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Calibration-Free Volume Flow Measurement Principle Based on Thermal Time-of-Flight (TToF)

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Abstract

For measurement problems with unknown fluids a new calibration-free volume flow measurement technique is developed. This measurement technique includes a discontinuous heat source associated with a minimum of two thermal sensors arranged downstream. The heat source is used to generate a signal code [dT/dt] by injection of local thermal pulses into the flow line. The thermal sensors detect the time-dependent thermal gradients in the fluid at different positions. Herewith, the measurement technique aims at the determination of the flow velocity by ToF, with the particular advantage of applying to measurements of any fluids with unknown properties. The volume flow is determined by integrating the flow profile.

Keywords: Volume flow measurement, Thermal Time of Filght (TToF), signal processing, correlation technique

1. Introduction

The use of mass and volume flow measurement techniques is essential in industries for process control purposes. In recent years several different types of sensors were developed. Depending on the specifications, for example metering precision, flow ratio, permitted decrease of pressure and also for the cost of production, different measurement principles are applied. The utilisation of these measurement systems is dependent on pressure, in the majority of cases temperature, density, viscosity and homogeneity of the fluid. At present, conventional flow sensors are restricted to the flowing medium that they are calibrated for.

Thermal flow sensors are commonly used due to their low cost and simplicity. Their measurement method is currently based on detecting the heat displacement from a permanently heating element in dependence of the velocity of the passing fluid with known properties. Furthermore, ToF correlation flow

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sensors are already used for optic, acoustic and capacitive flow measurement techniques. A problematical fact is that the measurement pattern formed by particular signifiers changes between the flow sections.

Hence, sensors cannot sufficiently measure fluids with unknown properties. Therefore, a new calibration-free volume flow measurement technique is developed. This measurement technique is applicable to any kind of fluid.

2. Methods & Materials

The proposed measurement technique is based on the ToF of thermal signals [d*T*/d*t*] due to forced convection. For this purpose a minimum of two thermal sinks (e. g. thermocouples) for the sensor is required. The thermocouples detect temperature over time. The time delay of the thermal signals and the distance of the thermal sinks yield the velocity of the flowing medium. Should temperature gradients as natural signals in the flow stream not be inherent in the medium, a signal generator is to be applied. The generated heat signal could be e. g. sinus, rectangle, PN-sequence or triangle shape. For the following investigation a sequence of rectangle pulses of 50 ms duration is applied.

2.1. Experimental Setups

The experimental setups were realised by a conveyer for the respective flowing medium (air & water), a reference flow sensor (hot-wire anemometer / magnetic-inductive flowmeter) and a specifically constructed sensor consisting of a filament to generate the necessary discontinuous heat pulses and three thermocouples type K ($\O = 50$ µm) arranged downstream. Considering the pipe's diameter, the filament and the thermocouples are vertically plugged into the middle of the pipe. The thermal signals are sampled at a frequency of $f = 800$ Hz with a resolution of $\Delta T = 0.0005$ K.

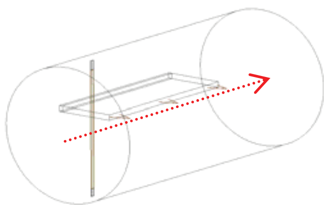

Fig. 1: Sensor model for gas with a filament (Fi) and three thermocouples (TC). Red dotted line is the velocity vector of the flowing medium which has to be detected out of the laminar flow profile.

2.2. Signal Processing

Due to the construction of the thermocouples as closed loops, the detected thermal signals are influenced by diffusive effects. These are on the one hand produced by thermal and electrical noise and on the other hand by undesired electrical signals. Therefore a Chebyshev-filter with the order $n = 3$ and a cut-off frequency $\omega_0 = 0.8$ is used. The sampling value is 80 [8]. For the signal filtering the Chebychev-filter is selected because of its steep edge behaviour of a specific cut-off-frequency [1]. For observing a time delay by signal processing the sensor signal needs signal conditioning. Therefore, the signal offset is corrected to zero and normalised. For the calculation of the time delay τ of the thermal signal between the signal sinks (thermocouples) cross-correlation techniques are used. Correlating the first output signal $x_{T1}(t)$ with both, the second $x_{T2}(t)$ and the third $x_{T3}(t)$ signal, two cross-correlation functions $Rx_{T1}x_{T2}(\tau)$ and $Rx_{T1}x_{T3}(\tau)$ are obtained. The time delays τ_{12} and τ_{13} between these signals are determined.

3. Results

The main target of the described investigations consists in the detection and characterisation of the propagation of heat pulses in the flow of air and water at 20 °C temperature. The measured heat pulses at the thermocouples had a temperature range of 0.01 K < ΔT < 4 K. Thereby the thermal and electric noise and the interfering signals were $\Delta T = 0.2$ K.

In the investigation each velocity is measured nine times, values above 60 % of the average velocity were neglected – in most of the cases velocity values > 1 m/s of air flow. The measured range is for air flow $v_{max} = 0.005$ m·s^{-1} – 2.1 m·s^{-1} and for water $v_{max} = 0.006$ m·s^{-1} - 0.65 m·s^{-1}. The calculated velocities (CV) are shown up to a *Reynolds Number* $Re \approx 2300$ (air flow $v_{max} = 1.9$ m/s and water flow $v_{max} = 0.18$ m/s) from where the flow profile is getting instable.

In the experimental setup of testing the air velocity measurement a factory calibrated hot-wire anemometer (h-wa) is used as reference. The continuously measured referenced velocity (RV) is averaged over the measurement period. The measurement precision of the h-wa is as of a velocity of 1 m/s ca 8 %, for velocities down to 0.01 m/s the error of measurement could increase up to 55 %.

The results for air are shown in fig. 3. The velocities v_{12} and v_{13} show a linear behaviour to the RV. The mean precision of repeated measurements is for velocities less than 0.5 m/s 10 % and increases for higher velocities to 25 %. The inaccuracy occurs due to the effect that with higher velocities vortex appear at the filament and thermocouples and disrupt the thermal signal which has to be measured. A second reason of the increasing deviation is the sampling rate of 800 Hz. For higher velocities smaller time steps between the detected values are needed for the cross-correlation.

The results for water are shown in fig. 3. The measured velocities show a high linear behaviour to RV detected by a magnetic-inductive flowmeter. The precision of repeated measurement in this case is up to RV of $v \approx 0.09$ m/s less than 1 %. For velocities up to 0.12 m/s the deviation for MVw_{12} is 6 % and for MVw_{13} it is 18 %. At a velocity of 0.65 m/s the deviation is 25 %. The accuracy remains constant even if there are particles in the flowing media of up to 1 mm.

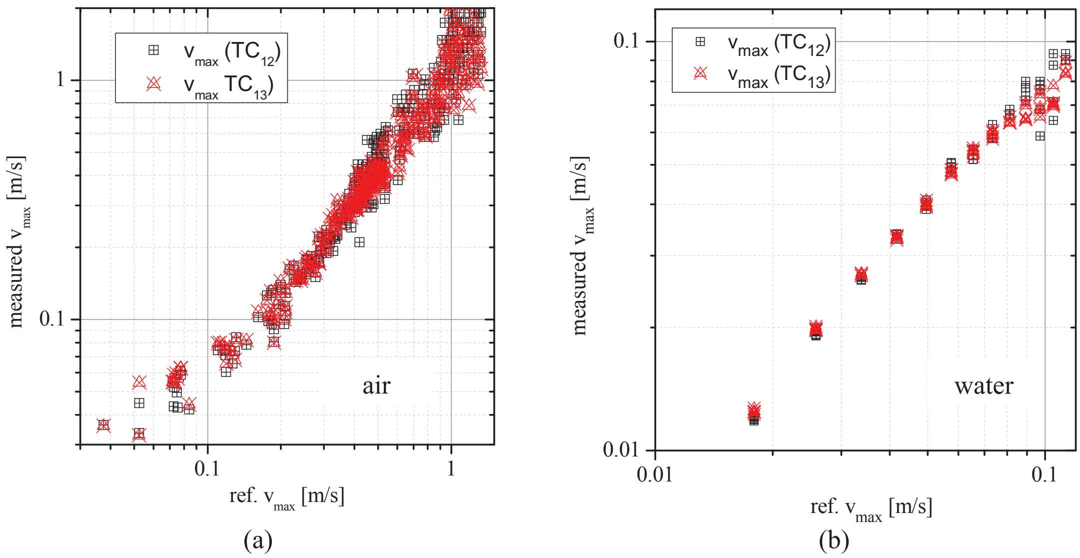

Fig. 2: (a) Measured velocity (MVa) by the signals TC1 – TC2 (black/□) and TC1 – TC3 (red/Δ) in the middle of the pipe for air. (b) Measured velocity (MVw) by the signals TC1 – TC2 (black/□) and TC1 – TC3 (red/Δ) in the middle of the pipe for water.

The measured values shown in fig. 3 deviate at first considerably from the desired values. The values are very stable but only reach 65 % of the reference values. Furthermore, these expected results coincide with previous analysis on the basis of numerical simulations [7].

4. Conclusion

In the present paper, a new technique for volume flow measurement was introduced by the comparisons of flow velocities. With the results outlined in 3. it could be shown that the measurement technique is effectually applied to air and water and in particular it could be expanded to fluids with unknown properties e. g. for gases and liquids as well as for mixtures of gases and liquids and mixtures containing solid additives.

Especially for *Reynolds Number Re* < 2200 in the case of water the precision of repeated measurement is < 1 % and for air < 10 %. This is partly due to the fact that for $Re > 2000$ the signal disappears progressively in noise and interference signals and that signal processing becomes more and more important. In this case mistakes in processing, e. g. inappropriate choice and adjustment of the filter, lead to a drift of the signal centre, which causes up to 100 % deviation from the calculated delay time.

Based on present investigations the measurement technique is object to the following limitations: one sensor distance measurement allows a velocity determination in a range of 1 : 100 and dissolution is limited for velocities similar to the propagation of the natural convection ($v \approx 0.02$ m•s-1).

Future investigations will firstly lead to an enhanced sensor construction design to measure the designated velocity vector in the flow profile. Secondly, they will focus on pre-processing especially for $Re > 2000$. Finally, further analysis of the decay behaviour of the thermal signals will be done via investigations on the time constant $\tau = cp \cdot \lambda$ to draw conclusions from the flowing media.

Acknowledgements

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