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A new approach to measuring the temperature fields in reflow ovens

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Electronics play an increasingly significant role in our lives. Consequently, the demand for both production volume and quality in electronics is continuously rising. Conveyor reflow ovens are the most widely used technology for soldering electronic assemblies onto printed circuit boards. The implementation of these ovens directly affects the quality of solder joints and, most importantly, the reliability of manufactured electronic assemblies, which are present in virtually all aspects of daily life. The solder joint is formed by the reflow of the solder alloy and is defined by the thermal profile, which represents temperature over time. The most common heating method relies on forced hot air convection, where the printed circuit board with mounted components moves through the oven. One of the key design requirements for these ovens is maintaining a consistent thermal profile to achieve a homogeneous temperature field across the reflow zones. To assess this condition, it is essential to measure convection under operating conditions. A new method for measuring the temperature field directly within the conveyor oven has been developed and experimentally verified during production.

Keywords: reflow soldering process, heat transfer coefficient, gas flow velocity, Reynolds number, temperature field

1 Introduction

The complexity of electronics is constantly increasing, leading to growing demands on soldering equipment. Each conveyor reflow oven consists of a certain number of independent heating zones arranged sequentially in the direction of product movement through the oven. By regulating the temperature in each zone, an appropriate thermal profile is achieved.

With the transition to lead-free solder alloys, the so-called process window has narrowed, meaning that components must be soldered using a lower heating gradient to prevent thermal damage. Precise control of the soldering process is therefore crucial. Since heat transfer to the product occurs through thermal exchange between the flowing gas and the product, the direction and gas flow velocity are key factors to ensure a technologically correct process.

This study focuses on measuring gas flow velocity, specifically through a newly developed method for measuring temperature fields inside a conveyor oven. [1] The FS7.4W sensor is used to measure the temperature, as it can operate at temperatures corresponding to the reflow of soft solder alloys. It is characterized by excellent long-term stability and low thermal mass, which enables a fast response time. This sensor allows for airflow velocity measurements over a wide range, from 0.01 to 100 m/s, at temperatures of up to 400 °C [2].

2 Subject and methods

Airflow velocity can be measured in several ways. However, the choice of measuring device and method always depends on the maximum temperature at which it can be used. Mechanical vane anemometers can typically be used at temperatures up to 150 °C. Measurements based on micro-pressure principle are limited to even lower temperatures, with a maximum of 50 °C. Since temperatures in the soldering process reach up to 250 °C, an alternative measurement method had to be chosen. The Swiss company IST AG has developed airflow sensors capable of operating at temperatures up to 400 °C. These sensors operate based on the calorimetric principle (CTA – Constant Temperature Anemometer) and follow an empirical equation defined by King's law:

$$P_{\mathrm{H}} = I_{\mathrm{H}}^2 \cdot R_{\mathrm{H}} = (A + B \cdot v^n) \cdot \Delta T \qquad n = 0.3 \ldots 0.5 \tag{1}$$

where P_{H} represents the power of the heating element, I_{H} is the current of the heating element and R_{H} is its resistance. A and B are calibration constants, v is the gas flow velocity. The measuring electronics maintains a constant temperature difference between the sensor and the measured medium. For gases, a temperature difference (ΔT) of 30 °C is recommended. Exponent n depends on the measured medium, for air is n = 0.5.

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These sensors are based on very thin ceramics (0.2 mm), with the functional parts made of platinum. The measuring system uses the signal from two sensors and monitors the temperature on a test pad that simulates a 1.6 mm thick printed circuit board. To differentiate the direction of airflow, the sensors are equipped with a shutter that allows airflow only in the desired direction. The measured data, in CSV format, are downloaded via a USB interface using a terminal program and are available for further analysis. The measurement frequency is 4 times per second. Several measurements were performed on three ovens from different manufacturers. A similar length of the process chamber was chosen to make the results more comparable.

The issue of thermal protection for the measuring device itself is also essential. The temperature should not exceed 80 °C inside the measuring device. Three layers of cork were used to create an insulating layer, which proved to be fully sufficient within the given temperature range. The schematic diagram of the developed measuring device is shown in Fig. 1.

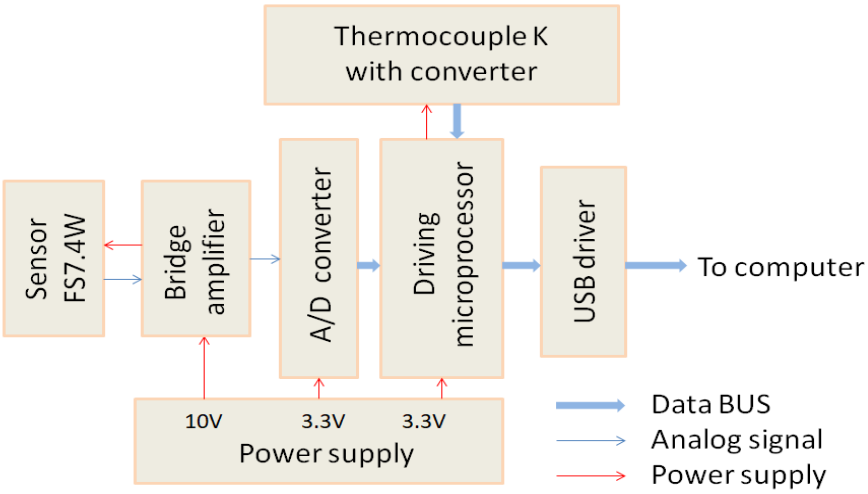

Fig. 1. Developed measuring device

3 Experimental part

The newly developed method was verified using three different types of soldering ovens, each having different nozzle field arrangement designs. These ovens, from various manufacturers, have been used in production for several years.

3.1 Oven No. 1

Detailed parameters of the flowing gas volume for this oven are known [9] for various heating zone settings, such as different fan frequencies (see Tab. 1). The heating zone is based on a uniform nozzle field design. Each nozzle field consists of 247 holes with a diameter of 4 mm and each hole is beveled for the product side (Fig. 2).

Table 1. Settings for oven No. 1

Fan frequency (Hz)	Gas volume in the zone (m^3)	Flow velocity in the nozzle (m/s)	Flow velocity in the suction zone (m/s)
35	170	15.21	1.54
40	190	17.00	1.72
45	210	18.79	1.90

Fig. 2. Oven No. 1 with 247 nozzles in the nozzle field

Distinction between laminar or turbulent flow is made by calculating the Reynolds number, which is defined by the following equation:

$$R_e = \frac{\rho \cdot v \cdot d}{\eta} = \frac{v \cdot d}{\upsilon} \qquad (2)$$

where v represents the flow velocity, d corresponds to the characteristic dimension (diameter) of the nozzle and υ is the kinematic viscosity of air at the given temperature.

A Reynolds number greater than 2320 indicates that the flow is turbulent. In this case, after substituting the appropriate values for a temperature of 20 °C and a fan frequency of 45 Hz, R_e = 4.200 is obtained, which means the flow is turbulent. Even with increasing temperature, the flow remains turbulent.

During soldering, the temperature of gas (air) varies in different zones, which in turn causes the density of the flowing air to change within a certain range. When the fans are set to 35 Hz, the volume of air moving in each zone is approximately 170 m³/hour. When the fan frequency is increased to 45 Hz (the standard setting), the volume of blown air becomes approximately 210 m³/hour. As the gas (air) is heated in the oven, its density decreases with rising temperature. The air (containing approximately 80% nitrogen) changes its density from 1.149 kg/m³ to 0.722 kg/m³ at 220 °C. This means that, volumetrically, the oven must "blow" a much larger volume of air at higher temperatures. A simple calculation can demonstrate a change of approximately 26 to 33 m³/hour at temperatures of 100 °C and 210 °C, respectively.

As seen in Fig. 2, the nozzle arrangement along the longer side of the nozzle field has (3) relatively large gaps. This geometric arrangement also affects the flow inside the oven, as shown in Fig. 3.

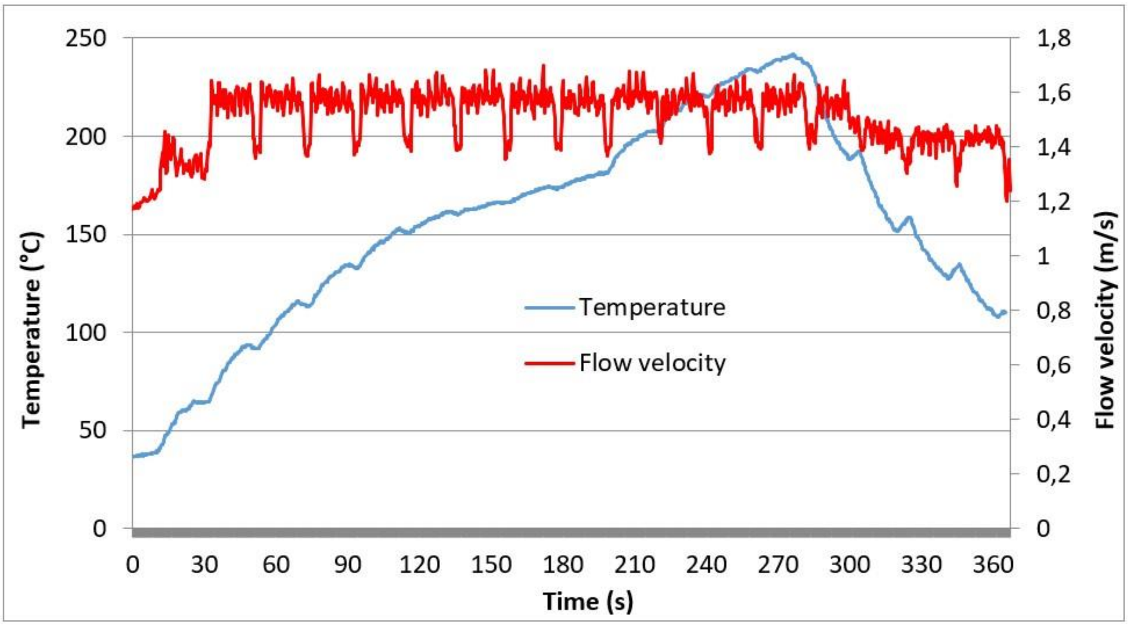

Fig. 3. Flow velocity and thermal profile in the measured oven along the Z-axis direction

Figure 3 illustrates that the measured values in oven No. 3 show a very pronounced separation of zones. This could result in a larger temperature difference between the zones (e.g., due to a faster transition from solid to liquid), but on the other hand, this may cause issues when automatically evaluating the thermal profile. The evaluation software may struggle to recognize the transition to liquid. The significant separation of zones is also reflected in the thermal profile of the oven.

Figure 3 also shows that the first zone has a significantly lower gas flow velocity. This is because, for lead-free alloys, the maximum temperature change in time for the oven is limited to 3 K/s. Some companies introduce even stricter internal regulations for this limit. Therefore, the oven manufacturer responded by providing separate fan control for the first zone (both top and bottom). This ensures that the stricter requirements are met.

3.2 Oven No. 2

The openings in the nozzle field are arranged in regular rows (a total of 221), through which hot gas flows towards the soldered electronic assembly (Fig. 4). Slightly different geometry in the arrangement of the nozzles has a significant effect on the flow pattern and, consequently, on the thermal profile.

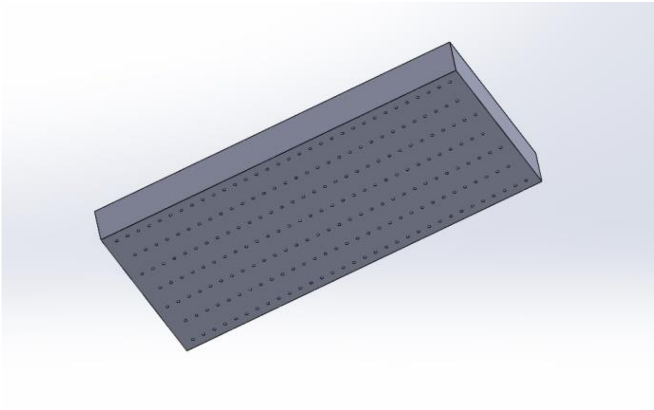

Fig. 4. Nozzle field – oven No. 2

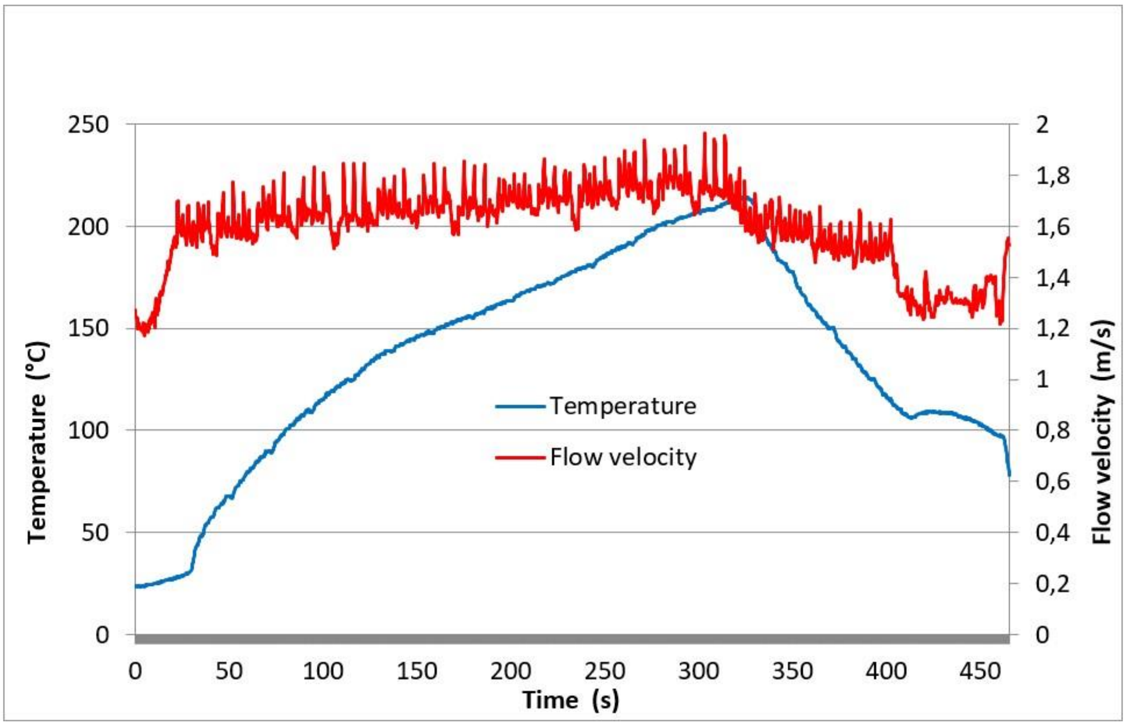

Fig. 5. Flow velocity and thermal profile for oven No. 2

The modified geometry of the nozzle field shows significantly smaller separation between the zones, as seen in Fig. 5. The same effect is also reflected in the thermal profile curve. In this oven, a smaller temperature difference between the zones can be achieved while maintaining a smooth temperature curve. On the other hand, further investigation reveals that the oven exhibits some unevenness in the flow, as seen from the overall flow velocity profile.

3.3 Oven No. 3

Oven No. 3 differs significantly from the previous two ovens. It uses forced convection by axial fans, in contrast to the radial fans used in the first two ovens. The nozzle field consists of longitudinal slits, whose area is several times larger than that of the first two ovens (Fig. 6). This fact also significantly affects the flow pattern. The flow velocity is higher than in the first two ovens, and the volume of gas flowing inside the oven is also considerably larger.

Due to the significantly higher flow of hot gas in the individual zones, there is also a higher risk of unwanted component displacement on the PCB. Therefore, when setting up this oven, it is necessary to consider its specific mechanical design and adjust the thermal profiles accordingly. The flow velocity and thermal profiles are shown in Fig. 7.

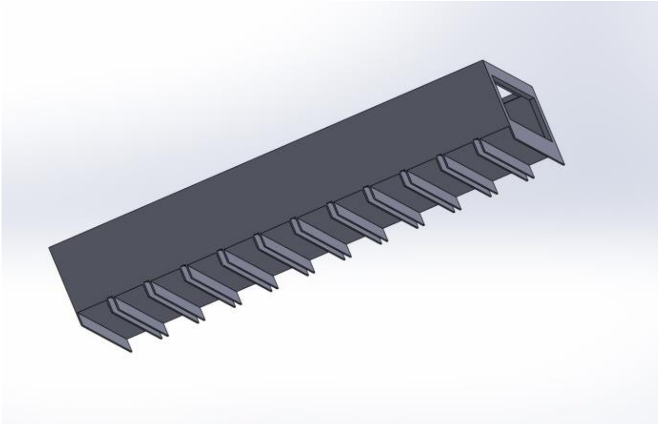

Fig. 6. Nozzle field – oven No. 3

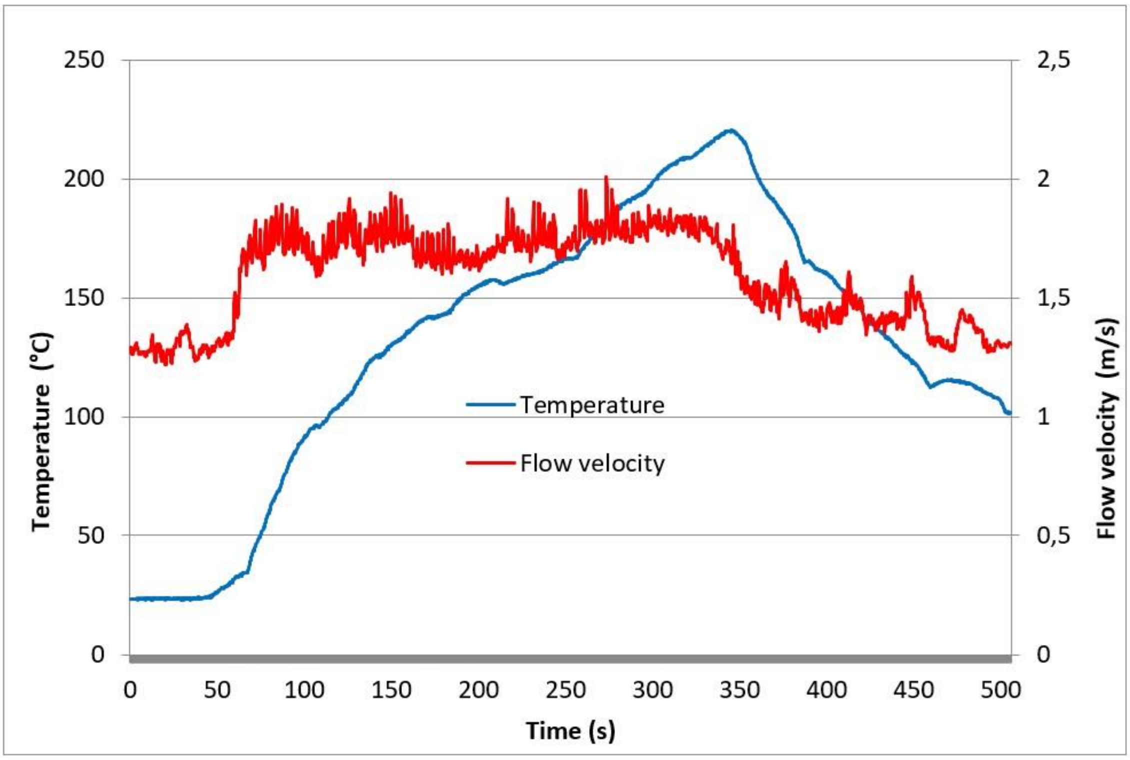

Fig. 7. Flow velocity and thermal profile for oven No. 3

4 Discussion

The newly developed and validated method allows for temperature field measurements under operating conditions, compared to previously published methods [5-7]. The measurement results clearly demonstrated a direct correlation between the geometric design and the flow pattern. It was shown that even small changes in the nozzle field design can affect the behavior of individual heating zones, particularly the flow pattern between the zones.

Each solution has its pros and cons. In the case of the first oven, the geometry of the nozzle field clearly creates a significant separation between zones. This may be highly desirable for a specific thermal profile. On the other hand, it may pose a problem in the automation of the thermal profile control process. In oven No. 2, the temperature curve is smooth and shows no abnormalities. Oven No. 3 reflects a different type of forced convection with the use of axial fans. Given the significantly larger volume of gas heating the soldered assembly, increased caution must be taken when setting it up due to the potential displacement of components.

The shown solution has proven effective in comparing ovens from different manufacturers and can be used in benchmarking tests as one of the evaluation parameters. Even during the design phase of the soldering oven, it can help optimize the flow and thus the efficiency of the oven. In light of the increased production volume, this represents a significant opportunity for production cost savings while maintaining the quality of the soldering process.

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