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Analysis and optimization of a thermal sensor system for measuring water flow

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ABSTRACT

A simple thermal sensor system was designed for measuring water flow in the water mains using the heat loss principle with a NTC thick film segmented thermistor as a self-heating sensor. Thick film segmented thermistors were screen printed on alumina substrate. NTC thermistor paste was formed of very fine $Cu_{0.2}Ni_{0.5}Zn_{1.0}Mn_{1.3}O_4$ powder obtained by a combined mechanical activation/thermal treatment process, an organic vehicle and glass frit. The thermal sensor system was analyzed in the static and dynamic regime. A range constant voltage power supply was defined in the range 9–19 V for input water temperatures of 30–2 °C, maintaining a supply voltage in steps of 2 V for a change in 5 °C of input water temperature. This enables optimal operating power, i.e. heat generation on the self-heating thermistor. Measured calibration curves for different input water temperatures and input water flow rates were modeled, enabling interpolation of additional calculated curves to cover a wide range of input water temperatures.

1. Introduction

The volume flow rate and velocity of water can be measured using different types of flow sensors [1]. Their application depends on the volume flow (quantity), turn down ratio, pressure and temperature of water and other specifications. Thermal flow sensors have been extensively studied and applied for measuring low volume liquid flow and gas flow [2,3]. Flow measuring with a thermal sensor can be performed using the following principles: heat loss, thermal time-of-flight and thermal transfer (calorimeter) [4]. Heat loss sensors generally operate in constant power or constant temperature modes.

Negative thermal coefficient (NTC) thermistors are thermally sensitive semiconductor resistors. They are characterized by a large temperature coefficient of resistance and operate as sensors using the heat loss principle [5]. The specific resistivity (ρ) of NTC materials follows the well known Arrhenius equation: $\rho = \rho_0 \exp(E_a/kT)$, where ρ_0 is the resistivity at infinite temperature, E_a is the electronic activation energy, k is the Boltzmann constant and T is the temperature [6–8]. The thermistor constant B (B-value) is defined as E_a/k (with unit temperature in Kelvin) and represents the measure of sensitivity of the thermistor device over a given temperature range.

NTC thermistors are commonly used to measure temperature as they offer good sensitivity and accuracy at a relatively low price. Changes in the resistance of a NTC thermistor are the result of self-heating. This is the consequence of electric current flowing through the thermistor and raising its temperature above that of its environment [4]. Self-heating of a thermistor can be achieved by a constant current or constant voltage supply. In our previous work we proposed a range constant voltage (RCV) concept. The operating point in the case of a constant voltage supply is optimized by changing the voltage in steps in accordance with changes of the incoming water temperature in order to enable operation of the sensor at optimal sensitivity for different water temperatures [9]. We designed a simple thermal sensor system (flow-meter for water) for determining running water flow operating using the heat loss principle. It consisted of a self heated NTC thick film thermistor used as a heat loss sensor and a second "cold" thermistor used to measure the temperature of the incoming water. Though this sensor system showed good performance, one of the disadvantages was the required input voltage that was relatively high and in the range 50–125 V to attain a self-heating current of 20 mA. Another disadvantage was the actual size of the segmented NTC thick film of 50.8 mm × 6.35 mm × 0.5 mm.

Nickel manganite based spinel oxides are the most common NTC materials due to their low cost, ease of manufacturing and

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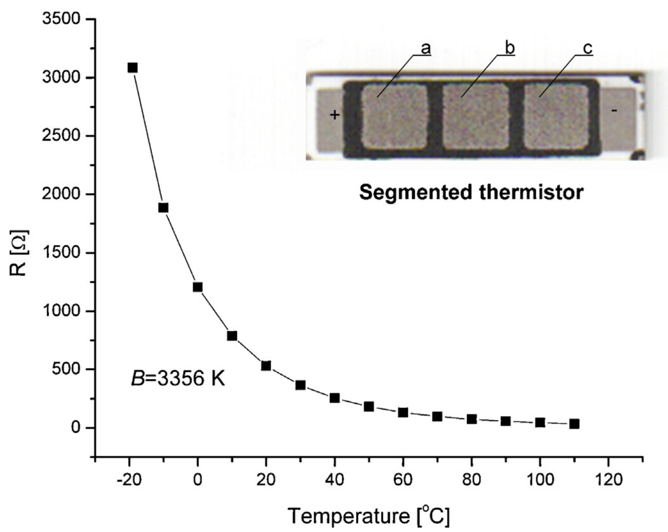

Fig. 1. Temperature dependence of NTC thick film segmented thermistor resistance measured in a climatic chamber; inset – top view of a NTC thick film segmented thermistor: NTC layer (black), PdAg electrodes (gray), alumina substrate (white).

good thermistor properties [10]. In our previously analyzed thermistor system we used pure nickel manganite powder [9]. In order to lower the resistance of the starting thermistor powder we have performed a detailed investigation of co-doping with Cu and Zn by applying a combination of mechanical activation and thermal treatment [11]. Thick film segmented thermistors printed from the obtained $Cu_{0.2}Ni_{0.5}Zn_{1.0}Mn_{1.3}O_4$ powder had a typical dendrite structure with small grains and a developed surface area. The actual size of these thermistors was 25.4 mm × 6.35 mm × 0.6 mm that is two times smaller than the previously used segmented thermistor (50.8 mm × 6.35 mm × 0.5 mm) [9,11]. Other advantages of these segmented thermistors compared to the previously used segmented thermistors [9] were lower sheet resistivity and reduced dissipated power. The determined thermistor constant of $B = 3356$ K and resistivity drift of 0.23% confirmed possible application of these thermistors in thermal sensor systems for water [11]. Preliminary investigations of current/voltage characteristics of these thermistors have shown that a five times lower applied input voltage is needed to achieve a two times higher self-heating current [12]. In this work we have performed a detailed analysis and optimization of a thermal sensor system (high pressure flow meter for water) using these newly produced thick film segmented thermistors and supplied with a RCV voltage supply. Modeling of heat loss was performed in order to calibrate the water flow as a function of the self-heating current.

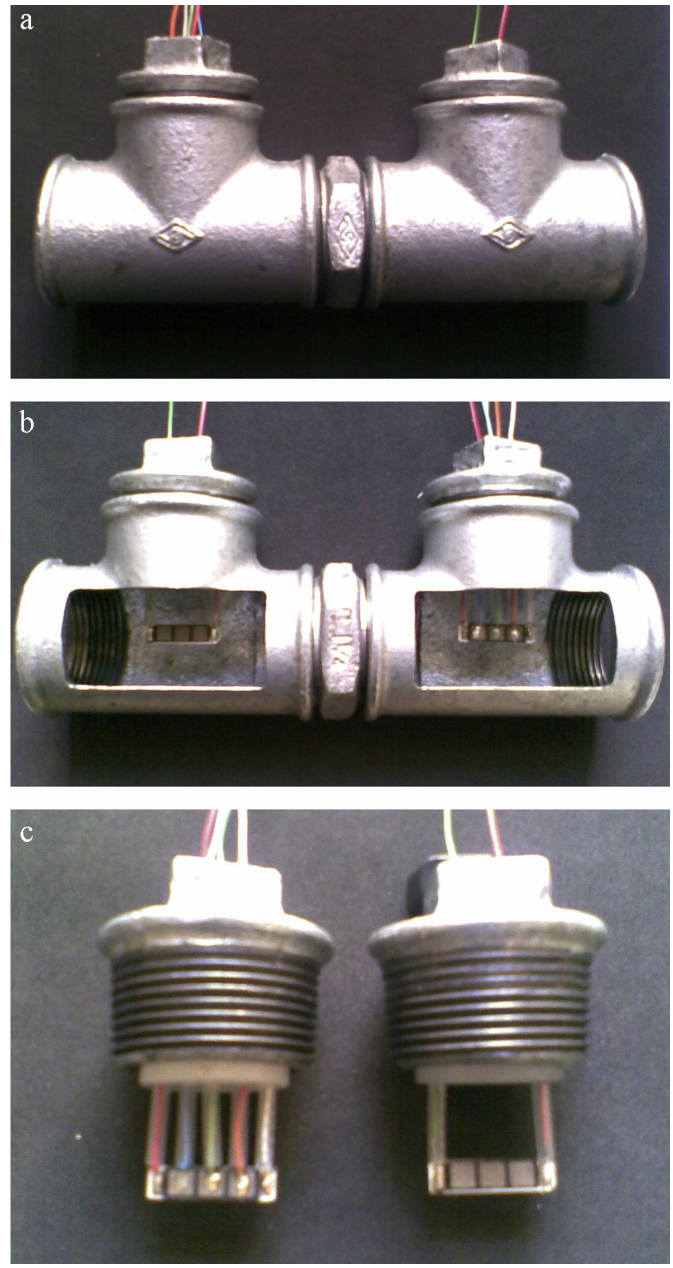

Fig. 2. Realized RCV thermal sensor (flow meter) for water: (a) prototype with two tees, (b) showing the two NTC thermistors inside and (c) NTC thick film thermistors placed on the cap fitting.

2. RCV thermal sensor

Thick film segmented thermistors were produced by screen printing of thermistor paste composed of $Cu_{0.2}Ni_{0.5}Zn_{1.0}Mn_{1.3}O_4$ powder an organic vehicle and glass frit as described in detail in [11]. The NTC thermistor powder was prepared by a combined mechanical activation/thermal treatment procedure. Initial $MnCO_3$, NiO, ZnO and CuO oxide powders (Aldrich, purity 99.9%) were mixed in the appropriate ratio to obtain $Cu_{0.2}Ni_{0.5}Zn_{1.0}Mn_{1.3}O_4$. The oxide mixture was milled in a planetary ball mill for 120 min in stainless steel bowls with stainless steel balls (15 mm in diameter). The powder to ball ratio was 1:20. The obtained powder mixture was slowly heated in air to 1100 °C, held at this temperature for 2 h and then slowly cooled to room temperature. The calcined powder was milled again for 30 min under the same milling conditions. Analysis of the crystal structure and microstructure of this powder performed in [11] showed that a cubic spinel structure was obtained. The powder particle size was uneven and irregular with a distribution of small particles (around 200 nm) and larger agglomerates. The NTC layer was printed on alumina substrate (actual size 25.4 mm × 6.35 mm × 0.5 mm) and fired at 850 °C/10 min in a hybrid conveyer furnace in air. Electrodes were printed using conductive PdAg paste (DuPont 9308) on the top and bottom of the NTC layer as shown in Fig. 1 (inset). This enables distributed voltage along the thermistor and zig-zag flow of self-heating current between two electrodes. The power supply electrodes are designated with + and −, while *a*, *b*, and *c* are control electrodes for measuring partial voltages V_{ab} and V_{bc}. Their difference $\Delta V = V_{ab} - V_{bc}$ is caused by water flow forming a temperature gradient in the flow direction (along the thermistor). When the water flow $Q = 0$, $\Delta V = 0$, as Q increases ΔV also rises and can be correlated with the water flow and incoming water temperature.