Modelling Thermal Time-of-Flight Sensor for Flow Velocity Measurement

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Abstract:

This communication reports on a numeric fluid dynamics simulation on a pipe flow model. The basic background is to determine the velocity of a flowing fluid in a pipe by using the Thermal Time-of-Flight (TTOF) method on water. The visualisation of the temperature and velocity distribution in the pipe model is being carried out in order to enable proper design and optimisation of the TTOF sensor. The work is accomplished in two dimensional and three dimensional simulations. Transient simulations have been realised using the 2D simulation model. The flow velocity is calculated by means of the FFT-correlation technique. At several detection points the time-dependent temperature signal is measured in a time period of ten seconds. The time delay of the output signals combined with the knowledge of the covered distances yields the flow velocity. In this work, a flow measurement technique in the velocity range 0.01 m/s ≤ v_m ≤ 0.1 m/s is presented for water.

Keywords: *FFT-correlation, flow velocity, fluid flow, heat transfer, signal processing, Thermal Time-of-Flight (TTOF)*

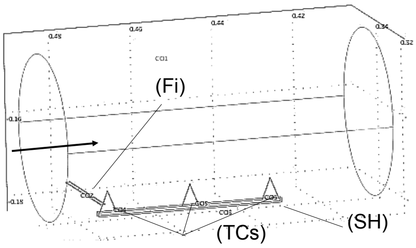

Figure 1: 3D pipe model of flow sensor construc-tion with a filament (Fi) and a sensor holder (SH) including three thermocouples (TC).

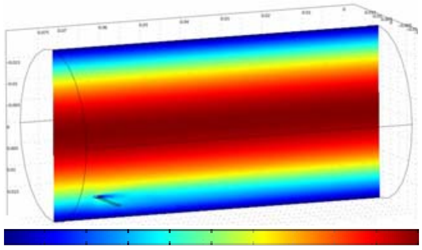

Figure 2: Stationary velocity distribution from 0 to 0.1 m/s (steps 0.01 m/s) of water with a mean velocity of v_m = 0.05 m/s for the 3D pipe model with filament and thermocouples.

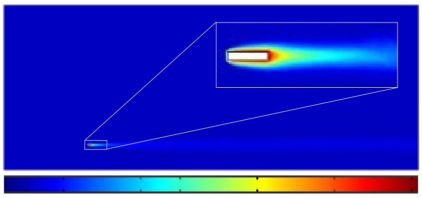

Figure 3: Stationary temperature distribution from 293 K to 303 K (steps 1 K) in the 2D model with a filament.

Introduction:

The present investigation includes a discontinuous heating element offering a measurement technique to determine the flow of any kind of fluid with unknown properties (volume flow measurement). This basic approach is intended to be low-maintenance and exempt from calibration. The Thermal Time-of-Flight (TTOF) principle based on the induction of mobile heat pulses in the flow of gases and liquids is the key point of the investigations.

Methods:

For the simulation of the TTOF sensor models (**Figure 1**) three basic equations are applied.

Fluid Mechanics

$$\rho\frac{\partial \boldsymbol{u}}{\partial t}+\rho\cdot\boldsymbol{u}\cdot\nabla\boldsymbol{u}-\boldsymbol{F}=\nabla\cdot\left[-p\mathbf{I}+\eta(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^{T})\right]$$
$$\nabla\boldsymbol{u}=0$$

F body force term [N·m^{-3}], ρ density [kg·m^{-3}], v velocity [m·s^{-1}], η dynamic viscosity [N·s·m^{-2}] and *p* pressure [N·m^{-2}]

Heat Transfer

$$\rho\cdot c_p\frac{\partial T}{\partial t}+\nabla\cdot\left(-\lambda\nabla T\right)=Q-\rho\cdot c_p\cdot\boldsymbol{u}\cdot\nabla T$$

T temperature [K], λ spec. thermal conductivity [W·m^{-1}·K^{-1}], c_p spec. heat capacity [J·kg^{-1}·K^{-1}] and *Q* heat source [W·m^{-3}]

Joule Heating

$$-\nabla\cdot(\sigma\nabla V-J^{e})=Q_j$$

σ electrical conductivity [m^{-1}·W^{-1}], *V* electrical potential [V], J_e external current density [A·m^{-2}], Q_j current source [A·m^{-3}]

Parameter settings at different modes

Modes	Subdomain Settings	Boundary Settings
Incom. Navier-Stokes	-material library : *fluid type*	- inlet: *velocity, entrance length*
Convection and Conduction	-material library : *fluid type* -velocity field: *(u v w)* -init value: *temp.*	-inlet: *temperature* -filament: *temperature* -outlet: *convective flux*
Conductive Media DC	-material library : *filament type* -init value: *electric potential*	boundary condition: *-ground* *-electric insulation* *-electric potential*

Results:

The flow behind the filament streams in its original homogenous state in a distance of Δz = 3 mm. The temperature signals (ΔT = 0.2 K) can be measured downstream on the heat flow level of the filament to obtain the mean flow velocity.

The transient simulations applying on the 2D model are accomplished in a simulation time range of ten seconds. During this simulation time a short heat pulse with duration of Δt_P = 0.5 s is generated. The temperature signals are detected at five different points along the level of the filament in direction of the flow.

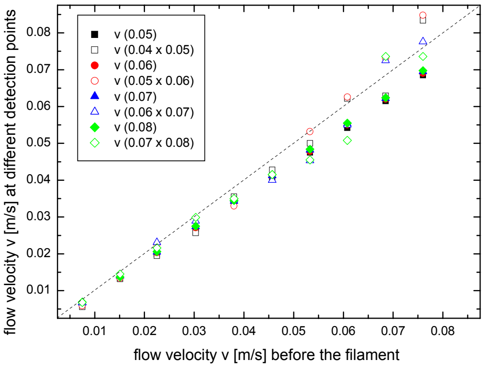

Figure 4 shows a comparison of the actual mean flow velocity detected before (abscissa) the filament and at the detection points behind (ordinate) the filament as well as the calcula-ted (FFT) mean flow velocity. The detection points are located from z = 0.04 m to z = 0.08 m every 0.01 m.

Discussion and Conclusion:

In the simulations the behaviour of the flow velocity v and the temperature T are clearly presented (**Figure 2** and **Figure 3**). The flow velocity is regained within the subsequent 3 mm behind the filament. A decay of the temperature of 2 % is observed. The remaining energy is sufficient to be detected by TCs.

The results demonstrated in **Figure 4**, are calculated from the transient solved 2D model. This model is based on a previously stationary solved model. The values for the actual velocities result from the stationary model. Obviously the calculated velocities from the transient simulation do not match with the actual velocities from the stationary simulation.

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Acknowledgements: This project is supported by “Deutsche Forschungsgemeinschaft”.