



25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0698

CALORIMETRIC AND TIME OF TRANSIT FLOWMETER FOR MINICHANNEL THERMOSYPHON

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Abstract. *This paper describes the development, construction and experimental evaluation of a volumetric flow meter based on time of flight approach with reduced pressure drop. The prototype was designed aiming to be used in a closed loop two-phase thermosyphon based on minichannels, hence, the flowmeter should present reduced pressure drop. The inlet and outlet channels have inner diameter of 4 mm, and operates with liquid water. The prototype was built with low cost, and calibrated using the gravimetric process. A computational filter is proposed and implemented to eliminate the electric coupling from the sensor signal. The pressure drop is evaluated and the flow meter presents a reduction of approximately 50% of the pressure drop compared with a plain tube with the same length. The initial results indicate a mass flow meter with a high operational stability and reliability. The tests indicate a precision of 5.7% for 3.6 to 36 L/h range, corresponding to superficial velocities between 0.08 and 0.80 m/s for plain channels.*

Keywords: calorimetric sensor, time of flight sensor, flowmeter, minichannel.

1. INTRODUCTION

According to Doebelin (1990) the flowmeters can be roughly classified according to the operating principle as obstruction, variable area, averaging velocity, turbine, positive displacement, electromagnetic, ultrasonic, vortex-shedding, thermal mass, and Coriolis meters, which are selected based on their inherent advantages and disadvantages for a given application. The electromagnetic, ultrasonic and some models of velocity averaging are advantageous for conditions with requirements of reduced pressure drop. In this context, determination of flowrate in systems with natural circulation, such as laboratorial investigations of thermosyphons, requires low pressure drop, otherwise, the flow rate and the system capacity are significantly affected by the flowmeter. For the specific case of thermosyphons based on minichannel the thermal mass and Coriolis are the most common flowmeters reported in the literature. There are three types of thermal flowmeter: anemometer, calorimetric and time of flight sensor (Ashauer 1999), and some concepts have been proposed such as described by Sabaté (2004) and Lammerink (1993). However, in order to sustain a low uncertainty of the flow rate these devices require a high temperature difference, and consequently disturb significantly the fluid and flow characteristics.

Thermosyphons are heat transport devices used in several applications, such as solar collectors, heat management of electrical systems, among others, and are based on natural circulation induced by density variation due to heat transfer process along the circuit, which can operate with single or two-phase flow. Khalid (1997) performed a numerical investigation of thermosyphons and concluded that thermosyphons operating with phase change processes have higher performance than systems operating without phase change.

Therefore, in this study a new model of flowmeter is proposed to operate with minichannel in conditions of reduced pressure drop. The prototype operates with a combination of the principles of calorimetric and time of flight methods. The tests and calibrations were performed with liquid water as the working fluid.

2. FLOW MEASUREMENT TECHNIQUE AND NUMERICAL ANALYSIS

The conceptual idea of the flowmeter proposed in this study is based on the combination of calorimetric and time of flight sensors. The calorimetric sensor consists of a heater section that provide thermal energy to the fluid to promote variation of enthalpy, and based on measurement of temperature variation by knowing the fluid properties it is possible to infer the mass flow rate. Conversely, the time of flight sensor is based on determination of period of time for a traced portion of fluid to flow between two regions, which can be for example by increasing the enthalpy of a small portion of fluid or by dyeing it with fluorescent tracer, and based on the channel geometry it is possible to infer the volumetric flow rate. The portions of fluid are traced intermittently to allow definition and identification of the pattern that moves from between two regions. In the case of heating, the pulses increase the temperature of portions the fluid, and the traced portions are measured by temperature sensors installed at certain distance from the heater (Ashauer, 1999).

The proposed flowmeter is based on the time of flight and calorimetric operating principles. The time of flight characteristics consists in heating a portion of fluid by electrical resistance with pulsed and controlled power supply, and by evaluating the time of displacement from the heating to the measuring regions. The variation of fluid temperature is related to flow velocity according to the calorimetric aspect. Figure 1 schematically depicts the flowmeter with the electrical heater in the central region and a thermopile used to determine fluid temperature variation. The heater consists of a NiCr8020 wire with diameter of 0.1 mm twisted as a coil and installed in contact with the wall of the section, connected to a 5 V DC power supply via solid state relay, and the temperature sensor is a thermopile which is a combination of T type thermocouple installed crosswise at the flow direction. The temperature sensors are made from thermocouple wires with 0.1 mm in diameter.

The prototype aims to be used in a thermosyphon of the research group, which counts with channel of internal diameter of 4 mm, and in order of reducing flow velocity in the measuring section to increase the resolution and precision of the measurement, the channel was expanded for 8 mm in diameter.

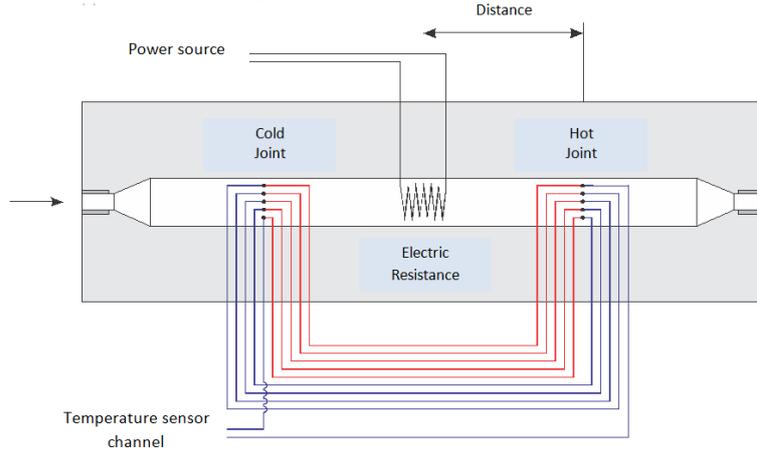


Figure 1 - Representation of the final assembly of mass flow meter

Due to the characteristic of natural circulation of thermosyphon, the mass flux tends to be lower in comparison with systems with propelling components, such as pumps and compressors, and high pressure drop would deteriorate the performance of the system. Therefore, the proposed flowmeter aims to impose low pressure drop to the flow. It is also desirable limited heat transfer to the fluid because the flow meter will be installed in a region where the fluid is slightly subcooled, and if excessive heat is supplied to the fluid a phase change can occur and this aspect would interfere in the thermosyphon operation and performance, as well as in the flowmeter operation.

A numerical one-dimensional model of the flow meter was developed to predict its operation in conditions characteristic of a thermosyphon based on minichannel, with internal diameter of 4 mm working with liquid water. A few assumptions were made as simplifying hypothesis:

- the heat flux from the electric wire resistance is transferred only to the fluid due to the high thermal resistance of the flow sensor body material made of PTFE;
- uniform heat generation along the resistance length;
- instantaneous steady state during the conditions of active or inactive electrical resistance;
- the NiCr wire temperature is considerate uniform, because the corresponding Biot number is of the order of 10^{-4} .

With the above simplifications the energy balance for the electrical heater and water confined in the region defined by the electrical heater are given respectively as follows:

$$\rho_N V_N c_N \frac{dT_N}{dt} = -h_f \frac{\pi d_N L_N}{2} (T_N - T_f) + \frac{(DDP)^2 \pi d_N^2}{4 \sigma_N L_N} \quad (1)$$

$$\frac{dT_f}{dx} = \frac{P q''}{\dot{m} c_p} \quad (2)$$

where T corresponds to temperature, d diameter, L length, σ electrical resistivity, DDP voltage, ρ density, V volume, c specific heat, P perimeter, \dot{m} mass flow rate, and the subscripts N and f stands for the wire and fluid, respectively. The term h_f corresponds to the heat transfer coefficient between the wire and the fluid, estimated according to Gnielinski (1976) for averaged velocities as approximately $650 \text{ W/m}^2\text{K}$.

Figure 2 depicts variation of fluid and heater temperature with time during the heating process. This result provides the information about the heating period required for proper operation of the flowmeter.

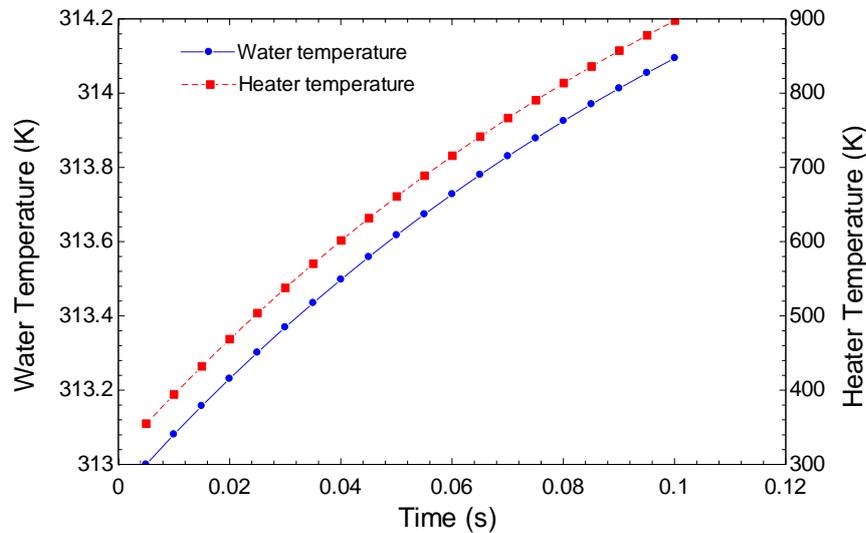


Figure 2 - Temperature variation during the heating process.

Therefore, the response time and the sensibility of the thermopile should be evaluated, that according to Doebelin (1990) for T type single-joint thermocouple has a sensibility of $52.18 \mu\text{V/K}$. In the present study, the thermopile has four pairs of joints and considering that the acquisition channel has the resolution of $0.05 \mu\text{V}$, it is possible to measure temperature variations of $2 \cdot 10^{-4} \text{K}$. The response time of the thermocouple joint is direct correlated with the accuracy of the flowmeter, and was calculated modeling each joint as a cylinder positioned perpendicular to the flow using the method of lumped-capacity solution. According to this approach, the time response is approximately 7 ms for average flow velocity of 0.02 m/s, and reduces with increment of flow velocity, which is lower than the required recording period of the acquisition system, equal to 50 ms.

3. PROTOTYPE

The mass flow meter was built from a billet of PTFE (polytetrafluoroethylene) because of its high mechanical capability and machinability, and high resistance of chemical attack and corrosion, low liquid absorption and low friction when working in non lubricated operation (Crawford, 1990).

The main body of the flow meter was designed and fabricated in five parts that were assembled using four compressing screws that pass across all the pieces to ensure its coaxial alignment, as shown in Figure 3, and sealed by NBR orings to avoid leakage. The central section counts with the electrical heater, and the two pieces immediately adjoined to the heating section aims to impose a certain length for fluid displacement, otherwise the identification of time interval would be impaired due to time response of the acquisition system. The distance between the heater and the cold and hot joints of the thermopile is 30 mm, considering that the expected flow velocities were between 0.025 and 0.25 m/s, the transit time would be respectively 1.2 and 0.12 seconds, which is feasible for the 20 Hz of acquisition frequency of the thermocouple channels, corresponding to approximately 0.05 s of interval between successive measurements.

The thermopile joints were assembled using four thermocouple joints separated 1 mm from each other and installed perpendicular to the main axis of flow meter, as shown in Figure 3. To ensure the water tightness each joint filament was inserted across the oring wire using a 0.3 mm diameter needle. All thermopile joints have an approximate projection area of 3.08 mm^2 , which corresponds to obstruction of 6.1% obstruction of the channel cross sectional area of 52.26 mm^2 .

There are two visualization sections on the body of the flow meter to observe possible bubble formation due to phase change process of the fluid during his passage through the heating section. However, no bubbles were detected during all the calibration and tests.



Figure 3 - Prototype final assembly and thermopile visualization

4. CALIBRATION

The approach presented by Abernethy and Thompson (1973) was performed for calibration of the prototype. This procedure was originally described for a gas turbine flowmeter, thus, some steps were adapted to adjust it to the present work. A gravimetric approach was used as reference for the calibration, in which a measured mass of fluid through the meter is determined by a precision balance during a time interval, and based on the knowledge of fluid density it is possible to relate to the volumetric flow rate. Figure 4 it is represented a scheme for the calibration process setup.

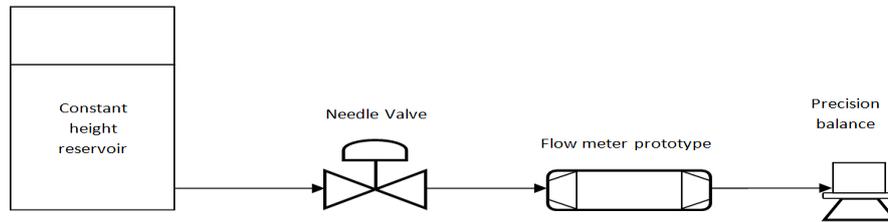


Figure 4 - Calibration hierarchy for the gravimetric method.

The time of transit measurement is evaluated by cross correlation between the thermopile signal and the electrical pulse supplied to the heater. At the present work the method returns the time interval between the two cyclical signals occurred and this time difference represents the time of transit necessary for the traced portion of the fluid to move between the heater and hot joint region. The Cross Correlation was calculated using Scilab built in function. Therefore, the peak value of the cross correlation τ_{peak} was considered as the time of flight, and then the volumetric flow can be estimated as follows:

$$\dot{Q} = \frac{A_s \cdot L}{\tau_{peak}} \quad (4)$$

where A_s is the cross sectional area of the flowmeter, and L is the distance between the measuring and heating section.

5. RESULTS

The calibration process was performed for flow rate ranging from 3.6 to 36 L/h (10^{-6} to 10^{-5} m³/s), corresponding to mean velocities ranging from 0.025 to 0.25 m/s in the flowmeter, and between 0.08 and 0.8 m/s in plain tube of 4 mm. Five experiments were performed for each condition during at least one minute with acquisition rate of 20 samples per second. Below, the procedure for data analysis is described, and the results are presented and discussed.

5.1 Electric coupling filter

An issue reported on the literature about time of flight flow meters is the electric coupling or electrical crosstalk between the heater element and the thermo sensor. The phenomena occur when the heater is activated, which impacts the measured signal by the sensor. In general, a peak voltage occurs just after the heating pulse, such as illustrated in Figure 5 for the raw data. The high peak of the measured signal occurs due to electric coupling, and the results indicate that the peak tension can reach values as high as twice of the regular peak tension from the thermopile.

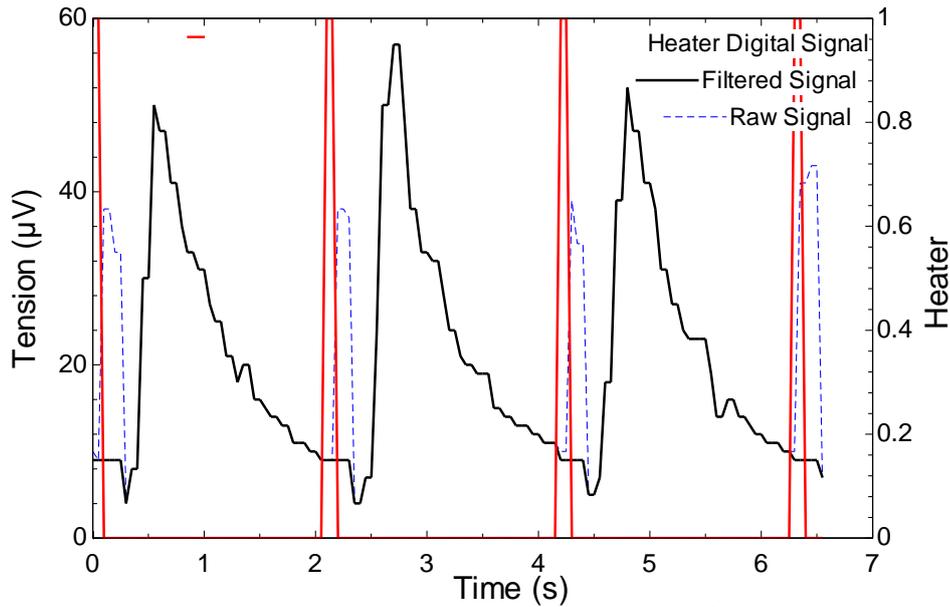


Figure 5 - Signal treatment for a flow rate of $2.9 \cdot 10^{-6} \text{ m}^3/\text{s}$.

This distortion on the sensor data are outliers and have a significant impact on the results of the cross-correlation method. Preliminary results indicate that accounting the coupling implies in lower values for the time of flight, which increases the uncertainty of the flowmeter. Hence, an algorithm was developed as a computational filter to ensure the smoothness, and better agreement between measured and reference value, shown in Figure 5 by filtered signal, according to the following steps:

1. The derivative of the measured signal is estimated by finite difference for each pair of consecutive data points;
2. By evaluating the variation of the derivative absolute value, it is possible to identify the rising and falling edges corresponding to the heater crosstalk;
3. The signal is then interpolated between the values immediately before and after the rising and falling edges, respectively.
4. Then the filtered signal is processed with the heater input signal by cross correlation to estimate the time of transit.

5.2 Cross Correlation results

The figure 6a and 6b presents the results obtained from the cross correlation between the thermopile and heater signals for volumetric flow rate of $1.26 \times 10^{-6} \text{ m}^3/\text{s}$, corresponding to mean velocity of 0,036 m/s in the flowmeter. According to this analysis, the peak occurs for delay of 1.2 seconds. The periodicity of the signals can be also observed from the slightly symmetrical shape of the cross-correlation results.

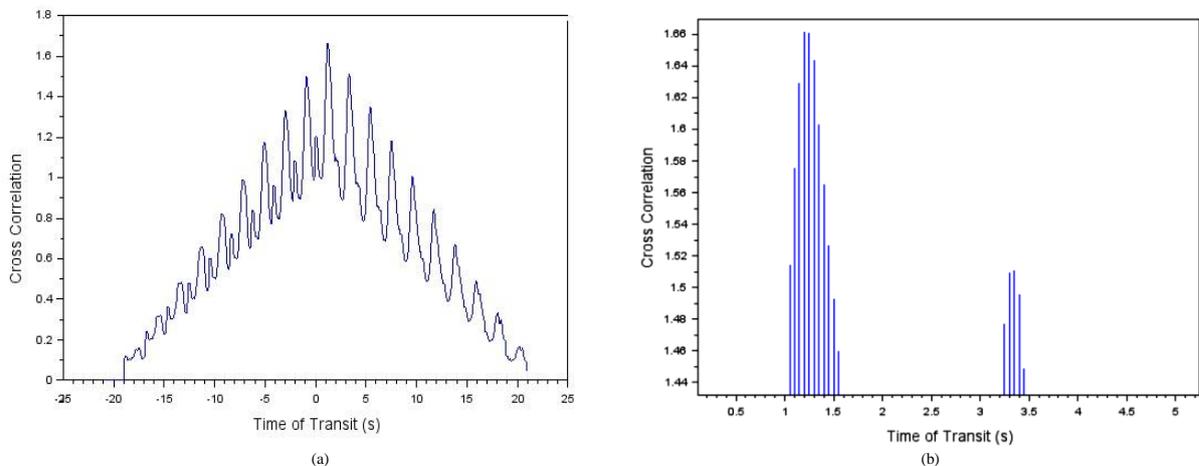


Figure 6 - (a) Cross Correlation result from a flow rate of $1.2 \times 10^{-6} \text{ m}^3/\text{s}$ (b) Detailed at the peak cross correlation.

For flow rates lower than $8 \times 10^{-6} \text{ m}^3/\text{s}$ ($V \leq 0.2 \text{ m/s}$) the prototype has showed high repeatability for measures with relative differences lower than 5%. Figure 7 depicts the comparison between the estimated flow rate value according to

the prototype and Eq. (4), and the evaluation according to the gravimetric method. According to this figure, it is possible to observe that the estimated flow rate presents good agreement with the results obtained with reference method. In general, the deviation between the reference and the estimated value increases with the flow rate, which is related to the acquisition frequency, which is limited by the acquisition system.

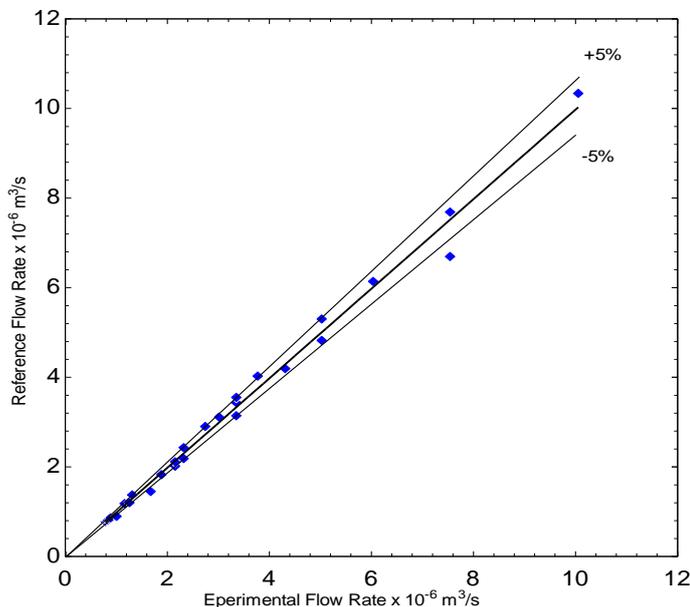


Figure 7 - Referential flow rate versus flow rate measured by the flow meter

5.3 Pressure Drop

As mentioned before, the proposed flowmeter aims to impose reduced pressure drop, hence, an analysis of the pressure drop is performed by comparing the estimated values for stainless steel tube section with 4mm inner diameter and the flow meter. The flow rate range corresponds to Reynolds number lower than 2442 for the tube of 4mm, and lower than 1221 for the section of 8mm, therefore, corresponds to laminar flow regime for both cases.

For the flow meter the pressure drop was estimated for each section. The flow path sections are: two sections with inner diameter of 4 mm and 30 mm long corresponding to entrance and outlet, one section with 8mm inner diameter and 90 mm long, one diffuser and one nozzle with 120° angle. The pressure drop was evaluated by using the method proposed by Perry (1997). The pressure drop caused by the thermopile was evaluated by considering a tube bundle approximation. The results indicate that the thermopiles cause pressure drop at the order of 0.008 to 0.01% of the total pressure drop at the flow meter and based on this results their influence was neglected on further analysis.

For the straight section the pressure drop is given by the following relationship:

$$\Delta P = \frac{f L \rho V^2}{2D} \tag{5}$$

and for the diffuser and nozzle by the following equation:

$$\Delta P = \frac{K \rho V^2}{2} \tag{6}$$

where f is the friction coefficient, L is the length of the section, D is the diameter, K is the pressure drop coefficient, V is the velocity of the flow and ρ is the specific mass of the fluid.

Figure 8.a presents the estimated pressure drop variation with the flow rate for the flowmeter and for the plain tube. According to this figure, the flowmeter causes lower pressure drop in comparison with a tube with 4 mm of internal diameter and same length. Figure 8.b depicts the ratio between the estimated pressure drop for the transducer and for plain tube, and according to this figure, the difference between the pressure drop reduces with the increment of flow rate, however the pressure drop along the flowmeter is always lower than the case of plain tube. Hence, the proposed flowmeter presents reduced impact on the pressure.

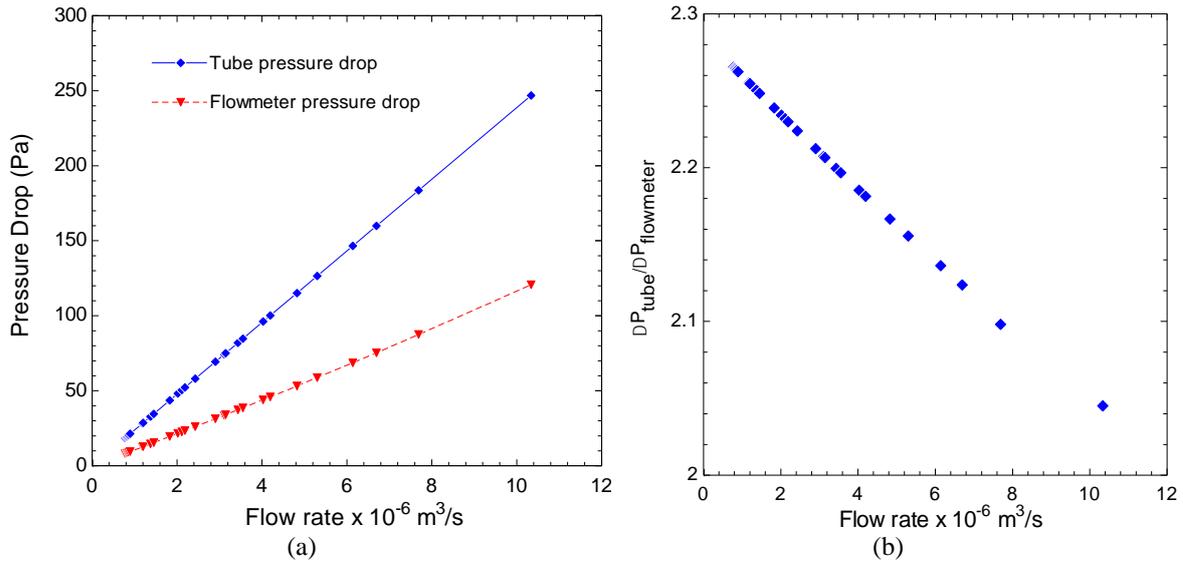


Figure 8 - Pressure drop comparison. a) Variation of pressure drop with flow rate. b) Pressure drop ratio.

6. CONCLUSION

This study comprises the development and experimental analysis of a flowmeter prototype based on time of flight and calorimetric methods, focused on application with low flow disturbance. The following conclusions can be addressed:

- The developed flowmeter is sensitive for flow rates between 10⁻⁶ and 10⁻⁵ m³/s, and present reduced impact on the flow characteristics. The estimated pressure drop is even lower than the case of plain tube, and the power supplied to the fluid is considerably low in comparison with a pure calorimetric sensor, because the power supply is pulsed;
- Preliminary results showed good agreement with reference value, which corresponds to gravimetric method, with general uncertainty of 5.7% of the measured volumetric flow rate;
- Electrical coupling between the heater and the sensors was present during the experiments, which was filtered from the signal by edge detecting algorithm followed by interpolation;
- The pressure drop caused by the flowmeter is lower than 50% of the tube section with same length, and approximately 80% of the total pressure drop is caused by the entrance and exit sections of the flow meter.
- The prototype has capability of measuring volumetric flow rates in both directions due to the construction characteristic.

7. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support for this work through the PROPPI/UFF, Capes – Conselho de Aperfeiçoamento de Pessoal e Ensino superior and the technician Alex for his help at the prototype construction.

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