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Rapid Characterisation of Mixtures of Hydrogen and Natural Gas by Means of Ultrasonic Time-Delay Estimation

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Summary:
In this work we present a possible application of ultrasonic time-delay estimation to characterise mixtures of natural gas and hydrogen by the speed of sound. We constructed two prototypes based on two variants of micromachined ultrasonic transducers, both out-of-plane (CMUT) and in-plane (L-CMUT), operating at different frequencies (1.6 MHz and 40 kHz respectively). A calibration of these devices under controlled conditions will enable their assessment as potential hydrogen-sensitive gas counters.

Keywords: hydrogen, natural gas, CMUT, ultrasound, pitch-catch

Introduction

In the coming years, hydrogen will be widely distributed in the German pipeline network as a mixture with natural gas, seeking to enable its application in domestic and industrial environments [1]. Monitoring the hydrogen content in this mixture at different stages of the distribution network will therefore become a need, considering that different components of the gas infrastructure (e.g. pipes, compressors, turbines) offer different levels of tolerance to hydrogen, and that this gas mixture possesses a lower calorific value per unit volume in comparison to natural gas [2,3]. Although the composition of such mixtures can be accurately measured in gas chromatographs, a fast, on-site, and low-cost method—even if less accurate—would offer a significant advantage for monitoring hydrogen in households and factories.

Ultrasonic transducers have been widely implemented in pipelines for monitoring volume flow, and a minimal adjustment in their control unit enables a further report of the speed of sound of the fluid, given that both variables are directly calculated from the two measurements of the time of flight (upstream and downstream) [4]. By monitoring the speed of sound of the hydrogen-enriched mixture, a first, quick estimation of its composition can be performed. If mixture were binary (e.g. H_2 in CH_4), the speed of sound would offer a direct measurement of the hydrogen content, provided that the temperature of the mixture is known. This can be evidenced in Laplace's equation for the speed of sound in ideal gases (1), which reveals its dependence on three variables (C_p, C_v, M) that in turn depend directly (in fact, linearly) on the amount of each substance [5].

$$c = \sqrt{\frac{\gamma P}{\rho}} = \sqrt{\left(\frac{C_p}{C_v}\right)\frac{RT}{M}} \qquad (1)$$

Nonetheless, natural gas does not consist purely of methane, but is itself a mixture that includes ethane, propane, nitrogen and other gases. Depending on the geographical source and the extraction method, the content of CH_4 in natural gas can vary from 98%vol to around 80%vol [6]. If, however, the source of natural gas is kept constant, its composition varies only very slightly, and the concentration of hydrogen can be calibrated with a series of measurements of the speed of sound—or with the knowledge of the composition of the respective sort of natural gas.

Method

We have constructed two prototypes to measure the speed of sound by means of a "pitch-catch" measurement of an ultrasonic wave packet. The devices are designed to act as a new kind of gas counter that reports not only the volume flow but also the hydrogen content, including a temperature correction (for which a corresponding sensor is included). The first prototype relies on a CMUT (Capacitive Micromachined Ultrasonic Transducer) that operates at a frequency of 1.6 MHz [7]. Given the high attenuation losses at this operation frequency, the travelling range of the waves is kept at 11 mm. The second prototype relies on a low-frequency, laterally oscillating CMUT [8] that generates a wave packet with a centre frequency of 40 kHz. This wave packet is then detected by a MEMS microphone (Knowles® SPU1410LR5H) located at a distance of 150 mm from the “L-CMUT” transmitter. A scheme of these two prototypes is found in Figure 1.

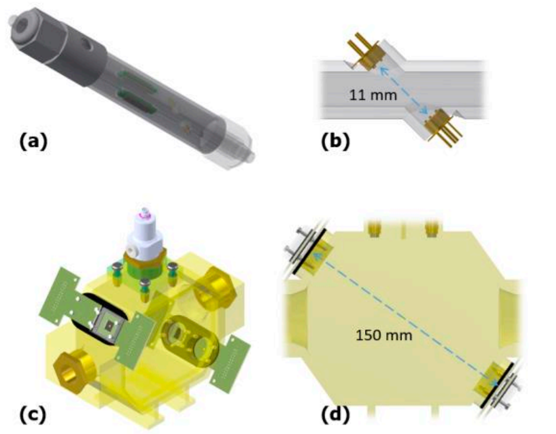

Fig. 1. Overview of the two MUT-based devices through which the speed of sound of the gas mixture is characterised. (a) CMUT device and a detail view (b) of the location of the transducers. (c) L-CMUT device and a detail view (d) of the location of the transducers.

The calibration of the speed of sound for different mixtures of hydrogen and natural gas is to be performed under controlled conditions. A mass flow controller (Brooks® 5851S) is used to regulate the mixture, whose composition is then monitored with a gas chromatograph (Thermo Scientific® TRACE 1310). A drum-type gas meter (Ritter® TG5/1) is implemented to control the flow that enters the devices. With this set-up, both the concentration of hydrogen and the volume flow can be adjusted in order to calibrate the ultrasonic devices.

Results

A preliminary test was performed to verify that the MUTs can operate under natural gas and pure hydrogen. The exposure to both gases was well withstood by both types of sensors, CMUT and L-CMUT. Figure 2 shows a representative measurement of the time of flight in a pilot L-CMUT set-up (a measurement chamber with 10 cm side length) under natural gas and hydrogen. It is evident how the speed of sound was increased when hydrogen was introduced. The results of the calibration under controlled conditions will be presented in the full version of this article.

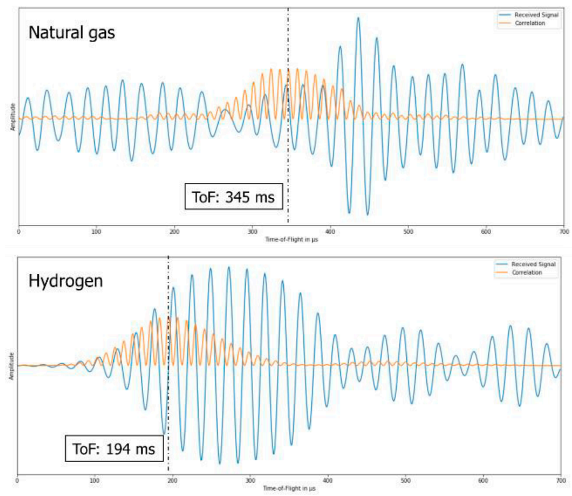

Fig. 2. Preliminary test with the L-CMUT transducers exposed to natural gas and hydrogen, observing a clear reduction of the time of flight.

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