Measurement 95 (2017) 210–215

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Use of the thermal wave method for measuring the flow velocity of air and carbon dioxide mixture

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ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form 7 October 2016
Accepted 7 October 2016
Available online 10 October 2016

Keywords:
Anemometer
Thermal waves
Time of flight
Flow velocity
Carbon dioxide

ABSTRACT

In the paper the use of the thermal wave method for measuring flow velocity of air and carbon dioxide mixture is described. The research was conducted using a moving probe, placed in a closed chamber. A parallel configuration of the transmitter-detector configuration, with two wave detectors, was applied. A rectangular wave of 4 Hz frequency was generated. By the use of the Fourier transform, the velocity of signals from the wave detectors was determined. Results for velocity of 10–50 cm/s and carbon dioxide concentration up to 50% are shown in the paper.

1. Introduction

Measurements of the flow velocity by the use of classical thermal anemometry methods require prior calibration of the sensor. Calibration is necessary for each gas, of which the flow is to be measured because heat transfer from the heated element, which is an indicator of the flow velocity, depends on the type of gas. This limits the use of these methods for measurements in gas mixtures, especially when the composition of the flowing gas is unknown or variable during the measurement. The thermal wave method, in simplification, is based on the measurement of the time of flight of a thermal signal at a given distance along the direction of the flow. The idea of using thermal waves to measure the flow velocity has been known since described by Kovasznay in his early works [1]. Then Walker and Westenberg [2] presented an absolute method of measuring gas flow velocity, by the use of a set with a sinusoidal thermal wave. Later, Bauer [3] and Bradbury with Castro [4] used waves with a short-pulse energized source for measurement. To date, various constructions of gas flow-meters have been presented, based on the phenomenon of thermal waves. They were designed for automotive engineering [5], the mining industry [6], and medical measurements [7,8]. More recently, a field of research has developed into the use of the thermal-wave method in integrated sensors for the measurement of micro- and nano-flows [9–11].

Propagation of a thermal wave in flowing gas is based on two phenomena: forced convection, and heat diffusion. In conditions where convection is a dominant factor, the influence of diffusion on velocity of the wave propagation can be neglected and velocity of the thermal wave is almost equal to velocity of the flow. This allows absolute measurement of the flow velocity, which means that the method is insensitive to changes of parameters in the flowing gas, and hence its composition. For very low flow velocities (for air below 30 cm/s) the influence of thermal diffusion on the velocity of thermal wave propagation cannot be neglected. This is why anemometers and flow-meters based on the thermal wave phenomenon must be calibrated. This limits their use to measuring the flows of gases, for which they have been calibrated. The postulated [12] model of the phenomenon of thermal wave propagation in a flowing gas allows the determination of flow velocity on the basis of the measured thermal wave velocity, taking into account the phenomenon of thermal diffusion. In the studies, a mixture of air and carbon dioxide was used. The thermal diffusivity of carbon dioxide is, according to the literature, far lower than that of air.

2. The idea of the method

The starting point for any consideration of the phenomenon of thermal wave propagation in flowing gas is the energy conservation equation:

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http://dx.doi.org/10.1016/j.measurement.2016.10.019
0263-2241/

Nomenclature

c	specific heat of gas	V_G	flow velocity
j	imaginary unit	V_T	thermal wave velocity
t	time	$\Delta\varphi$	phase shift
x	spatial coordinate	ρ	gas density
Q	intensity of heat source	κ	thermal diffusivity of the gas
T	gas temperature	ω	angular frequency of the wave
Δx	distance between detectors		

$$\frac{\partial T}{\partial t} = \mathbf{div}(\kappa \mathbf{grad} T) - V_G \frac{\partial T}{\partial x} + \frac{Q(t)}{\rho c} \tag{1}$$

Solving the above equation analytically, for a spatial configuration of transmitter and detectors in the flow, shown in Fig. 1, the following expression has been obtained for a wave phase shift between two detectors [12]:

$$\Delta\varphi(\Delta x, \omega, \kappa, V_G) = \frac{V_G \Delta x}{2\kappa} \sqrt{\frac{1}{2}\left(\sqrt{1 + \frac{16\kappa^2\omega^2}{V_G^4}} - 1\right)}. \tag{2}$$

A sketch of this solution was also placed in the work [13]. From the above, the following relationship between thermal wave velocity and gas flow velocity can be obtained:

$$V_T = V_G \sqrt{\frac{1}{2}\left(\sqrt{1 + \frac{16\kappa^2\omega^2}{V_G^4}} + 1\right)}. \tag{3}$$

This shows that wave velocity in flowing gas is always higher than flow velocity. Moreover, the thermal waves show dispersion. Analysis of the dimensionless term $16\,\kappa^2\omega^2 V_G^{-4}$, shows that for low flow velocity the difference between V_T and V_G may be significant. If the following inequality is fulfilled:

$$\frac{16\kappa^2\omega^2}{V_G^4} \ll 1, \tag{4}$$

by means of elementary transformations, we get:

$$V_G = \frac{\omega \Delta x}{\Delta\varphi} = V_T \tag{5}$$

This means that gas flow velocity is almost equal to the velocity of the thermal wave. When the relationship is not fulfilled, flow velocity can be determined by the relationship (2) between phase shift and frequency [14]. This requires use of some waves of different frequencies in measurement. Eq. (1) is linear, thus to determine the velocity, phase shifts of harmonics can be used. In this way, we obtain a system of equations with two unknown values – gas velocity V_G and thermal diffusivity κ:

$$\Delta\varphi_i(\Delta x, \omega_i, \kappa, V_G) = \frac{V_G \Delta x}{2\kappa} \sqrt{\frac{1}{2}\left(\sqrt{1 + \frac{16\kappa^2\omega_i^2}{V_G^4}} - 1\right)}, \tag{6}$$

where $\Delta\varphi_i$ is the measured phase shift of the harmonic component of frequency ω_i. Solving a system of Eq. (6), we determine at the same time the flow velocity V_G and thermal diffusivity κ.

In this regard, it does not matter whether the diffusivity changed due to a temperature change or due to the gas composition, or in any other way. Obviously, diffusivity should be constant during measurement, and hence also the gas temperature. Thus, the method of determining velocity is not sensitive to gas thermal diffusivity changes and, consequently, those determine thermal diffusivity. Because the system can be indeterminate (due to the inaccuracy of phase measurement), it should be solved numerically by the nonlinear estimation method. The presented solution (2) of Eq. (1) assumes sinusoidal wave excitation i.e. $Q(t) = Q_0 \exp(-j\omega t)$. Because of the assumption of constant diffusivity κ the equation becomes linear, therefore above considerations are valid also for the harmonic of any signal. In the paper [15], the measured phase shifts were compared for single sinusoidal and rectangular waves of different frequencies. As stated, the phase shift of the first harmonic is the same for the sinusoidal as well as for the rectangular signal. The presented theoretical model takes into account the influence of thermal diffusion on wave velocity correctly. Velocity of a thermal wave is often assumed to be the sum of wave diffusive velocity (velocity in the absence of the flow) and velocity of lifting (equals to flow velocity) [16,17]. The assumption is not justifiable theoretically. Moreover, analysis of the solution, presented in that work, shows that it is not true for a sinusoidal wave.

An important issue in the measurement of very low velocities is the proper definition of the time of flight. When we measure velocity in the range where the dominant phenomenon is convective lifting of the wave, then the way of defining the time of flight is mostly dictated by the wave type and convenience in the calculations. Applied methods are: cross-correlation of the signals [18], point of crossing with time axis "interception point" [4,7], the position of the signal maximum [4]. The first method "loses" information about thermal diffusivity and calibration of the instrument is essential. Method of cross point for very low velocities, when the signal is very fuzzy, is not precise enough. Because, as is well known, dispersion of the thermal wave occurs, meaning that the shift obtained by the use of correlation depends on the frequency and spectral composition of the applied signal. Velocities obtained by this method can differ significantly from the real velocity [14]. Application of the signal's Fourier analysis provides additional information about the process of wave propagation and increases the accuracy of measurement [14].

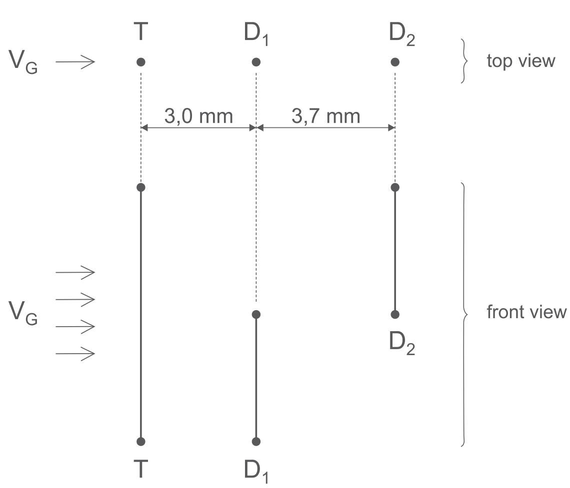

Fig. 1. Spatial orientation of the transmitter and detectors in the flowing gas.