural gas is mainly composed methane, it is a mixture of a variety of other flammable and inert gases. Furthermore this composition is subject to change over time since the gas is pumped from a variety of sources, thus making the measurement of the calorific content, quantified in terms of its Wobbe number, at regular intervals critical for efficient operation of gas burners.

Rather than measure the precise concentration of each element in the gas to determine its quality it has been shown in previous research that the viscosity of flammable gasses can be related directly to its Wobbe number [1, 2]. This paper reports on the theory and design of a miniature gas viscometer based in Low Temperature Co-fired Technology (LTCC). A model of the system is described along with an overview of the main components of the portable system. The results from a single measurement are described in detail to show how the sensor operates and the results from 350 consecutive measurements of air samples are presented to demonstrate the stability of the sensor.

2. Experimental procedure

The viscometer is based on a membrane that holds a small volume of the gas to be measured (See figure 1). The gas is subsequently heated which, due to the small volume, causes a rapid increase in pressure within the membrane relative to the pressure outside the sensor. Gas then flows through a fluidic resistance in the form of a capillary to the sensor outlet while the pressure within the membrane is measured continuously. As will be shown in this paper the pressure decreases in the form of an exponential decay from which the time constant can be related directly to the viscosity of the gas.

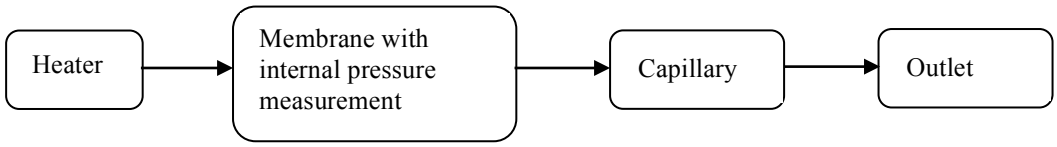

Fig. 1. Sensor model

2.1. Model of capillary viscometer

In order to accurately determine the viscosity of sampled gas from the data generated a system model was developed. The operation of the sensor was based on a capillary viscometer where the drop in pressure ΔP is expressed in terms of a constant volumetric flow rate Q and a fluidic resistance which is defined by the dimensions of the capillary, in this example a channel with a rectangular cross section, $L \times W \times H$ and the dynamic viscosity μ (See equation 1).

$$\Delta P = Q \frac{12 \mu L}{\pi W H^3} \tag{1}$$

However, as the operation of the viscometer is based on a membrane, the pressure decays exponentially, meaning that this steady state model is not sufficient. Equation 2 equates the pressure difference between the inside of the membrane and the external pressure ΔP to the time elapsed t where P_0 is the initial pressure and τ is the time constant of the system. The two factors affect the value of the time constant are the stiffness of the membrane k, i.e. the resistance of the membrane to deformation to pressure applied, and the fluidic resistance of capillary R_f (See equation 3).

$$\Delta P = P_0 e^{-t/\tau} \tag{2}$$

$$\tau = \frac{R_f}{k} \tag{3}$$

Using the fluidic resistance of element equation 1 the dynamic viscosity μ can be related to the stiffness of the membrane, the dimensions of the capillary and the time constant of the system. It can be seen that since k, L, W and H are constants only the measurement time constant is needed to determine the dynamic viscosity (See equation 4).

$$\mu = k \frac{\pi W H^3}{12 L} \tau \tag{4}$$

2.2. Fabrication of system

The sensor was fabricated using LTCC technology and consisted of a heater module, a membrane, a capillary channel or a rectangular cross section and an outlet port. A method utilizing sacrificial carbon paste demonstrated by Birol et al. was used to fabricate the membrane and capillary [3]. The heater module used a ruthenium oxide resistive element and was also fabricated from LTCC using the method described by Maeder et al. in a previous study [4]. The deformation of the membrane was measured by a capacitive sensor, one of the plates of the sensor was placed on top of the membrane and the other plate was placed directly underneath. Figure 2(a) shows the completed LTCC sensor, which was glued to an alumina base plate for mechanical support.

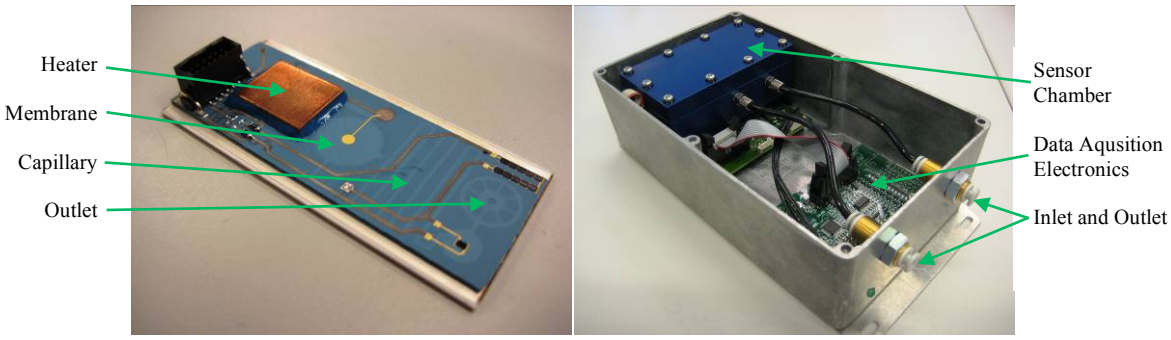

Fig. 2. (a) LTCC Sensor; (b) System enclosure

Figure 2(b) shows the completed portable unit. The LTCC sensor was placed within an air-tight aluminium chamber, external to this was a LabJack U3 data acquisition board (LabJack Corporation, USA) and an AD7745 (Analog devices, USA) based electronics board for capacitive sensing. All the components were placed in an aluminium enclosure with an inlet and outlet port that allowed gas to circulate through the system. The sensor was powered and controlled by a USB connection to a PC were a LabVIEW program controlled the operation of the sensor and the acquisition of data.

To take a viscosity measurement a current of 100 mA was passed through the heater to heat up the gas in the membrane causing it to expand. Then the capacitance across the membrane was measured continuously as the pressure between the interior and exterior of the sensor equalized. In order to calculate the time constant the exponential decay the natural log of the decay was calculated. Equation 5 shows that the natural log of equation 2 gives the equation for a straight line were $-1/\tau$ is the slope allowing τ to be determined. Afterwards a current of 10 mA was passed through the heater, causing a rapid decrease in temperature and pressure under the membrane. This allowed a second measurement to be taken as the pressure equalized.

$$\ln(\Delta P) = \ln(P_0) - {}^{t}\!/_{\tau} \qquad (5)$$

3. Results and Conclusions

Figure 3 shows the plot of the systems response after the current through the heater was switched from 100 mA to 10 mA. Initially the capacitance showed a rapid increase as the membrane contracts and then begins to decay slowly as pressure normalized. The calculated natural log shows a near linear slope but begins to deviate near the end of the plot and is due to the simplicity of the sensor model. However it shows the model to be a valid approximation of the sensor behavior. The time constant was calculated only from the initial slope of the natural log giving a value of 71.6 seconds.

To show the stability of the sensor 350 separate measurements were taken and the time constant calculated. The results are detailed in figure 4. It can be seen that there is difference in measurement between when the heater was powered by 100 mA from when it was power by 10 mA. Additionally it can be seen that the data for when the heater was at high power shows more variability. The difference in time constant measurement could be due to a hysteresis in the deformation of the membrane or a difference viscosity due to the heating of the gas and will have to be investigated further. The variability of the heater on data was most likely due to the inaccurate control of the temperature of the gas under the membrane.

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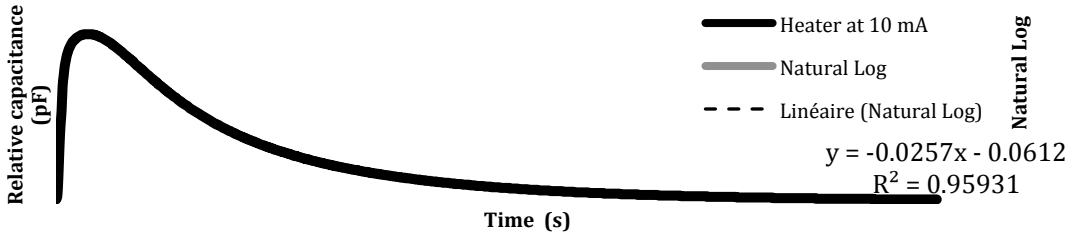

Fig. 3. Plot showing a typical measurement with corresponding natural log and linear regression with the heater off

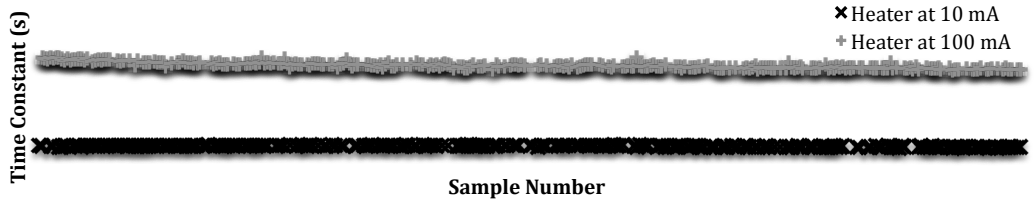

Fig. 4. Plot of time constant over 350 consecutive measurements