The effect of temperature gradients on ultrasonic flow measurement

Problem formulation for ESGI – 2005

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Background

Siemens Flow Instruments (SFI) develops and produces three types of instruments for flow measurement: Magnetic flow-meters, Ultrasonic flow-meters and Coriolis-force flow-meters. This problem relates to the Ultrasonic flow meters.
An ultrasonic flow meter measures liquid flow velocity by sending ultrasonic sound signals up- and downstream through the flowing medium and measuring the difference in travel-time between the two directions. An ultrasonic flow meter often employs two sets of ultrasonic transducers, with each of the transducers acting both as transmitter and receiver. Figure 1 shows a picture of a cut-open sensor-tube indicating the positions of the transducers and the sound paths.

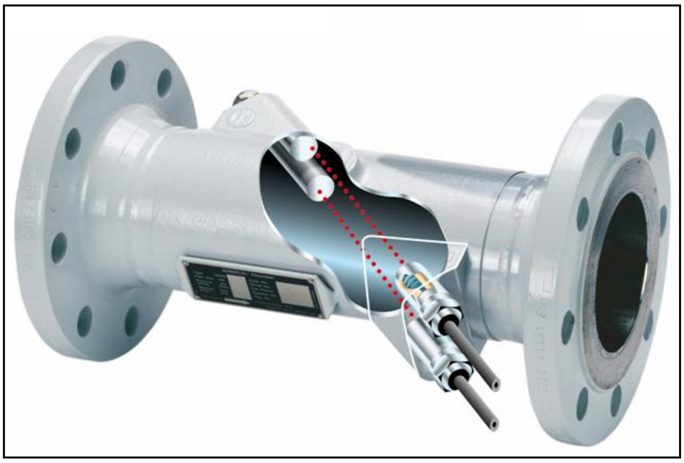

Figure 1: Ultrasonic measurement tube.

The sensors are made in sizes from app. 50mm to 1200mm in diameter and they are used for a variety of liquids and gasses, for pressures up to 40 bars. According to specifications the temperature of the flowing medium may vary within the range -20°C to 200°C. Typically the guaranteed accuracy is in the range of ±2%. The flow velocity ranges from app. 10 m/s down to app. 10 mm/s.
It has been established that ultrasonic flow meters are influenced by thermal conditions. Physical properties of the flowing medium, such as viscosity and density, are influenced by temperature, and temperature gradients will thus influence the flow pattern, the question is exactly how. In order to get a clearer picture of the influence from temperature gradients SFI would like to pose the question of how the meter accuracy is influenced by a radial and longitudinal temperature gradient caused by a temperature difference between the flowing medium and the surroundings. This is a very relevant and important question to answer since the specifications allow temperature differences in the range of 200K between the ambient and the flowing medium.

Theory

The principal working of the ultrasonic flow-meter is simple. Sound signals are generated by a set of pizo-acoustic elements and sent in opposite directions with and against the flow direction. The difference in travel time between the two signals is used to determine the flow velocity ($v_{measured}$):

$$v_{measured} = \frac{L}{2}\left[\frac{1}{\Delta t_{down}} - \frac{1}{\Delta t_{up}}\right]$$

With L being the distance between the transducers, and Δt_{up} and Δt_{down} are the up- and down stream travel times. Figure 2 shows a sketch of the measurement principle.

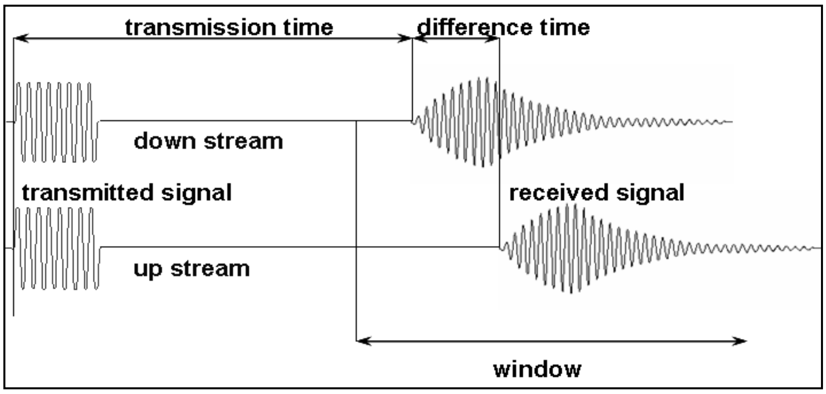

Figure 2: Flow velocity measurement.

Figure 3 shows a sketch of the flow meter. The sensors are placed at a certain distance Y* from the center plane in order to produce a measurement result which is the closest possible representation of the average velocity ($v_{average}$).

$$v_{average} = \frac{Q}{A} = \frac{1}{A}\int_A v\,dA$$

With Q being the volume flow rate and A is the cross section area of the tube. The flow velocity profile will change with average flow velocity and it is not possible to obtain an exact measurement of the average velocity over the entire velocity range, a linearity error will be present:

$$error = \frac{v_{measured}}{v_{average}} - 1$$

The linearity error is measured for each sensor before leaving the factory. When no temperature gradients are present the media viscosity can be assumed constant and the flow velocity profile may be derived from Navier-Stokes equation for constant viscosity. The presence of a temperature gradient will destroy the ideal situation because the liquid properties will become a function of position. Because of this, an error is introduced but its size and variation with flow velocity is so far not clear.

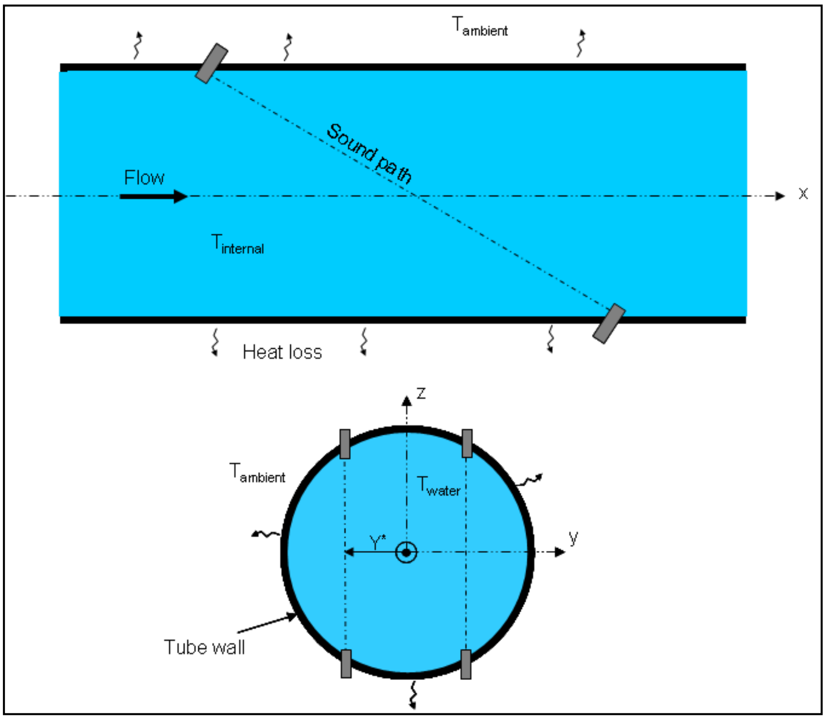

Figure 3: Sketch of the flow meter.

Problem formulation

It seems appropriate to start with an analysis of the relatively simple situation where no temperature gradients are present and then afterwards try to implement them, this will give a clearer picture of the differences between the two situations.

$T_{internal} \cong T_{ambient}$

At first, axis-symmetric fully developed flow is assumed and temperature effects are ignored.

$$v = v(r) \qquad \frac{\partial v_x}{\partial x} = 0 \qquad \mu = const.$$

- Deduct the expressions for the flow velocity profiles, for fully developed flow in tubes, in both the laminar and the turbulent case - or even better, a general expression for both cases.

- Determine if there is an optimum radial position Y^* in which the relative axial flow velocity (v/v_{av}) does not change with average velocity and find an expression for this.

- Find an expression for the sensor linearity error in the optimum point.

$T_{internal} \neq T_{ambient}$

The temperature of the flowing medium is different form the ambient temperature and heat is exchanged with the surroundings. The viscosity and density of the media can no longer be assumed invariant and the flow profile can therefore no longer be assumed fully developed and probably not axis-symmetric.

$$v \neq v(r) \qquad \frac{\partial v_x}{\partial x} \neq 0 \qquad \mu \neq const.$$

- Is it possible to derive an exact or nearly exact, analytical expression for the flow velocity profile when radial and longitudinal temperature variations are present?
- Derive an expression for the temperature distribution in the tube, in both radial and longitudinal directions.
- Use this to estimate the linearity error introduced to the measurement by the radial and longitudinal temperature gradients.

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