Research on temperature field model of hot air reflow soldering process

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Abstract. In this paper, two typical temperature models on the hot air reflow soldering process are studied. The critical difference between the two model is the approach used to compute the convective heat trans coefficient during the soldering process. In the model 1, the Martin formula and k-epsilon (2eqn) equation is applied to obtain the average convective heat transfer coefficient. And in model 2, the liquid and solid coupling CFD model is built to compute the convective heat transfer coefficient inherently. The comparing between the simulation and the test is conducted and shows that the simulation result of model 2 are closer to the real value. The comparing between these two models shows that the gas temperature, the gas velocity and the convective heat transfer coefficient around the PCB A is quite different. It is indicated that the average convective heat transfer coefficient calculated by Martin formula was larger. The CFD model is prefer for simulating the temperature distribution of the PCBA during the air reflow soldering when higher result precision is needed.

1. Introduction

At present, reflow soldering technology is still the most widely used technology in SMT of electronic industry. Although the temperature can be measured by a large number of sensors, it costs too much resources. Therefore, finite element simulation is one of the most effective methods to study reflow soldering. In the research of simulation model, the average convective heat transfer coefficient was used as the boundary condition of simulation model, 2D and 3D models were established, and the temperature field, post weld residual stress and reliability were studied [1]. However, in the actual reflow furnace, the convective heat transfer coefficient is a dynamic parameter, whether the process needs to be considered into the simulation model was a problem worthy of consideration [2, 3]. Some researchers have studied the factors affecting the convective heat transfer coefficient and introduced a measurement method, but it is still unable to get the convective heat transfer coefficient of the whole PCBA area [4, 5]. some researchers paid more attention to the gas velocity in the reflow soldering furnace [6]. It can be seen that the dynamic convective heat transfer coefficient on PCBA was lack of overall research in reflow soldering process.

In this paper, in order to solve the problem of loaded convective heat transfer coefficient in the simulation model, the average convective heat transfer coefficient simulation model and dynamic convective heat transfer simulation model were established. By comparing the simulation results of the two models, the reasons for the difference of the simulation results were analyzed, which provides an idea for the loading boundary conditions of the simulation model.
2. Materials and methods

2.1. Experimental measurement

The research was conducted on 1809EXL type infrared hot air reflow welding furnace produced by Heller company of Germany, which has 12 temperature zones in total. The infrared heating zone which keeps the plate temperature consistent is ignored and the longer transition zone in the furnace cavity is considered. Finally, the temperature distribution and length distribution of the reflow furnace are shown in Table 1. The speed of the conveyor belt (V) was 13.3 mm/s.

| zone | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|------|----|----|----|----|----|----|----|----|----|----|----|----|
| T/℃ | 160| 170| 180| 180| 210| 260| 250| 150| 130| 130| 130| 130|
| L/mm | 360| 257| 267| 250| 295| 315| 270| 240| 110| 310| 310| 310|

According to the previous test experience, connect the thermocouple in the furnace temperature tester to the 8 failure prone points, as shown in Figure 1. The temperature change curve of 8 detection points is obtained by loading the temperature curve in Table 1, which is used for comparison of the simulation model results.

![Figure 1. Positions of thermal couplings.](image)

2.2. Average convective heat transfer coefficient model 1

The average convective heat transfer coefficient simulation model 1 was established by Workbench mechanical. When the reflow process curve is input, the gas flow velocity and gas temperature of the nozzle in the furnace cavity was determined regardless of the geometry of PCBA. In view of these constants, Martin summarized a large number of results about the convection coefficient of jet impingement, and proposed the calculation methods of the average convection heat transfer coefficient and nozzle flow velocity of jet array with square and circular cross section. The related formulas are shown in formulas (1), (2) and (3).

\[
\overline{N_u} = f(R_e, Pr, A_r, H/D)
\]

\[
\overline{h} = \frac{k}{D} \frac{\overline{N_u}}{D}
\]

\[
V_e = \left[ \frac{1}{\sigma R_p^{0.42}} \right]^{3/2} \overline{v} \overline{h}^{3/2}
\]

where \(A_r\) is the ratio of the cross-sectional area of the nozzle outlet to the surface sum of the unit; \(H\) and \(D\) are the size parameters of the nozzle, unit: m; \(k\) is the heat conductivity coefficient of convective gas, unit: W/m·K; \(\nu\) is the viscosity of gas movement, unit: m²/s.

According to the furnace related parameter information, it can be known that \(A_r=0.03499\), \(K=0.7549\), \(G=0.2035\), \(\delta=0.4353\). In order to confirm the average convective heat transfer coefficient, it was necessary to confirm the flow temperature of PCB. Aluminum alloy A plate is used as the test plate to measure the relevant parameters. Aluminum alloy 2A12-H112 plate is used as the test plate to measure the relevant parameters. Finally, the average convective heat transfer coefficient and nozzle velocity are obtained based on Martin's formula, as shown in Table 2.
Table 2. Convective heat transfer coefficient and nozzle wind speed in different temperature zones.

| zone | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|------|---|---|---|---|---|---|---|---|---|----|----|----|
| \( h \) | 42.6 | 63.9 | 71.2 | 69.8 | 65.1 | 50.4 | 58.5 | 52.1 | 76.0 | 79.4 | 43.6 | 29.2 |
| \( Ve \) | 4.51 | 9.79 | 11.55 | 10.25 | 6.97 | 9.19 | 7.66 | 13.43 | 16.0 | 5.52 | 2.97 |

In order to improve the calculation efficiency, the model was simplified on the basis of ensuring the accuracy. The meshing is shown in Figure 2.

Figure 2. Model 2 Grid distribution diagram.

The average convective heat transfer coefficient model 1 was established by loading the reflow soldering temperature curve in Table 1, the nozzle wind speed and the average convective heat transfer in Table 2. The simulation results of 8 detection points were shown in Figure 3.

Figure 3. Temperature chart of model 1 simulation results.

2.3. Dynamic convection heat transfer coefficient model 2

In reflow soldering furnace, gas was injected into furnace cavity vertically by nozzle, and radial laminar flow was formed on PCB board. The radial flow layer mainly flows to the entrance and exit of the region, but turbulence was formed due to the blocking points (walls, components, etc.) in the region. The k-epsilon (2eqn) model can well simulate the flow situation in the cavity. The model is shown in equation (4) [6].

\[
\frac{\partial}{\partial t} \left( \bar{\rho} \varepsilon \right) + \frac{\partial}{\partial x_j} \left( \bar{\rho} \bar{u}_i \varepsilon \right) = \frac{\partial \bar{\rho}}{\partial x_i} \left[ u \frac{\partial \bar{u}_i}{\partial x_j} \frac{\partial \varepsilon}{\partial x_j} + \left( u + \bar{u}_i \right) \frac{\partial \bar{u}_i}{\partial x_j} \frac{\partial \varepsilon}{\partial x_j} \right] C_1 \frac{\varepsilon}{k} - \bar{\rho} C_2 \frac{\varepsilon^2}{k} \tag{4}
\]

where \( \sigma_k = 1 \), \( \sigma_\varepsilon = 1.22 \); \( C_1 \) and \( C_2 \) are the applied constants, \( C_1 = 1.44 \), \( C_2 = 1.92 \).

The k-epsilon (2eqn) model was effectively constructed by Flunet software to realize the establishment of dynamic convection heat transfer model 2. Through the measurement of the furnace
cavity, the fluid domain of PCBA was constructed. Model 2 is obtained with consistent PCBA meshing, as shown in Figure 4.

![Figure 4. Model 2 Grid distribution diagram.](image)

Model 2 only needs to load temperature and nozzle velocity to simulate the temperature field. The loading temperature curve was the reflow temperature curve in Table 1, and the nozzle speed was the nozzle speed in Table 2. The system calculates the convective heat transfer coefficient at each moment to complete the establishment of dynamic convective heat transfer coefficient model. The temperature changes of 8 detection points in model 2 were shown in Figure 5.

![Figure 5. Temperature chart of model 2 simulation results.](image)

3. Results & discussion

The simulation results of model 1 and model 2 are compared with the real values, the subtraction results were shown in Figure 6 (the partial detection results are shown). It can be seen from Figure 6 that the simulation result of model 2 was closer to the real value than that of model 1. The next analysis of possible causes.

![Figure 6. The difference between simulation value and real value (a is point 1, b is point 4, c is point 8).](image)
The difference of gas velocity is one of the reasons for the difference of simulation results between the two models. In Model 2, the gas velocity changes at different times. The reason is that after the gas is ejected from the nozzle at a certain speed, the air flow is hindered by PCB and various components of different heights on its surface, resulting in complex changes in the gas flow rate, as shown in Figure 7. Therefore, the gas velocity around PCBA is not equal to the initial gas velocity. However, in model 1, the change of gas velocity is not considered under the average convective heat transfer coefficient, and the gas velocity around PCBA is equal to the initial gas velocity, so the simulation results of the two models are different.

![Figure 7. Fluid distribution inside the cavity (a) was Velocity diagram, (b) was the vector diagram.](image)

One of the reasons for the difference between the simulation results of the two models is that the temperature of the gas around the PCBA is different. The temperature of the gas close to PCBA is different from that in the cavity, which shows that the temperature of the gas around PCBA will be lower than that of the gas ejected from the nozzle, the result is shown in Figure 8. Model 2 takes account of this part of the temperature change, so it is closer to the real value.

![Figure 8. Temperature distribution of air around PCB board.](image)

The difference of convective heat transfer coefficient on PCB is one of the reasons for the difference of simulation results between the two models. This was shown in Figure 9 that model 1 has a large convective heat transfer and absorbs more heat. The dynamic convective heat transfer coefficient of model 2 is closer to the real situation. Therefore, it is necessary to consider the dynamic convection heat transfer coefficient in the simulation process.
4. Conclusions

Based on the finite element simulation, the temperature field of hot air reflow soldering process was studied. The model 1 with the average convective heat transfer coefficient based on Martin formula and model 2 with the dynamic convective heat transfer coefficient based on k-epsilon (2eqn) equation are analyzed and compared comprehensively. The conclusions are as follows:

(1) The temperature result by the model 2 is closer to the test comparing with the result of model 1, due to the influence of PCBA surface components on gas temperature and flow velocity can be more accurately considered in the model 2.

(2) In model 2, the detailed process of energy transferred from the gas to the PCB can be predicted, which is helpful to better understand the dynamic change of convective heat transfer coefficient and the reflow soldering process.

(3) In model 1, although the temperature tendency on PCB is consistent with the actual situation, the temperature is much higher than the actual temperature. The average convective heat transfer coefficient by the Martin formula in model 1 can be reduced appropriately.

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