27/28th International Conference
ENGINEERING MECHANICS 2022
Milovy, Czech Republic, May 9 –12, 2022
Paper **#119**, pp. 357–360, doi: 10.21495/51-2-357

ANALYSIS OF MULTI CONSTANT CURRENT FLOWMETER HEATED ELEMENTS

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Abstract: *This paper deals with the initial analyses in the development of a new generation of Multi Constant Current Flowmeter. It is a specialized measuring instrument combining hot wire anemometers and tomographic evaluation of measured data. The meter is designed especially for the automotive industry for measuring directly on heat exchangers. The presented initial analyses focus on verifying the properties of the existing copper hot wire element and the possibility of replacing it with an element with better functional properties. Analyses include experimental parameter determination, Computational Fluid Dynamics simulations and calculations with use of criterion equation used in hot wire anemometers. The paper briefly presents the applied models and examples of calculated and measured results, which are discussed.*

Keywords: Hot wire anemometry, Multi constant current flowmeter, CFD, Criterion equations.

1. Introduction

Car powertrains have limited efficiency, resulting in residual heat that must be dissipated to the surrounding environment. This requires cooling systems with heat exchangers, usually located in the front of the car. Compared to the design assumptions, the flow around their heat transfer surfaces is strongly influenced by the external aerodynamics of the car, their position in the engine compartment, by the shapes of the grilles, fans and other elements. For this reason, experimental measurements directly on cars are necessary. These measurements are quite complicated because there is very limited space for the installation of measuring probes and gauges.

For these measurements, a unique measuring instrument Multi Constant Current Flowmeter (MCCF) is used, which is based on the principle of a hot wire anemometer with a similar evaluation of the measured data as on a tomograph. The MCCF contains up to several dozen cross-tensioned hot wires that cover the entire flow profile. To ensure increased accuracy, reliability and comfort of use of these meters, the development of their new generation is now underway. The aim is to improve the parameters of hot wire elements, their regulation and control, as well as communication and the entire arrangement of the meter from a technological point of view.

This paper focuses on the initial analysis of the hot wire element. The aim was to examine the properties of the existing copper hot wire and assess the possibility of replacing it with an element with better functional properties. The intention is to increase the sensitivity of the measurement, the life of the element, to limit its thermal expansion and ideally the ability to detect forward and reverse flow. The analyses combined experimental examinations with theoretical calculations – Computational Fluid Dynamics (CFD) and iterative calculations with the application of criterion equations used in hot wire anemometry.

2. Experimental investigation

An experimental test was performed to determine the characteristics and behavior of the copper hot wire elements used. The wire with a diameter of 60 μm was fixed to the supporting frame and supplied with an

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adjustable constant current. Voltage drop on this wire was monitored. The measurement was performed for several selected wire lengths (4, 36 and 82 cm) from the range used in MCCF. The characteristics for the nature cooling, and subsequently in the wind tunnel, at air velocity from 0.5 to 14 m/s were investigated. For nature cooling measurements, the goal was also to determine the maximum currents that the wires can withstand.

The measured values (see Fig. 1) showed a very good sensitivity of the wires at flow velocity up to 5 m/s, where the voltage drop across the wire changes significantly. For higher flow velocities, the sensitivity decreases considerably. This has a more significant effect on short wires, where the overall voltage drop and therefore also its change are lower.

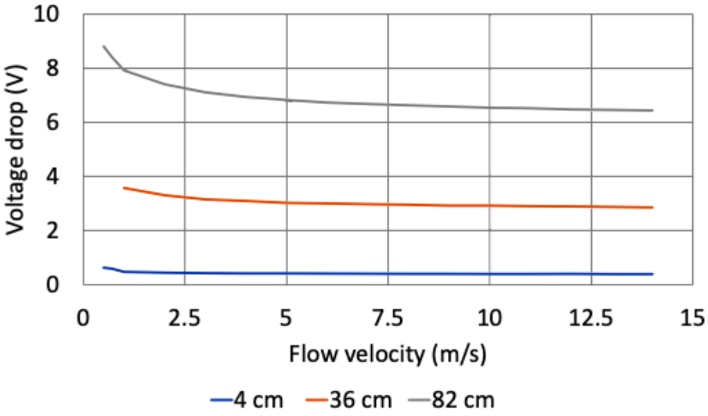

Fig. 1: *Measured voltage drop of the cooper wires used in MCCF in dependency on flow velocity (constant current 1.2 A)*

3. CFD simulations

The copper wire has been simplified to a 2D model for CFD simulations. This made it possible to use a very fine mesh around the wire to handle the heat transfer at the interface well, while maintaining a fast time response of the simulations. The wire profile was placed in a sufficiently large domain so that the flow in the wire area was not affected by boundary conditions. The air velocity and temperature were set on the inlet of the domain and the atmospheric pressure at the outlet. The side edges were considered as symmetries.

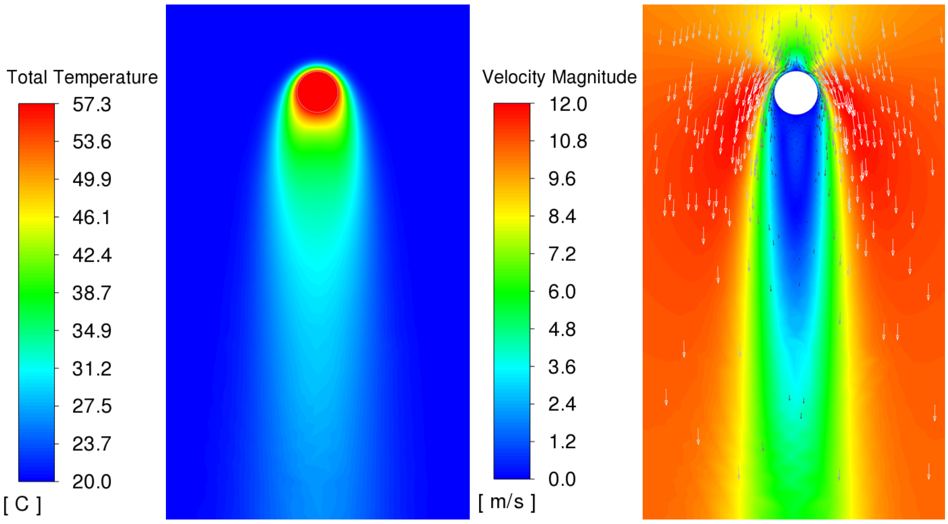

Fig. 2: *Contours of temperature and velocity (with velocity vectors) for hot cooper wire (inlet air velocity 10m/s and temperature 20°C)*

Given the low Reynolds numbers (from 2 to 49), the flow was assumed to be laminar. The air density was considered according to the equation for an incompressible ideal gas. Heat capacity, thermal conductivity and viscosity of air were defined as a function of temperature. An energy source was defined in the volume of copper wire. Its value corresponds to the Joule losses occurring in the conductor when passing a constant current of 1.2 A. The thermal dependence of the resistivity of copper was respected in the energy source calculation. The simulations were performed in relation to the measurement. The input velocities were in the range from 0.7 to 14 m/s and the inlet air temperature 10 °C and 20 °C. Figure 2 shows an example of the computed results: temperature and velocity field for an inlet velocity of 10 m/s.

4. Model based on criterion equation

A simplified zero-dimensional model was created to speed up the response of the calculations. This model allows a very fast comparison of a number of wire dimensions from different materials and for different flow parameters. The results are produced by iterative numerical calculation of the thermal balance of the hot wire in crossflow. The spatial temperature distribution is not solved, neither for the wire nor the surrounding fluid. A steady-state temperature at which the Joule heat generated in the wire dissipated to the surrounding air is searched. Perfect perpendicularity of the crossflow direction to the wire is expected. Constant voltage control is applied, the electric current adjusts to the change in resistivity.

The underlying Matlab script encapsulates all the necessary temperature dependencies of the physical properties of air and the hotwire material. A search for air thermal conductivity k_a (W/(mK)), kinematic viscosity ν (m^2/s) and Pr (-) is conducted, as well as wire electrical resistivity, thermal conductivity k_w (W/(mK)) and linear expansion coefficient α_w (1/K). Simple linear or power law functional relations found in accessible professional resources, NIST REFPROP database and tables (Groda, 1991) were used.

A variety of criterion equations mentioned in Uruba (2003) were surveyed for description of the forced convection at low Reynolds numbers and selection was performed to obtain a reasonable fit with experimental data. The significance of the cold end effect of wire finite length is checked in the terminal phase of calculation.

For purpose of dimensionless criterion equations, film temperature t_m (°C), Nusselt number Nu (-) and Reynolds number Re (-) are defined respectively in (2):

$$t_m = \frac{t_a + t_w}{2}; \; Nu = \frac{h d_w}{k_a}; \; Re = \frac{w \cdot d_w}{\nu}, \tag{1}$$

where t_a and t_w are the freestream air and wire temperatures (°C), h is heat transfer coefficient (W/(m$^2\cdot$K)) and d_w is wire diameter (m). All the selected criterion equations have the form of $Nu = f(Re, t_a, t_m)$ or $Nu = f(Re, Pr)$, where $Pr = f(t_m)$. The final variant is the Collis-Williams relation originally published by Collis (1959):

$$Nu = (A + B \cdot Re^N) \cdot \left(\frac{t_m + 273.15}{t_a + 273.15}\right)^M ; \begin{cases} Re \in < 0.02, 44 >: N = 0.45; A = 0.24; B = 0.56 \\ Re \in < 44, 140 > : N = 0.51; A = 0; B = 0.48 \end{cases} \quad M = 0.17 \tag{2}$$

The main part of the calculation lies in an iterative cycle, which starts from a certain reasonable initial estimate and continues in the following order: 1. Determine air properties at film temperature, calculate Re; 2. Evaluate the heat flux by convection from wire surface based on heat transfer coefficient h determined from criterion equation for Nu; 3. Find values of resistivity at wire temperature and obtain total resistance of wire, use Ohm's law for electric current at given constant voltage, get the generated Joule heat; 4. Compute the theoretical wire temperature needed to dissipate the Joule heat by convection at current h value, noted t_{wJc} (°C). As positive feedback and therefor divergence can occur easily for this value, the updated value for the next iteration is constructed as an underrelaxed value: $t_w^{n+1} = c \cdot t_{wJc}^n + (1 - c) \cdot t_w^n$.

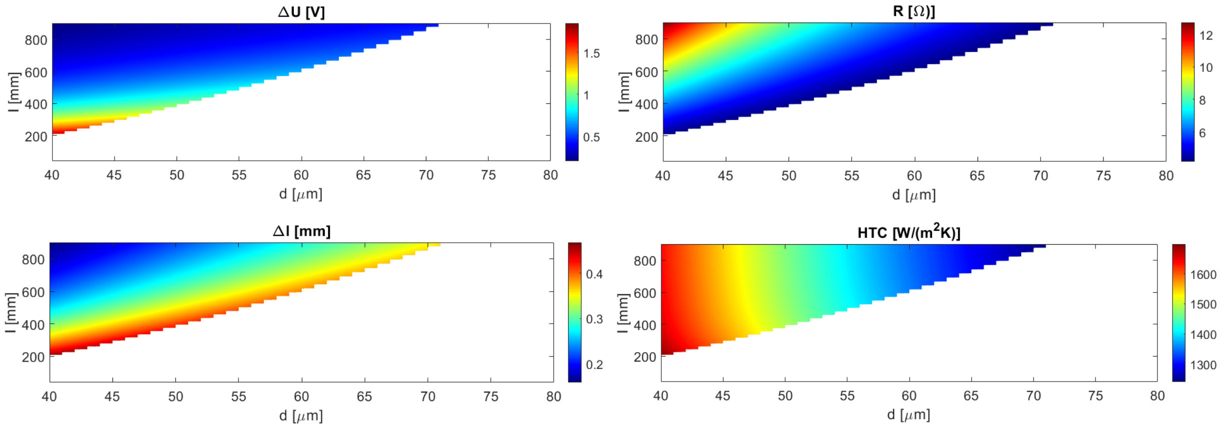

Fig. 3: *An example of selected graphical outputs of calculations from criterion equations*

For $c = 0.5$, the computation is stable and reasonably fast converging; 5. Convergence is checked by relative change in temperature between iterations as well as the relative difference of the convective heat flux from the Joule heat established in current iteration.

A range of wire lengths and diameters is batch-processed (taking advantage of data vectorization) to obtain a complete picture of certain wire material behavior. The calculated wire temperatures, or also electric currents and wire thermoelastic elongation, can be easily checked for viability for the desired application when allowable values are known. An example of the results is shown in Fig. 3.

5. Conclusions

The two model approaches and measured data were finally compared. As can be seen from Fig. 4, the calculated results from both models show negligible deviations for the same air temperature (20 °C) and electric current (1.2 A) over the entire range of flow velocity. Comparing these models with the measured values at the same air temperature (16 °C), a deviation for the considered wire diameter of 60 μm was found. After analyzing the influence of the different input parameters of the calculation in the Matlab model, a very good agreement with the measurement for a wire diameter of 61 μm was obtained as can be seen in the figure 4. This dimensional deviation appears to be quite realistic with respect to the wire manufacturing tolerances. It is difficult to measure this deviation in these partial tests, especially over the entire length of the wire. In the case of the MCCF measuring device, such deviations are eliminated by calibration.

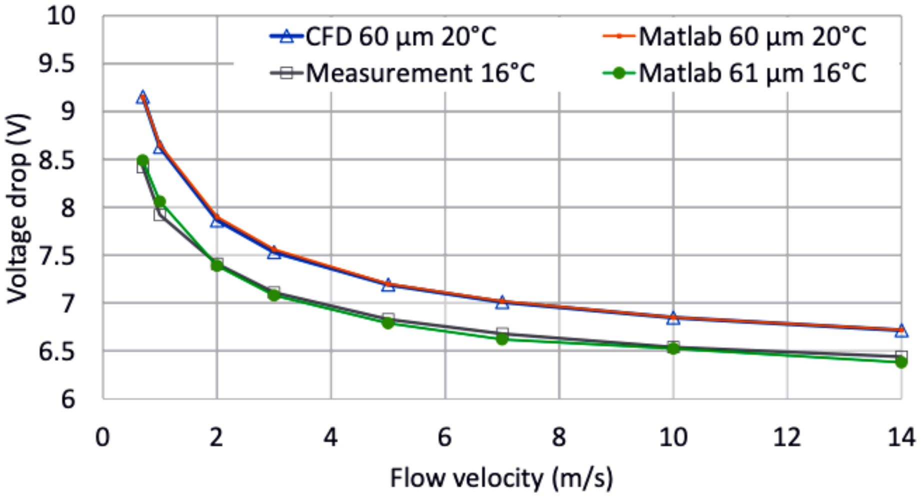

Fig. 4: *Comparison of measured results with CFD and calculations from criterion equations*

In addition to the results presented for the initial copper hot wire, analyses were subsequently performed for some alternative heated elements. Different wire materials were tested using the iterative model in Matlab. Tungsten appears to be promising in terms of properties as well as price. Using CFD, a two-sided flexible printed circuit and an element with multiple hot wires were also analysed. The expected significant advantage of these elements which is the detection of the flow direction was confirmed by the CFD simulations. Flexible printed circuit samples with a cross-section of approximately 0.1 × 0.1 mm were produced by laser cutting and basic measurements were taken.

Acknowledgement

This project is funded with state support from the Technology Agency of the Czech Republic and the Ministry of Industry and Trade within the TREND Program (project FW03010199).

References

Collis, D.C. and Williams, M.J. (1959) Two-dimensional convection from heated wires at low Reynolds number. *Journal of Fluid Mechanics* , Vol. 6 , No. 3, pp. 357 - 384.

Groda, B. (1991) *Thermodynamics and hydrodynamics - thermodynamic tables*. Student text, Agricultural (Mendel) University in Brno (in Czech).

Uruba, V. (2003) *Anemometry - heated elements*. Student text, Institute of Thermomechanics, Czech Academy of Sciences, online (in Czech).