

Integrated SMD pressure / flow / temperature multisensor for compressed air in LTCC technology – thermal flow sensor

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ABSTRACT

In this work, we present an integrated flow / pressure / temperature multisensor in LTCC (low-temperature co-fired ceramic) technology designed for diagnostics monitoring of standard industrial compressed air circuits and devices, such as valves and actuators. The pressure sensor is based on a membrane carrying a thick-film piezoresistive Wheatstone bridge. Flow is sensed using the constant-temperature anemometric principle, with the sensing thermistors placed in a fluidics channel, which also comprises similar thermistors for temperature sensing. All three sensors are integrated into a single surface-solderable LTCC unit, with the solder fulfilling the roles of mechanical fastening, electrical connectivity and fluidic sealing. In this work, the flow-sensing part is demonstrated, and possible improvements in efficiency outlined.

Key words: multisensors, flow, pressure, temperature, LTCC

1. INTRODUCTION

Recently, LTCC technology has attracted considerable interest due to its ease of 3D structuration [1-3], combined with good thermal stability [4]. These advantageous features, coupled with the high achievable degree of compatibility with different thick-film materials, naturally predisposes LTCC for application to a wide variety of devices [5-12] that can be integrated into a single efficient LTCC package.

In fluidics, while LTCC cannot achieve the degree of miniaturisation of traditional silicon MEMS (microelectromechanical systems), it is better suited to less controlled industrial environments, where the presence of contaminants, for instance, would clog minute micromachined channels. Therefore, we endeavoured to apply this technology to an integrated flow / pressure / temperature multisensor (Fig. 1) for diagnostics of industrial compressed air systems [13-15].

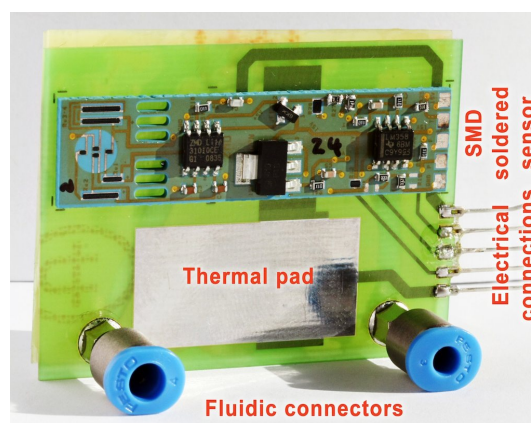


Fig. 1. Multisensor soldered onto fluidic test PCB.

The device [15] is intended for oversight of valves / actuators, in order to improve system reliability by early detection of anomalies such as excessive friction (high temperature), leaks and defective actuation (flow and pressure).

2. MULTISENSOR CONCEPT

Both the pressure and flow measurement sections were first developed as separate devices [13,14] before their integration into the present one (Figs. 1 & 2), whose salient features are:

- Anemometric flow sensing using a heated LTCC bridge in an inner channel [11]
- Temperature sensing in the same channel using passive structures identical to that of the flow sensor
- Piezoresistive pressure sensing
- Combined electrical + fluidic surface-mount device (SMD) – style assembly onto a printed circuit board (PCB) or similar substrate.
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The device comprises 5 LTCC layers:

- T1** Top lid & pressure-sensing membrane
- T2** Flow channel above sensing bridges
- T3** Temperature-sensing bridges (Fig. 3)
- T4** Flow channel below sensing bridges
- T5** Bottom lid – soldering

The (yet unoptimised) footprint is 50×12.7 mm. For convenience, the electrical connections are also provided at the edge. When mounted onto a PCB (Fig. 1), the solder joints are also used for heat dissipation, especially the central ground pad. The nominal supply voltage is +15 V, but the sensor can work with any voltage (above ca. 6 V) sufficient for flow measurement.

3. PRESSURE SENSOR DESIGN

The pressure sensor (Fig. 2, left) is based on a 3.6 mm diameter membrane carrying a thick-film piezoresistive Wheatstone bridge, with a dedicated IC (integrated circuit) for signal conditioning, the ZMD 31010 (ZMDI, Dresden, Germany), that also provides, through a field-effect transistor (Fig. 1 #3), a local 5V voltage supply used for pressure and temperature measurement.

The pressure measurement lies at the nominal fluidic inlet, but the flow direction may be reversed if required. In order to ensure a clean pressure signal, several features were carried over from the non-integrated flow sensor [14]:

- Outlying cantilever structure (i.e. not directly soldered to PCB, Fig. 2) for the pressure-sensing membrane, in order to avoid stresses due to soldering, with additional stress-decoupling slits.
- Pressure channel coming from deep below the surface (i.e. T2 complete around membrane opening) to avoid weakening the membrane.

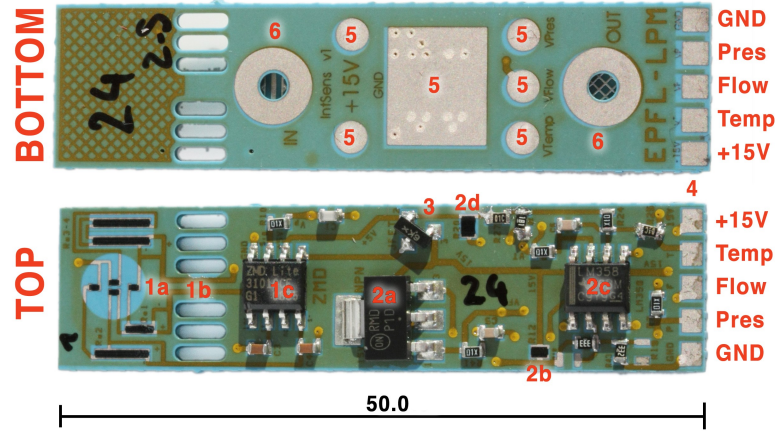


Fig. 2. Sensor top & bottom side. Elements / components: pressure sensor (1), flow & temperature sensor (2), power supply (3), edge electrical (4), SMD electrical (5) and SMD fluidic (6) connections.

4. FLOW SENSOR DESIGN

The flow measurement, is based on the hot-wire anemometric principle, with an LTCC bridge acting as the filament in a flow channel defined by the LTCC structure in the flow, and carrying a thick-film PTC thermistor used for both heating and measurement (Figs. 3-5).

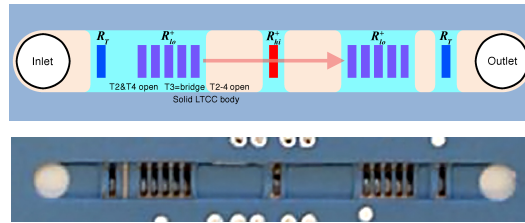


Fig. 3. Layout in flow channel – bridges & thermistors. Top: schematic diagram; bottom: actual photograph of open test device fabricated without T1.

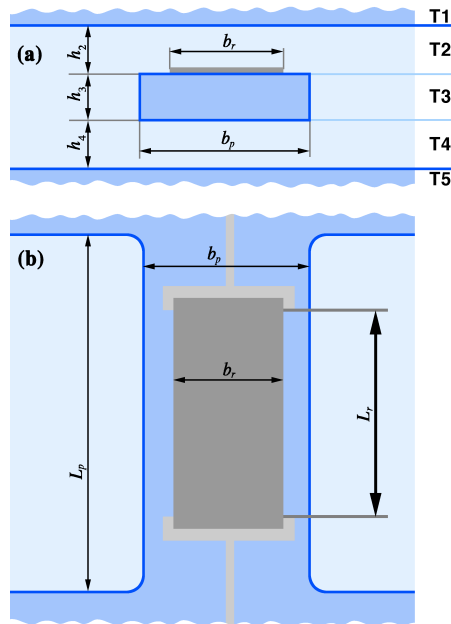


Fig. 4. Flow-sensing bridge geometry: (a) cross section with indicated tape levels, (b) layout. Standard dimensions [mm]: $h_2 = h_3 = h_4 = 0.21$; $b_r = 0.3$; $b_p = 1.0$; $L_r = 1.6$; $L_p = 3.0$.

To complete the resistive divider used for sensing, 10 (5 upstream + 5 downstream, Fig. 3) thermistors nominally identical to the sensing one and connected in parallel act as the reference resistor. Due to the nominally 10x better overall thermal coupling to the flowing gas and the LTCC structure and 10x lower dissipation, the temperature increase of the reference resistor vs. the package is very small compared to that of the measuring one.

In contrast to the pressure sensor, simple analogue signal conditioning is used for flow (Fig. 5), where the voltage applied to the flow measurement resistive bridge comprised of the four resistors $R_{hi/lo}^{\pm}$ is controlled by an LM358 operational amplifier across an NPN transistor, so that the output of the measuring resistive divider ("+" branch) matches that of the setpoint divider ("-"). The flow output signal is simply this applied bridge voltage U_{flow} , which increases with flow due to the heat carried away by convection. A pull-up resistor ensures "start-up" of the circuit by always supplying it with a minimal amount of current, and the target temperature rise is set by the initial imbalance (in the "cold" state) between the passive and active voltage divider.

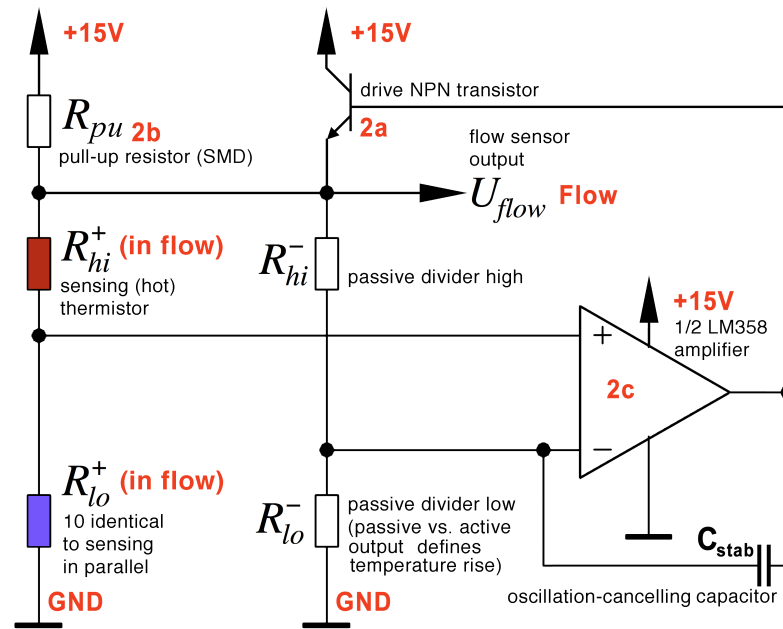


Fig. 5. Simplified electronics schematic of the flow sensor. See Fig. 2 for component location.

Table 1. Sensor fabrication – materials.

Element	Code	Notes
LTCC tape	DP 951 PX	All 5 layers ; 254 μm thick unfired, $\approx 210 \mu\text{m}$ fired
Via fill	DP 6141	Ag, for all vias
Inner conductor (1)	DP 6145	Ag, only for some tracks + shield ground plane
Inner conductor (2) Outer conductor	DP 6146	Ag:Pd \rightarrow tracks, solder pads & all resistor terminations
Piezoresistor	DP 2041	On T1; co-fired; for pressure measurements + misc.
Thermistor (PTC)	DP 5092D	On T3; co-fired; for flow + temperature measurement
Overglaze	DP QQ550	Post-fired 510°C ; also serves as solder stop mask
Solder (1)	SnAgCu or SnAg	On T1; Sn-Ag[-Cu] eutectic for components on sensor
Solder (2)	SnPbAg or SnBi	Lower-temperature eutectic solders for soldering to PCB

5. TEMPERATURE SENSING

The thermal flow measurement also allows easy integration of a temperature measurement, using two outlying extra thick-film PTC thermistors manufactured in the same step as the flow-sensing ones (Fig. 3, " R_T ") and connected in series, making the measurement relatively insensitive to flow direction. Passive resistors are added to build a bridge, whose signal is amplified by the second operational amplifier of the LM358 package.

6. DEVICE FABRICATION

The device was fabricated using DuPont (DP) 951 LTCC tape and associated materials (Table 1), with DP 2041 (10 k Ω sheet resistance piezoresistive composition) and DP 5092D (100 Ω PTC thermistor) compositions being classical alumina thick-film compositions, i.e. not designed for LTCC. After printing and drying, the tapes were aligned and stacked, then laminated at 160 bar at room temperature. Finally, firing was carried out in a lamp furnace, using a standard LTCC profile, with a maximum temperature of ca. 875°C [13].

7. RESULTS - FLOW SENSOR

Fig. 6 gives the flow response (0...20 normal litres / min) of a sensor. The regulated hot-wire temperature increase is ca. $\Delta T \approx +60$ K, and the no-flow thermal resistance of the bridge is estimated to be ca. 750 K/W, dropping to 180 K/W at the maximal investigated flow.

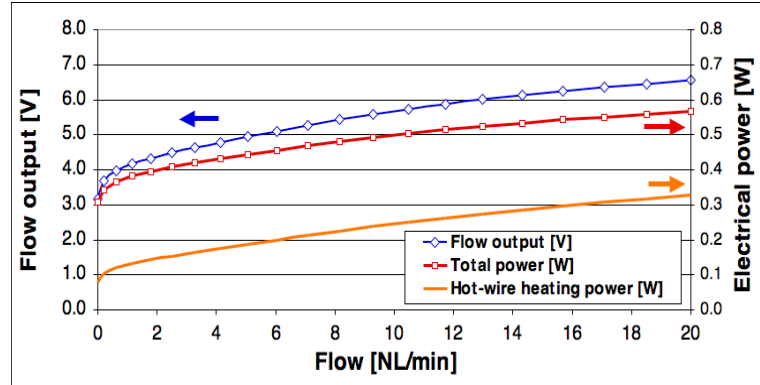


Fig. 6. Flow sensor output voltage and power consumption (measuring resistor alone and total) vs. flow, at 5 bar outlet gauge pressure and with +10 V supply.

While the measurement is robust and repeatable, the power consumption is still too high. This is due to the inefficient linear regulation electronics, and the high ΔT value for the measuring thermistor. Given the high thermistor response, ΔT (and hence the power) could be decreased by a factor of at least 5, which would however require higher bridge resistances, e.g. by switching from DP 5092D (100 Ω) to 5093D (1 k Ω) thermistor composition. This would in turn allow replacing both the LM358 and the transistor by a high-current rail-to-rail amplifier, bringing further improvements in size and efficiency (less voltage drop).

8. CONCLUSION

In this work, a multisensor for industrial compressed air, combining the measurement of flow, pressure and temperature, was presented and its flow-sensing part demonstrated. Further improvements will concentrate on reducing the power drawn by the flow sensor.

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