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Integrated temperature microsensors for the characterization of gas heat transfer

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Abstract. A new method for the integration of silicon-based miniaturized sensors in microchannel systems is proposed. Unlike existing designs realized with IC-technologies, the new design allows flexible integration of temperature sensors in a variety of microchannel materials. Since no bonding technology is required, it is possible to employ the same sensor array with different test sections, broadening the possible applications of the experimental device. The designed experimental device has been employed for the characterization of gaseous heat transfer in microchannels. Conventional temperature measuring technique and CFD simulations have been employed to compare the obtained results and validate the new experimental approach. The local measurement technique enables investigating the influence of the channel material and local surface characteristics (i.e., roughness) on the heat transfer performance at varying flow conditions.

1. Introduction
Thanks to the recent technological advances of micro- and nano-machining, the miniaturization of mechanical and electrical devices has become a common procedure to achieve process intensification and efficiency enhancements. To fully understand the governing physical mechanisms at small scales, new integrated tools for direct in-situ observation and control are required [1]. With the development of IC fabrication and silicon planar technologies it has been possible to create miniaturized transducers for sensing and actuation [2]. Small scale devices integrating microsensing elements with transduction units are the core components of micro electro mechanical systems (MEMS) [3]. The employment of MEMS-based sensors with microfluidic devices is particularly appealing since they present high frequency responses and small sizes not achievable with conventional measuring techniques [1]. In particular, the possibility of a local flow characterization allows investigating those phenomena which are driven by surface effects, such as the interaction of the fluid with the system walls.

Along with "scaling effects" such as viscous dissipation, conjugate heat transfer effect and compressibility [4], slip effects may also appear for gas flows in microchannels [5]. When scales are reduced, some assumptions at the basis of the conventional model equations (namely the Navier-Stokes and energy balance equations for compressible flows) do not hold anymore. Rarefaction, and in particular slip flow conditions, refer to a non continuous behaviour of the gas flow in proximity of the gas-wall interface [5]. In these cases the boundary conditions of the Navier-Stokes equations must be modified [6]. As the discontinuities first appear near the wall, it is clear that the gas-surface interactions play a major role in determining the flow behaviour in this
region. Several experimental studies have been done to characterize gas flows in microchannels under slip flow (some examples can be found in the works proposed by Arkilic [7], Turner [8] and Pitakarnnop [9]). Yet, most of the produced results are based on the indirect evaluation of the rarefaction parameters with measurements performed outside the channels and do not offer a complete overview of the flow characteristics. Even if these studies are useful for the validation of theoretical models, they do not help in identifying the actual role of the surface interactions on the flow. This is a typical local scale phenomenon which requires direct measurements inside the channels and could therefore benefit from the measuring technique proposed in this work.

In literature, many designs of integrated systems have been proposed. A common example of integrated sensors are miniaturized flow sensors, proposed, e.g., by Lammerink et al. for both liquids [10] and gases [11]. A suspended microchannel with embedded temperature sensors has been developed for high pressure application studies by Wu et al. [12]. Internal temperature measurements have been presented also by Park et al. [13], who developed a silicon channel bonded to a glass cover with integrated platinum resistance temperature detectors (RTD). Micro sensor fabrication technologies have been developed also on glass substrates. Xue and Qiu [14] presented an integrated array of temperature sensors for a glass microchannel generated by planar technology. Low temperature manufacturing processes for integrated sensors employing particular materials for heat transfer studies have also been developed and described, i.e., by Liu et al. [15] and Ko and Gau [16].

Despite the progresses in miniaturized sensor fabrication techniques and the high number of configurations proposed over the years, a full implementation of these systems in terms of integrating the sensors into a multi-objective micro-scale device has not been achieved yet.

The highly process-tailored designs available from literature limit the use of the sensors to the single application they have been designed for. Moreover, planar fabrication technologies, which offer great manufacturing potentials, limit the employable materials to a few (basically silicon and its compounds and glass). In most applications, the microchannel is fabricated along with the sensors, or bonded to the sensor substrate. This means that, whenever the microchannel configuration needs to be changed (i.e. channel geometry, material, surface finish, etc.), a new complete sensor-microchannel assembly becomes necessary.

To overcome some of these limitations, a sensor integration system has been developed and tested in a new microchannel device. This work presents the validation of the integrated sensor prototypes. The thermal characterization of a gas flowing inside a microchannel, in terms of internal temperature distribution, has been considered as relevant application to test the sensors functioning. Possible implementations of the newly developed system are however not limited to gas flows only. The main advantage of the present configuration is the absence of material limitations for the microchannel. The sensor integration can be broadened to those fields which typically do not employ silicon or glass and for which the available integrated sensors designs are not suitable. A representative example is the area of micro process engineering where usually metallic microstructured devices are used. In these cases the monitoring of the local temperature could avoid deviations from the process optimal conditions, allowing a better exploitation of the resources. The analysis has been performed using two experimental approaches. The first one is based on integrated microsensors, the second employs conventional measuring systems. Finally, comparisons with a CFD numerical model have been performed, too.

2. Experimental setup

The experimental device design is based on a previously developed system employed for microchannel heat transfer studies [15]. It has a multilayer configuration where each part is designed for a specific function and works independently from the others.

The device is showed in Fig. 1 and includes (from the bottom of the figure), gas inlet and outlet fittings, a base frame of stainless steel, three separated heating/cooling units in copper,
a channel layer, a sensor layer and a stainless steel cover.

The heating/cooling copper blocks present two receptacle holes each, for the installation of electrically powered heating cartridges or tubes connected with a cooling loop. The blocks are separated by an air gap, which ensures an insulation layer between them. The power source for the electrical heating elements is provided by three separate channels (one per block), using three independent temperature controllers. On top of each block two grooves for the installation of thermocouples are included. These can be employed to record the block temperature and can be connected to the temperature controller as feedback sensors. This configuration allows the imposition of controlled temperature boundary conditions below the channel sections and the possibility of achieving steep temperature profiles along the microchannel bottom wall [17].

The microchannel section installed above the heating/cooling unit can be easily removed and replaced after opening the device. This allows investigating different materials, and different microchannel configurations with the same measuring system and in the same housing. The microchannels are realized on planar foils of the chosen material and by using the desired manufacturing technique. All the microchannels are open to the top, to allow the installation of the sensors as a cover.

The sensor layer is constituted by a polytetrafluoroethylene (PTFE) support frame with a recess for the positioning of a silicon chip. On top of it an array of temperature sensors have been realized with planar fabrication technologies. The chip, once installed, covers the microchannels entire length and constitutes its upper wall. The PTFE support is used also as channel sealing, thanks to the elastic properties of the polymeric material. Once the device is closed, the channel foil presses directly on the PTFE frame, ensuring leak tightness of the assembly, even when the sensor chip is installed.

Finally, the structure is closed by a cover and fixed by screws, which allow for an easy disassembling of the device and the exchange of the test sections. The different layers constituting the experimental device are shown in Fig. 2.

**Figure 1.** Scheme of the multilayer experimental device with integrated measuring system (4) and exchangeable test sections (3).

**Figure 2.** Photographs of the different parts constituting the experimental device, including the vacuum vessel for the thermal insulation of the device.
The outer metallic frame gives the device a large thermal inertia compared to the small gas volume flowing inside the microchannel. This results in relatively long transitories (depending on the set temperature, the warm-up time ranges between some minutes and one hour) but also in very stable boundary conditions for the microchannel (once the system reaches the steady state).

The device is installed into an experimental rig (see Fig. 3) including a vacuum pump for the regulation of the pressure levels at the channel inlet and outlet and a complete measuring system to monitor the pressure and the temperature of the gas at the inlet and outlet of the device. To eliminate the influence of thermal losses to the environment, the device is installed into a vessel which can be evacuated during the experiments.

The leak tightness of the device and of the whole experimental circuit has been verified with vacuum tests. Overall leakage rates of about $6.63 \times 10^{-3}$ mbar·l·sec$^{-1}$ have been measured. Even though this value is higher than for typical gas-tight systems it represents less than 1% of the mass flow rates established during the experiments and was therefore considered acceptable. Leakage occurs mainly where the cables exit the device. However to maintain an easy exchangeability of structures the design chosen was considered a good compromise.

![Figure 3. Scheme of the experimental rig. Mass flow controller (1); inlet temperature controller (2); inlet pressure measurement (3); flange vacuum system with the device and the integrated sensors (4); outlet temperature measurement (5); outlet pressure measurement (6); mass flow meter (7); vacuum pump (8).](image)

Four different kinds of microchannel sections have been realized; their geometrical and surface characteristics are listed in Table 1. The average roughness has been measured with a chromatic white light sensor along the entire microchannel length. This non-contact technique is very precise and convenient for surface characterization at small scale.

### 2.1. Integrated measuring system

The manufactured microsensors present a thermopile configuration which exploits the Seebeck thermoelectric effect and presents several junctions in parallel to achieve an acceptable sensitivity [18]. In the present case the thermopiles are constituted by ten junctions between aluminum and n-doped polysilicon. To avoid thermal shortcuts (spoiling the sensor sensitivity), the sensors are fabricated on top of thin film membranes (10-15 µm thick) realized by wet etching of the chips back side and arranged along the chips longitudinal axis. Since thermopiles are temperature difference transducers, a reference temperature measurement is needed. This is provided by placing, in addition, a series of resistance temperature detectors (RTD) on the chip (outside the membranes), corresponding to the thermopiles “cold” junctions. The “hot” junctions...
Table 1. Microchannel test sections main characteristics.

| Material       | Manufacturing technique | Section Shape            | Average dimensions | Average roughness |
|----------------|-------------------------|--------------------------|--------------------|-------------------|
| Stainless steel | Micro-milling           | Rectangular              | 400 ± 4            | 110 ± 4           | 0.08              |
| Copper         | Micro-milling           | Rectangular              | 405 ± 4            | 80 ± 4            | 0.300             |
| PEEK           | Micro-milling           | Rectangular              | 401 ± 4            | 108 ± 4           | 0.140             |
| Stainless steel | Wet-chemical etching    | Semi-elliptical          | 422 ± 4            | 140 ± 15          | 0.460             |

are positioned on the membranes and, once the chip is installed, face the inner part of the microchannel. The thermopile signal must be interpreted then as the temperature difference between the chip and the gas inside the channel. The thermistors measure the absolute chip temperature (directly proportional to the contact resistance) and allow the calculation of the absolute gas temperature, as described by Eq. 1. The layout of the integrated sensing unit is shown in Fig. 4.

\[ T_{gas} = T_{chip} + \Delta T \] (1)

Figure 4. Schematic layout of a temperature sensing unit. The thermopile sensing junctions are included in the microchannel with a membrane configuration, while the reference temperature is measured by the thermistors (RTD) on the chip.

The sensor chip comprises 8 membranes 160 µm wide, each containing two thermopiles (one per side). This configuration allows a symmetric distribution of the heat conduction along the sensor leads and a redundant measure of the temperature at each position. Finally 16 RTDs have been manufactured in between the membranes. To collect the data registered by the sensors, flexible cables using polyimide as hose material are employed. These are bonded at four positions to the chip sides, where the sensor contacts end. The cables exit the device laterally, where printed circuit board (PCB) adapters and connectors are installed for the data recording. Despite the presence of the PTFE chip-holder, the major leaks occur at the four locations where the cables exit the device. However, the position of the cables prevents the use of conventional O-rings around the microchannels. To preserve the possibility of disassembling the different parts, no additional bonding has been foreseen, given also the small weight of the measured leakages on the overall mass flow rates. The cable bonding to the chip is realized by precise positioning of the two parts and by application of a two-step pressure/temperature...
cycle. This procedure is very delicate as proper contact between chip and cable is required for good signal propagation. Too high contact pressures or improper temperature cycles might result in the spurt of the contact material out of place and in shortcuts between the sensors. To verify the good functioning of the sensors, the resistances of all contacts have been tested before implementation of the chip. Typical values of some kΩ are characteristic for the sensor contacts, while an infinite resistance should be measured between non communicating contacts.

Figure 5 shows a sensor chip with thin cables bonded to the sides, installed in the PTFE holder.

2.2. Conventional measuring system

Normally, the integration of conventional temperature sensors (e.g., commercial thermocouples) is not feasible for microchannel systems. Indeed, since even the smallest available sizes for the sensing tips are comparable to the microchannel dimensions, major flow disturbances may occur, which may negatively affect the measurements.

For the present case, a special design has been created, allowing the precise positioning of thermocouples in a microchannel, with minimal interaction with the flow. The microchannel sections are covered with a Polyether-ether-ketone (PEEK) cover along the axis of which 6 type-K thermocouples with 125 µm sensing tips have been installed with vertical orientation. The sensors are inserted in pre-fabricated holes on the cover and fixed with precision gluing. The sensor tips face the inner part of the microchannel, where they are in contact with the gas and measure the temperature distribution. The actual capability of sensing the gas temperature with this layout must be assessed before its implementation.

A photograph of the PEEK cover with embedded thermocouples is shown in Fig 6.

3. Numerical model

CFD simulation was used to model the behavior of the microchannel-sensors assembly.

Based on symmetry considerations, only one half of the microchannel geometry is studied. To reproduce the actual thermal boundary conditions encountered during the experiments, the channel has been split into five parts, corresponding to the unheated entrance and exit lengths and the three heated lengths, respectively.

Both geometry and mesh have been created with GAMBIT®, while the flow simulations have been realized with FLUENT®.
The boundary conditions for the problem (i.e., inlet, and outlet pressures, inlet temperature and wall temperatures) have been directly taken from the experimental results, and the calculated temperature distribution for the gas has been compared to the corresponding data.

The model includes compressibility effects for the flow, conjugate heat transfer, and slip flow at the microchannel walls.

4. Results

Before use of the integrated sensors the measuring principle and the calibration of the transducers was validated. This has been performed with a series of different tests described in the following.

4.1. Calibration of the RTDs

The thermistors are absolute temperature sensors, and the calibration can be performed by registering the signal for given temperature set points on the heaters and no imposed gas flow.

As reference temperatures for the RTDs the signal recorded with the embedded thermocouples on the PEEK cover have been used. In particular, as the wall temperature is to be measured, a blind foil (without the channel) has been installed during the calibration tests. For every temperature set point on the power supply, the steady state signals of the RTDs and the embedded thermocouples have been recorded separately. The results have been then reported in a resistance-temperature plot, where, with a least square fitting method, the calibration coefficients for each sensor have been calculated. The ranges for the temperature set points have been chosen within the limits encountered for the mechanical stability of the chip. The chip has been heated up to about 350 K without major fractures occurring. However, a confidence interval from ambient temperature up to 330 K has been chosen for the calibration. The relative fragility of the chip is not connected to the materials themselves, which could stand higher temperatures, but is rather related to the mechanical and thermal stresses occurring during the tests. The whole chip structure is indeed relatively large and presents several points for crack growth, especially concerning the membranes. For these reasons, particular attention had to be paid during the mounting of the chip in the PTFE holder and during device assembly. Sudden thermal stresses together with severe pressure gradients along the chip also had to be avoided.

Figure 7 presents an example of a calibration fitting for one RTD. A good linear behavior in the tested temperature range has been found for all thermistors. This trend is consistent with commercial RTDs showing a linear response over relatively small temperature ranges, as in the present case.

Considering the followed calibration procedure for the RTDs, the uncertainty associated with their signals has been calculated based on three different contributes as shown in Eq. 2:

$$\Delta T_{tot} = \pm \sqrt{\Delta T_{ref}^2 + \Delta T_{fit}^2 + \Delta T_{calib}^2}$$

(2)
The different error contribution are classified as follows:

\( \Delta T_{ref} \) : uncertainty associated with the reference sensors (contribution of the reference temperature measurements);

\( \Delta T_{fit} \) : uncertainty associated with the fitting procedure (contribution considering the deviations between the experimental points and the fitted line);

\( \Delta T_{calib} \) : calibration uncertainty associated with error propagation of the resistance measurement (contribution that takes into account the uncertainty of the resistance measurements and how this is converted into an uncertainty for temperature evaluation).

Typical uncertainties in the range of \( \pm 0.7 \) K - \( \pm 0.8 \) K have been found for the RTDs, where the main error contribution is given by the temperature reference sensors (\( \Delta T_{ref} \approx 0.5 \) K).

4.2. Thermopile tests
Whenever a temperature difference is established along the membranes, the thermopiles produce a proportional voltage signal. The sensors calibration requires the imposition of controlled temperature differences across each sensor, the recording of the corresponding voltage signal and the fitting of the experimental data. As a first step, to assess the functioning of the thermopiles and understand the answer to different boundary conditions, a series of tests have been realized.

In Fig. 8 the results of one of the performed sequences are shown for two different thermopiles. In the first case (Fig. 8-a) the thermopile is positioned directly above the heated area, while in the second case (Fig. 8-b), the sensor lay on the unheated length close to the microchannel exit. The test has been performed as follows:

(i) The thermopile signals have been recorded at rest (i.e., neither the heating nor the gas flow were activated).
(ii) A gas flow is established without heating the microchannel.
(iii) The heating of the copper blocks is turned on, and the desired temperature is set on the power supply controllers.
(iv) The heating is turned off.
The gas flow is closed.

**Figure 8.** Comparison of the results of two thermopiles for a test sequence. (a) thermopile positioned over the heated area. (b) thermopile positioned outside the heated area and close to the microchannel exit.

For both thermopiles, the absence of any gas flow (at the beginning and at the end of the test) corresponds to a zero signal, independent of the microchannels absolute temperature. In this case, indeed, the membrane and the chip have the same temperature and $\Delta T = T_{gas} - T_{chip} = 0$.

When the gas flow is activated, the thermopiles record a negative step. This means that the gas flowing into the microchannel decreases the temperature of the membrane due to convection effects (which has a much lower thermal inertia with respect to the chip), while the chip temperature remains unvaried. The negative step is more evident for the thermopile close to the exit which suggests that the gas is cooler close to the exit. This can be an influence of the inlet and outlet microchannel openings, which act as sort of plena for the gas and are at constant ambient temperature.

When the heating is activated, the two thermopiles show a quite different behavior. For the sensor positioned over the heated area (Fig. 8-a), the signal has a small positive variation only at the beginning of the heating. The average value remains, however, almost unchanged and around zero. This means that the temperature difference between the gas and the chip is almost
constant. The gas at the sensor position has increased its temperature from the upstream heated area, but also the chip is heated according to the temperature set at the heating blocks.

On the contrary, the thermopile closer to the exit (Fig. 8-b) shows a big positive step of the voltage signal in correspondence to the beginning of the heating. As the temperature of the block increases, the thermopile signal rapidly falls back to zero (the gas reaches the temperature of the chip), then progressively decreases as the chip is heated by conduction from the microchannel central area and a negative signal is established again.

Besides the different behavior of the thermopiles according to their relative position on the microchannel, some common characteristics for the integrated sensors-microchannel assembly can be highlighted. As expected, the miniaturized sensors show very fast responses in transient regime. The thermopiles have a high sensitivity (due to the membrane configuration) and thus very small temperature variations can be detected. Axial heat conduction takes place along both the microchannel foil and the chip layer from the directly heated to the entrance and exit regions.

Since the gas temperature along the channel rapidly changes with the position, direct calibration of the sensors by assuming a uniform temperature distribution can not be performed (even if constant temperature boundary conditions are imposed). A possible solution is an indirect calibration, achieved by comparing the results of two different measuring methods. For this purpose, the experimental data obtained with the PEEK cover with embedded thermocouples have been used.

4.3. Comparison with commercial sensors

Two separate tests have been performed with the PEEK cover, repeating the same test procedure and imposing the same boundary conditions, one with the blind foil (without the channel) and one with the microchannel foil and an imposed gas flow.

From the two tests the temperature difference between the top wall (blind foil results) and the gas (microchannel foil results) along the channel is calculated. This is then compared to the thermopile signals recorded for the same test sequence and boundary conditions with the sensors chip installed in the device.

The main drawback of this method is the low sensitivity of the PEEK-thermocouple assembly, and its higher thermal inertia compared to the chip micro sensors. In particular, at low mass flow rates (around 100 ml/min), the thermocouple signals show no detectable differences between the tests with the blind foil and those with the microchannel and the gas flow. For these reasons a comparison between the two methods can only be done at high mass flow rates and relatively high temperatures.

In Fig. 9 the comparison between the PEEK cover and the silicon chip results is shown for two sensors. The plots refer to a test where, after an initial waiting period (phase 1), the gas flow has been activated (phase 2), and only the copper block close to the channel exit has been heated to 40 °C (phase 3). A short cut-off of the gas flow has been imposed (phase 4), to compare the signals in a transient regime, before turning off the heating (phase 5).

From the plots it is evident that the two techniques produces comparable data, as the trend of the thermopile signals can be reproduced by the calculated temperature differences recorded with the PEEK cover.

These results suggest that an indirect calibration technique for the thermopile could work with the present configuration, provided that it is performed within the range of conditions at which the reference system (PEEK cover) is reliable. Once calibrated, the thermopiles measuring range can be extended, as they demonstrated good sensitivity also for smaller temperature differences or flow rates.
4.4. Numerical results
As pointed out, the validity of the temperature measurements with the PEEK cover embedded thermocouples must be verified. In particular, the ability of capturing the actual gas temperature must be assessed. For this purpose some of the measurements taken with the PEEK cover have been compared to numerical simulation results obtained from the CFD model. The boundary conditions for the channel bottom wall have been set at the temperatures registered by the thermocouples installed on the heating blocks. The upper wall temperatures have been derived from measurements with a blind foil. Finally, the inlet and outlet parameters have also been measured experimentally. The simulations have been run for steady flow, with the ideal-gas model for the density calculation. The actual thickness of the walls has also been taken into account, to include conjugate heat transfer effects in the calculations.

Figure 10 shows the results for a temperature set point at the heating blocks of 50 °C. The plot presents the axial temperature distribution for the top wall and for the gas flowing below it (namely 10 and 20 µm away from the wall). These profiles are compared to the measured values. The agreement is quite good, taken into account that the model dismisses the influence of the device surrounding the microchannel and the heat losses to the ambient (even though these have been minimized by the evacuated chamber).

5. Conclusions
A new sensor integration technique for studying microchannels fabricated from different materials has been presented. The developed prototype device allows overcoming the material limitations of previously developed integrated systems. Moreover, it allows the exchangeability of the microchannel test sections, broadening the flexibility and the range of possible applications for the integrated measuring system.

As a study case, the heat transfer of gas flowing in a microchannel has been investigated. This represents a typical case where the characterization of the local temperature distribution could be beneficial (especially when it comes to rarefied conditions where gas-surface interactions become important).

A special layout for the integration of commercial thermocouples in a microchannel has been developed, too. This was employed for validation and calibration of the integrated sensor.
The results showed the performance of the integrated sensors and highlighted the main issues encountered during the tests. These can be summarized as follows:

- The integrated measuring system allows the monitoring of the internal temperature distribution of a gas flow in a microchannel.
- The sensors show a good time response (compared to commercial sensors), thanks to the thin membrane configuration.
- The sensor calibration is not trivial and requires the implementation of indirect reference systems for temperature differences (thermopile calibration).
- The chip on top of which the membranes and the sensors have been manufactured presents major fragility issues. Defects of the chip created during the fabrication processes and the membrane itself can constitute crack starting points when the chip is mounted and exposed to thermal and mechanical stresses.
- The integration system for the commercial thermocouples allows a broader range of working conditions (thanks to a higher intrinsic mechanical stability). However, the sensitivity is lost at low mass flow rates and lower temperature.
- The validity of the results obtained with the commercial thermocouple array has been validated with CFD simulations.

Figure 10. Comparison between experimental data and CFD simulations for a wall temperature set at 50 °C, an inlet pressure of 150000 Pa and an outlet pressure of 83000 Pa (same as in the experimental conditions). Measures taken with the PEEK cover and embedded thermocouples. CFD simulation realized with FLUENT®.
As a final remark it can be said that, whenever local phenomena are investigated, the employment of integrated sensors allows a closer insight into microchannel flows. Commercial sensors can be employed in some cases, but presents some major limitations (e.g. can not be employed for rarefied gas flows due to the small quantities to be detected). The presented microsensor integration system showed the high potential of silicon-based sensors, and the possibility of broadening their use to applications not addressed yet. Further optimizations for the sensor layout are still needed (especially concerning the fragility during handling).

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