Excerpt from the Proceedings of the 2011 COMSOL Conference in Stuttgart

# Thermo-Fluidic Impulse Response and TOF Analysis of a Pulsed Hot Wire

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**Abstract:** In this work the authors report on a CFD simulation of a pipe flow model. Fluid mechanics are here combined with heat transfer phenomena. In order to create a mathematical model of a pulsed hot wire system i.e., the thermo-fluidic impulse response of a pulsed hot wire, a simulation model is analyzed which describes the impulse response according to the physics from thermodynamics. The thermo-fluidic impulse response is characterized by the heat transfer parameters. These heat transfer parameters are investigated for several fluids as well as for different flow velocities. Moreover, the thermal Time-of-Flight (TOF) analysis for different fluids is accomplished. The basic concept is to measure a flow velocity mainly by convective heat transfer applying the thermal TOF method.

**Keywords:** pulsed hot wire, thermal flow meter, thermo-fluidic impulse response, Time-of-Flight (TOF)

## 1. Introduction

Flow meters are widely employed in several industrial, automotive and medical areas primarily for controlling the volumetric or mass pipe flow rates of fluids i.e., gases and liquids, for various purposes. Different flow measurement principles are considered, since the amount of flow of a certain fluid influences many other relevant process parameters such as temperature, level, pressure, chemical composition and dose, depending on the velocity range and the fluid characteristics like viscosity, density, electrical conductivity etc. [1].

Recently, the authors have been conducting research on the realm of flow sensor modeling with the thermal TOF method [2] [3] [4] [5]. In particular, the pulsed thermal TOF method deploys the measurement concept of injecting a heat pulse by means of a pulsed hot wire into the flowing fluid. The electric signal applied at the pulsed hot wire system is treated as the system's input signal. The heat pulse is carried along the fluid by two main heat transfer forms i.e., heat convection and heat diffusion, and detected not only by time after a certain TOF but also by space at a certain flight distance with respect to the pulse generation point. One or more thermal sensors can be positioned downstream to sense the heat pulses from the heat flow and to measure the thermal time variable signals, which are treated as the system's output signals.

Regarding the flight distance of the heat pulse from its generation point to its detection point in this specific pipe area (region of interest, ROI) as an LTI-system, the input and output signals are described as conventional time-dependent signals [2] [3]. The aim is the analysis of the pulsed hot wire in several surrounding fluids and their TOF, regarded as a thermo-fluidic system.

For the measurements of flow velocity by means of a pulsed thermal method a hot wire is included into the flow. The flow sensor consists of a pulsed-wire and temperature sensors and is based accordingly on the pulsed thermal TOF principle.

## 2. Governing Equations

In this section the required equations are presented for the purposed pipe flow model. The basic equations of fluid mechanics, heat transfer and electric fields are applied to the simulation of the thermal TOF flow sensor. These will be described in the following part considering laminar flow and joule heating phenomena. In addition to the equations the material parameters will be described.

### 2.1 Laminar Flow

For simulating a fluid flow in a pipe Navier-Stokes equations from fluid mechanics are used. The fluid flow can be described by the conservation of momentum employing the Laminar Flow mode (spf) from the CFD Module of COMSOL Multiphysics:

$$\rho\frac{\partial \boldsymbol{u}}{\partial t}+\rho\cdot\boldsymbol{u}\cdot\nabla\boldsymbol{u}-\boldsymbol{F} = \nabla\cdot\left[-p\mathbf{I}+\eta(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^{T})\right] \quad (1)$$

$$\nabla \boldsymbol{u} = 0\,, \tag{2}$$

where $\boldsymbol{F}$ is the volume force vector [N/m$^3$], $\rho$ the density of the fluid [kg/m$^3$], $\boldsymbol{u}$ the velocity [m/s], $\eta$ the dynamic viscosity of the fluid [Pa·s] and $p$ the pressure [Pa]. In equation (1) the first two terms on the left side describe the inertia of the investigated volume, $\boldsymbol{F}$ is the external affected forces, $p \cdot \boldsymbol{I}$ describes the pressure at the volume in all directions and the last term is the friction. Equation (2) gives the boundary condition by constant or nearly constant density $\rho$ like in the case for all fluids.

### 2.2 Joule Heating

The transport and dispersion of the generated heat pulse result from a combination of forced convection and diffusion. The general heat transfer equation yields under the consideration of heat convection and heat diffusion:

$$\rho \cdot c_p \frac{\partial T}{\partial t} + \nabla \cdot \left(-\lambda \nabla T\right) = Q - \rho \cdot c_p \cdot \boldsymbol{u} \cdot \nabla T\,, \tag{3}$$

with $T$ as the temperature [K], $\lambda$ as the thermal conductivity [W/(m·K)], $c_p$ as the specific heat capacity of the fluid at constant pressure [J/(kg·K)] and $Q$ as the heat source [W/m]. Equation (3) characterizes the conservation of energy. Here, the first term on the left side is the internal energy of a specified volume, the second describes the thermal diffusion, $Q$ specifies the local heat sources and the last term on the right side describes the thermal convection. In COMSOL Multiphysics the Joule Heating mode (jh) from the COMSOL Multiphysics Module is adopted.

The Electric Currents mode, which is involved in the Joule Heating mode (jh) from the COMSOL Multiphysics Module, allows the effect of Joule heating in a filament whereby electrical energy is converted to thermal energy. Equation (4) describes the reaction of voltage at the ends of a filament to a temperature on the surface. The equation is given by:

$$-\nabla \cdot (\sigma \nabla V - J^e) = Q_j\,, \tag{4}$$

where $\sigma$ is the electrical conductivity [1/(m·Ω)], $V$ the electrical potential [V], $J_e$ the externally generated current density [A/m], and $Q_j$ the current source [A/m]. The conductivity is described in equation (5) as:

$$\sigma = \frac{1}{\rho_0 (1 + \alpha_0 (T - T_0))}\,, \tag{5}$$

with $\rho_0$ as the electrical resistivity [m·Ω] at the reference temperature $T_0$ [K], and $\alpha_0$ as the temperature coefficient of resistivity [1/K].

### 2.3 Material Parameters

In the numeric simulation model four fluids namely air, helium, oil and water have been investigated. The thermodynamic and fluidic parameters are given in Table 1 for a temperature of 293.15 K with the nondimensional Prandtl number Pr, kinematic viscosity $\nu$ [m²/s], thermal diffusivity $\alpha$ [m²/s], specific heat capacity $c_p$ [kJ/(kg·K)], density $\rho$ [kg/m³] and thermal conductivity $\lambda$ [W/(m·K)].

**Table 1:** thermodynamic and fluidic parameters of the investigated fluids.

| | helium | air | water | oil |
|---|---|---|---|---|
| Pr | 0.6865 | 0.7081 | 6.991 | 10243 |
| $\nu$ | 1.14e-4 | 1.53e-5 | 1e-6 | 8.9e-4 |
| $\alpha$ | 1.59e-4 | 2.16e-5 | 1.44e-7 | 8.7e-8 |
| $c_p$ | 5.193 | 1.0064 | 4.185 | 1.88 |
| $\rho$ | 0.1758 | 1.1885 | 998.21 | 887.6 |
| $\lambda$ | 0.1513 | 2.59e-2 | 6e-1 | 0.145 |

### 3. Numerical Model

Initially, the pipe flow models are described in this section. The alignments of subdomain and boundary conditions applying to COMSOL Multiphysics for the pipe flow models are explained afterwards.

### 3.1 Pipe Flow Model

For flow velocity investigations a pipe model has been created with respect to the existing experimental set up of the thermal TOF flow sensor [2] [3]. A 3D stationary solution has been computed in Figure 1 showing the simulated thermal TOF principle corresponding to the experimental setup. The 2D models provide the better possibilities for a good simulation with much less computation efforts. Hence, 2D models have been used for most part of the currrent time-dependent research study.

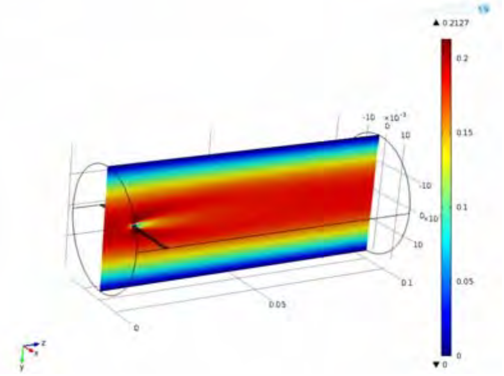

**Figure 1**. 3D velocity distribution for air at a mean flow velocity of $v_{mean} = 0.1$ m/s.

The ROI of the flow model has a length of $l_{ROI} = 0.1$ m and a pipe diameter of $d_{Pipe} = 0.04$ m. A tungsten filament i.e., pulsed hot wire, is placed at 0.01 m in the centerline of the pipe exhibiting a height and a length of $h_{Fi} = 0.2$ mm and $l_{Fi} = 0.8$ mm, respectively. At the ends of the pulsed hot wire, an electrical rectangular pulse has been applied to generate heat pulses. Heat detection is realized by deploying three thermocouples (TC1, TC2 and TC3) modeled through a nickel alloy (Haynes R-41: UNS N07041) with a diameter of $d_{TC} = 50$ µm. The distance between the TC1 and the TC2 is $\Delta x_{12} = 17.5$ mm and between the TC1 and the TC3 is $\Delta x_{13} = 35.5$ mm. One thermocouple is positioned directly at the pulsed hot wire. The thermocouples are arranged downstream into the pipe as shown in Figure 2a and 2b for oil and water, respectively. Water is more flowable as oil due to its much smaller kinematic viscosity and consequently has a lower influence on its flow characteristics than oil.

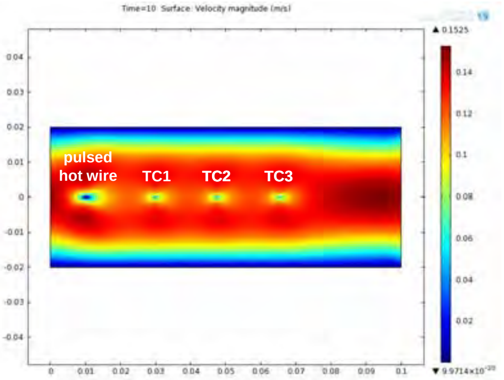

**Figure 2a**. 2D velocity distribution for oil at a mean flow velocity of $v_{mean} = 0.1$ m/s.

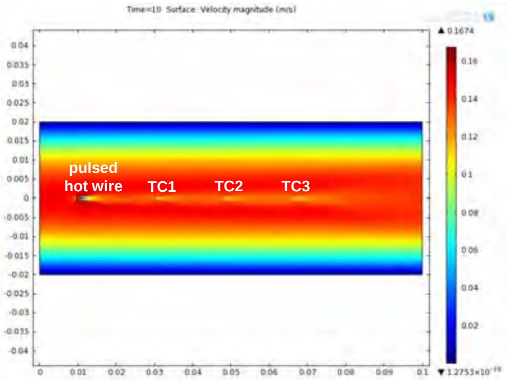

**Figure 2b**. 2D velocity distribution for water at a mean flow velocity of $v_{mean} = 0.1$ m/s.

### 3.2 Use of COMSOL Multiphysics

The Laminar Flow mode (spf) has been applied for study and visualization of fluid dynamics. The Joule Heating mode (jh) is applied for study of the effects of heat transfer and electric currents.

After the creation of the model geometry, materials are assigned to the fluid, the pulsed hot wire and the thermocouples. The Laminar Flow mode is computed first. The inlet and outlet conditions are defined in the boundary settings to an existing laminar inflow and to pressure with no viscous stress, respectively. The mean velocity value, the inflow type, and an entrance length of $l_e = 1$ m to form a laminar flow profile are modified for the inlet boundary. Remaining boundaries are set as wall types including the pulsed hot wire geometry and the pipe wall.

In the Joule Heating mode the initial temperature is set to $T_0 = 293.15$ K. In the boundary settings the initial temperature is assigned to the inlet boundary. The pipe wall boundaries are thermally insulated whereas the boundaries of the pulsed hot wire are electrically insulated. In the boundary settings the ground side and the electrical potential side have to be conditioned as the time-dependent electrical signal has to be determined for generating dynamic thermal pulses.

## 4. Results

This section presents initially the direct comparison between the experimental and simulated results for air. Then, the thermo-fluidic impulse responses of the pulsed wire are outlined for different flow velocities and for different fluids. Thereafter, the TOF analysis is carried out considering likewise different flow velocities and fluids. A discussion of the results is accomplished thereby.

A rectangular function with a pulse width of $\Delta\tau_p$ = 100 ms, a time shift of one second and an amplitude of 0.008 V is applied as an approximate Dirac delta function at the pulsed hot wire. For three mean flow velocities of $v_{mean}$ = 0.23 m/s, $v_{mean}$ = 1.14 m/s and $v_{mean}$ = 1.72 m/s the corresponding three impulse responses at the pulsed hot wire for air from the experiment as well as from the simulation are obtained and depicted in Figure 3a. The normalized temperature is displayed on the one hand to directly compare between experiment and simulation and on the other hand to characterize the fall time behavior of the signals which is mainly described by the flow velocity. It is observed, that the the signal forms from the simulation generally match well with the signal forms obtained from the experiment. The signal form shows an exponential characteristic. The fall time of the thermo-fluidic impulse response is decreasing with increasing mean flow velocity. This fall time is amongst others a function of the Nusselt number [6] [7]. The Nusselt number again is a function of the Reynolds number. Hence, the fall time depends on the flow velocity.

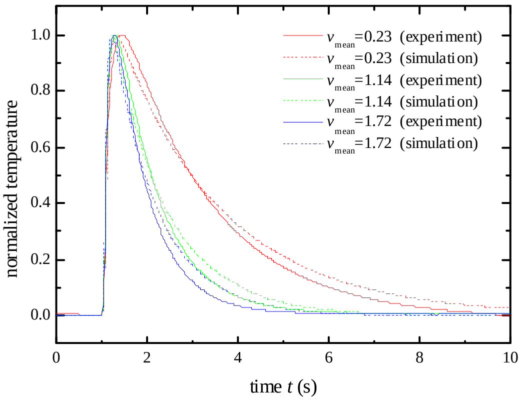

**Figure 3a**. Experimental and simulated thermo-fluidic impulse responses at the pulsed hot wire for air at three mean flow velocities.

In Figure 3b the thermo-fluidic impulse responses at the detection positions TC1 and TC2 for air at a constant mean velocity of $v_{mean}$ = 0.23 m/s are illustrated. The output signals TC1 and TC2 from the experiment show a slight time shift and additionally a higher rise time in comparison with the simulation. Due to the experimental arrangement of the thermocouples onto a sensor holder the velocity behavior is more influenced than in the simulation. Therefore, a time shift occurs and is caused through a deceleration of the propagating heat pulse in the experiment.

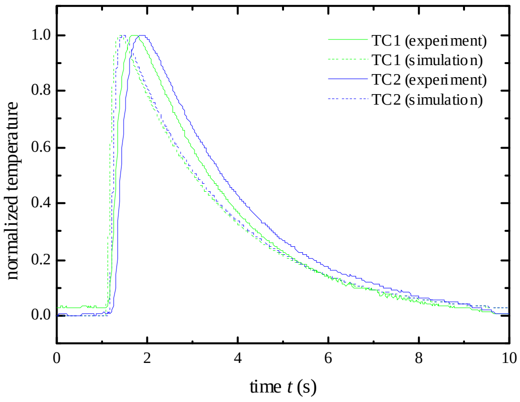

**Figure 3b**. Experimental and simulated thermo-fluidic impulse responses at the detection positions of TC1 and TC2 for air at a mean flow velocity of $v_{mean}$ = 0.23 m/s.

Once the results of the 2D simulation model for the pulsed hot wire in a pipe flow has been verified with the experimental results concerning air, this simulation model has been adopted for three further fluids i.e., helium, water and oil. Figure 4a depicts the thermo-fluidic impulse responses of the pulsed hot wire for water at different mean flow velocities. Because of its smaller thermal diffusivity $\alpha_{,water}$ the pulse widths are smaller than for air. With decreasing flow velocity the Peclet number, as the ratio of heat convection to heat diffusion, of water is descreasing as well which causes an increase of the heat diffusion part.

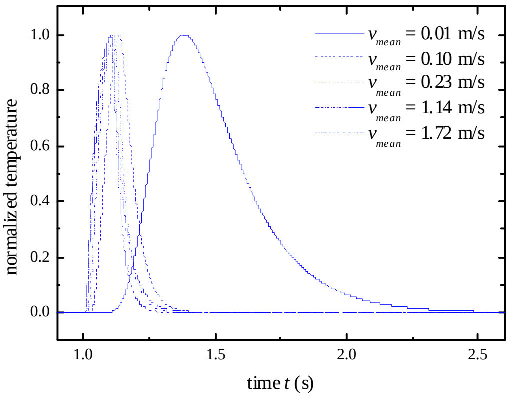

**Figure 4a**. Simulated thermo-fluidic impulse responses at the pulsed hot wire for water at different mean flow velocities.

The thermo-fluidic impulse responses of the pulsed hot wire are pictured for different fluids in Figure 4b. Since the four fluids show different Nusselt numbers, the thermal interaction between the pulsed hot wire and the surrounding fluid varies due to heat convection. Air has the greatest fall time of about three seconds compared with the other fluids. The fall time behavior agrees with the theoretical considerations of the pulsed wire principle [6] [7].

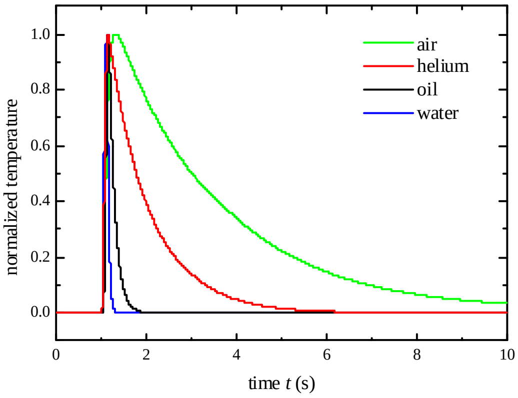

**Figure 4b**. Simulated thermo-fluidic impulse responses at the pulsed hot wire for different fluids at a mean flow velocity of $v_{mean}$ = 0.23 m/s.

In Figure 5a the TOFs are investigated for air and helium at different Peclet numbers. Each TOF is evaluated by the same crosscorrelation method of the thermo-fluidic signal output at TC1 with the signal output at TC2. For small Peclet numbers the TOF distinguishes even at the same simulated flow velocity. Since heat diffusion cannot be fully neglected for small Peclet numbers, it has an impact on the thermo-fluidic signal. Besides, the thermo-fluidic signal is characterized by thermal diffusivity. The more the heat diffusion is existing, the more the thermal diffusivity will influence the thermo-fluidic signal's local maximum which is the eminent indication calculating the proper TOF by correlation technique.

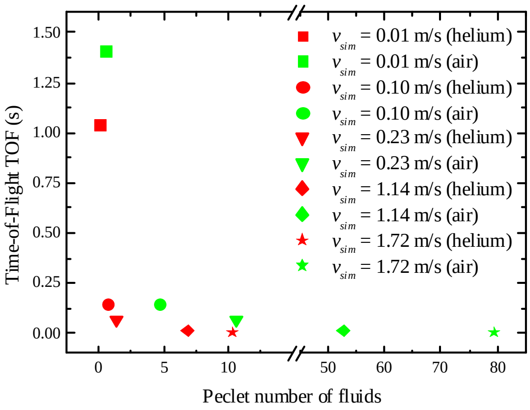

**Figure 5a**. TOF as a function of the Peclet number for gases.

Similar observations considering the TOFs can be made also for liquids like water and oil as shown in Figure 5b. With increasing Peclet number the TOF between these two liquids is more and more alike due to the increase of the heat convection and the heat diffusion ratio.

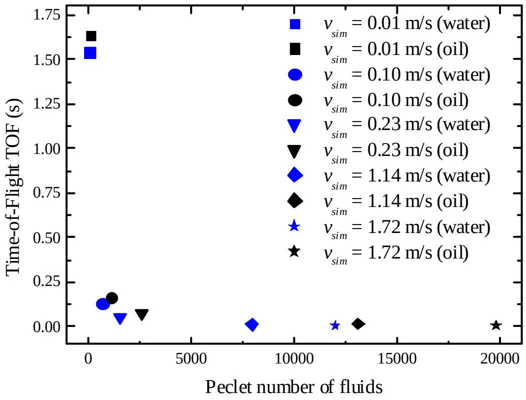

**Figure 5b**. TOF as a function of the Peclet number for liquids.

Figure 6a depicts the comparison of the simulated mean flow velocity with the measured flow velocity for air and helium gained from the TOF of TC1 to TC2 and TC1 to TC3. In this figure, the quads and circles with a cross filled inside represent the mean flow velocity of the simulation, whereas the pure quads and circles describe the maximum flow velocity of the simulation. The dashed line in the diagram shows the ideal velocity curve. The measured velocity values for air and helium are always closer to the mean flow velocity than for the maximum flow velocity. There is no major difference between these two fluids observed, since their thermodynamic and fluidic parameters are similar. On the contrary, water and oil vary in their flow velocities according to Figure 6b. As shown in Figures 2a and 2b, water is more flowable than oil due to its much smaller kinematic viscosity. However, this causes a different velocity field around the thermocouples and thus different flow velocities at the same detection position. Under the same circumstances oil is slower than water merely because of its fluidic parameters.

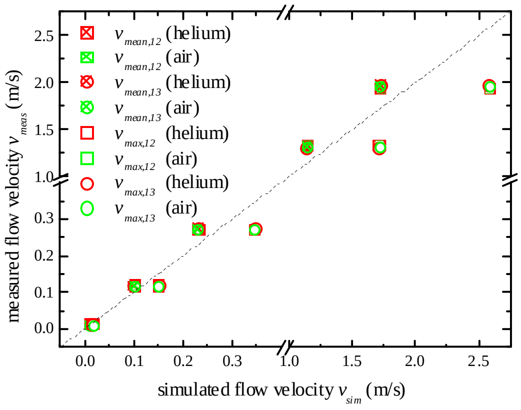

**Figure 6a**. Comparison of the simulated mean flow velocity with the measured flow velocity for gases.

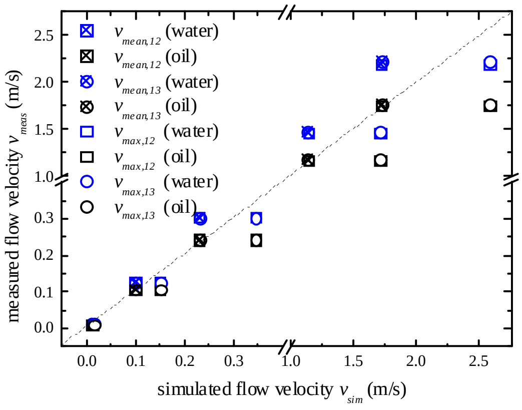

**Figure 6b**. Comparison of the simulated mean flow velocity with the measured flow velocity for liquids.

## 5. Conclusions

Summing up, the thermo-fluidic impulse response of an electrically pulsed hot wire and the TOF behavior in the environment of several fluids has been investigated and discussed in this work. This analysis gives system-theoretical information about the pulsed hot wire system considering the signal parameters with respect to the thermodynamic and fluidic parameters. The importance of the Nusselt number and the Peclet number has been proved respectively for the thermo-fluidic impulse response of the pulsed hot wire and the thermal TOF method. In future work, the thermal TOF analysis is going to be expanded for further temperature and pressure ranges.

## 6. Acknowledgements

This work is supported by the German research association (Deutsche Forschungsgemeinschaft, DFG) and is part of the sponsored project ANTEMES.

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