Research on Temperature Change of Reflow Furnace Based On Mathematical Modeling

Hao Chen*

School of Mathematics and Statistics, Wuhan University, Wuhan, China

*Corresponding author e-mail: chenho@whu.edu.cn

Abstract. After referring to many documents, this article comprehensively considers various heat transfer methods, analyzes the heat transfer process of welded components, and establishes a temperature field distribution model based on one-dimensional transient heat transfer equation by ignoring some irrelevant conditions, and using the finite difference method. We solve it and apply it to the optimization of furnace temperature curve. Due to the many types of reflow furnaces, this article mainly considers hot-air reflow furnaces. The heating methods are mainly heat convection and heat conduction, ignoring heat radiation. The welding area is established by the transient heat transfer equation. The temperature field distribution model is established, and the initial conditions and thermal boundary conditions are determined. Related heat transfer analysis is done for the front area, back area and gap areas. Finally, through the experimental data and the idea of least squares, the parameters of the electronic devices used in this experiment are obtained, and it also provides an idea to check whether the relevant parameters of the experimental materials are accurate. In order to make it easier for the staff to operate, this article proposes a method to find the maximum speed of conveyor belt, which has great practical significance.

1. Introduction

In the production of electronic products such as integrated circuit boards, printed circuit boards with various electronic components need to be placed in a reflow furnace, and the electronic components are automatically soldered to the circuit board by heating. In this production process, keeping all parts of the reflow furnace at the temperature required is essential to product quality. At present, many works in this area are done by being controlled and adjusted through experimental tests. Since the reflow furnace plays a great role in the chip manufacturing process, its operating mechanism is very complicated, and the heat transfer process is very complex. In previous studies, scholars often determined the convection coefficient through multiple experiments, and then obtained the furnace temperature curve. In 2016, Shang-Shuan Deng [1] used fluid mechanics software to simulate the forced convection reflow furnace, and observed the air flow field in the furnace through the simulation results. In 2019, Iqbal's research [2] studied the temperature change in the reflow furnace from the perspective of fluid mechanics. These studies often start from the perspective of experiments, requiring more professional experimental equipment, and the experimental conditions are relatively harsh, making it difficult for later scholars to continue to make full use of or develop. From the searching results, there are few scholars who directly study the temperature change of the reflow furnace from the perspective of mathematical modeling. The
scholar Paul Svasta [3] proposed in the 2002 research results to establish a mathematical model from the perspective of heat conduction and heat radiation to discuss the temperature change of the reflow furnace. These studies are often based on known experimental parameters, such as material width, thickness, and specific heat capacity. [4] However, when these parameters are not known, it is often difficult to complete the model construction. When the parameters are wrong, errors will occur in the prediction results and therefore cause losses. Therefore, a calculation method based on experimental data should be provided for the required parameters, and a more complete model of the temperature curve in the furnace should be given to solve some problems often encountered in production.

2. Methods and analysis

According to related documents, there are many technical classifications of reflow ovens, such as hot plate type, infrared type, hot air type, laser type and gas phase type, etc. Here we mainly consider air-heated full hot air reflow oven (the internal structure is shown in figure 1). Therefore, when establishing the heat transfer equation, two heat transfer methods, heat convection and heat conduction, are mainly considered, and the influence of heat radiation is ignored. Electronic components are solid, so there is less internal heat convection during electrons, and heat conduction is mainly considered. The surface heat convection occupies the main part during the air-to-electron period.

Figure 1. Internal structure of reflow furnace

2.1. Mathematical Model.

For the convenience of research, take the direction perpendicular to the electron period as the x-axis, and establish a coordinate system as shown below:
Therefore, we denote $T(x,y,z,t)$ as the temperature at time $t$ and position $(x,y,z)$. Since this article mainly considers the heat transfer of the YOZ plane, $T$ can be abbreviated as $T(x, t)$, so according to the law of heat transfer, $T$ satisfies the following formula:

$$\frac{\partial T}{\partial t} + \text{div}(\rho c \nabla T) = k \text{div}(\nabla T) + S_T$$  \hspace{1cm} (1)

When only considering heat conduction, the above formula is transformed into[5]:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c} \text{div}(\nabla T)$$  \hspace{1cm} (2)

Among them, $\rho$ represents the density of the object; $c$ represents the specific heat; $\lambda$ represents the thermal conductivity, $k = \frac{\lambda}{c}$. 

Figure 2. Front view of coordinate system

Figure 3. Top view of coordinate system
Since the conveyor belt will not send the electronic components into the furnace until the temperature in the furnace has stabilized, it can be considered that the temperature in the furnace remains constant during operation. Since the furnace is full of air, the main considerations for heat transfer are heat convection and heat conduction, and the temperature field meets:

\[ \text{div}(\rho u T) = \text{div}(k \nabla T) \]  

(3)

Since the air temperature field is considered to be in a steady state at this time, \( T \) has nothing to do with time. It can be known from the spatial structure of the reflow furnace that \( T \) only changes in the y-axis direction. Therefore, the above formula can be simplified to:

\[ \rho u \frac{\partial T}{\partial y} = k \frac{\partial^2 T}{\partial y^2} \]  

(4)

Since the gap between the cooling zone and the temperature zone before is only 5 cm in length, but the temperature difference between the two adjacent small temperature zones is too large, the model considers that there is a buffer zone in the cooling zone, that is, in this area the ambient temperature near the electronic device does not reach the temperature of the cooling zone, but there is a linearly changing temperature zone.

2.2. Boundary conditions

For electronic devices, since the boundary is in direct contact with the air, it satisfies Newton's law of cooling, that is, the following boundary conditions exist:

\[ h(T_{\text{sur}} - T_0) = -\lambda \frac{\partial T}{\partial x}|_{x=0} \]  

(5)

\[ h(T_{\text{sur}} - T_d) = -\lambda \frac{\partial T}{\partial x}|_{x=d} \]  

(6)

Among them, \( T_{\text{sur}} \) represents the air temperature, \( h \) is the convective heat transfer coefficient between the air and the welding area material, \( T_0 \) is \( T(0,t) \), and \( T_d \) is \( T(d,t) \).

For an air gap, the boundary condition is the temperature at the edges of the adjacent two temperature zones.

2.3. Maximum speed of conveyor belt

In production, it is often necessary to design the speed of the conveyor belt, and the speed of the conveyor belt is often related to the speed of the manufacturing process. Therefore, for the speed control of the conveyor belt, an optimization model can be established, and the optimization target is the speed \( v \). In actual production, there are often constraints on the indicators of the reflow furnace, and there are often the following:

- The time constraint. The time for temperature during 150°C and 190°C is generally required to be no less than 60s and no more than 120s.
- The time constraint. The time for temperature greater than 217°C generally requires a minimum of 40s and a maximum of 90s
- Peak temperature constraints
- Conveyor belt passing speed constraint:

\[ \frac{13}{1200} \text{m/s} \leq v \leq \frac{1.2}{60} \text{m/s} \]  

(7)

3. Results and discussions

Since the model involves the solution of partial differential equations, this paper uses the finite difference method (FDM) to find its numerical solution. The basic idea of the finite difference method
is to replace the continuous definite solution area with a grid composed of a finite number of discrete points. The definite solution of the function of the continuous variable on the area is approximated by the function of the discrete variable defined on the grid; the differential quotient in the original equation and the definite solution condition is approximated. The conditional approximation is replaced by a system of algebraic equations, that is, a system of finite difference equations. Solving this system of equations can get the approximate value of the original problem at discrete points, and then use interpolation to obtain the definite solution from the discrete solution.

Therefore, the following equations are obtained through simultaneous finite difference equations:

\[ a\Delta t \cdot T(x_{i-1}, t_j) + [(\Delta x)^2 - 2a\Delta x]T(x_i, t_j) + a\Delta t \cdot T(x_{i+1}, t_j) - (\Delta x)^2 T(x_i, t_{j+1}) = 0 \] (8)

From the boundary conditions, we have:

\[ (\lambda + \Delta x)T(x_0, t_j) - \lambda T(x_1, t_j) = \Delta x T_{\text{sur}}(t_j) \] (9)

\[ (-\lambda + \Delta x)T(x_n, t_j) + \lambda T(x_1, t_j) = \Delta x T_{\text{sur}}(t_j) \] (10)

From the initial conditions, we have:

\[ T(x_i, t_0) = T_0 \] (11)

Therefore, the temperature changes in each area of the electronic device can be obtained by solving the above linear equations. When the parameter is unknown or the value is in doubt, it can be fitted by experimental data.[6] The fitting algorithm is to minimize the following function:

\[ \sum_j (T(x_{d/2}, t_j) - \hat{T}(x_{d/2}, t_j))^2 \]

Among them, \( \hat{T} \) is the estimated value and T is the actual value.

According to the experimental data used, we can get:

\[ h = 22.59 \]
\[ a = 0.0048 \]
\[ \lambda = 504 \]

The obtained temperature curve is shown in the figure below:
Through calculation, the multiple correlation coefficient is 0.98, indicating that the fitting effect is better.

For the determination of the maximum speed, a search algorithm can be used. First we search in a larger range with large steps. After narrowing the range in this way, the step size can be reduced. So we can search in a smaller range, and finally the maximum speed can be obtained. Using experimental data and certain temperature conditions, the final calculation speed is: 1.12 m/min, and the corresponding temperature change curve is:
4. Conclusion
From the analysis above, it can be found that some basic parameters of electronic devices, such as specific heat, thermal conductivity, density, etc., can be obtained through experimental data through a proper optimization process. Through the method provided in this article, the staff can verify the accuracy of the various parameters of the material through some pre-experimental data before the process operation, to provide guarantee for the formal operation and prevent the loss caused by human error. In addition, the search algorithm can find the fastest conveyor belt speed under certain constraint conditions, which is beneficial to the staff to control the cost and production speed.

References
[1] Deng, S.-S., Hwang, S.-J. and Lee, H.-H. (2016) Temperature prediction for system in package assembly during the reflow soldering process, International Journal of Heat and Mass Transfer, 98, pp. 1–9. doi: 10.1016/j.ijheatmasstransfer.2016.03.008.
[2] Iqbal, A. M. (1,2) et al. (no date) Temperature Prediction on Flexible Printed Circuit Board in Reflow Oven Soldering for Motherboard Application, IOP Conference Series: Materials Science and Engineering, 530(1). doi: 10.1088/1757-899X/530/1/012019.
[3] Svasta, P., Simion-Zanescu, D. and Willi, C. (2002) Thermal conductivity influence in SMT reflow soldering process, 52nd Electronic Components and Technology Conference 2002. (Cat. No.02CH37345), Electronic Components and Technology Conference, 2002. Proceedings. 52nd, Electronic components and technology conference, pp. 1613–1616. doi: 10.1109/ECTC.2002.1008322.
[4] Lee, S. Y. et al. (no date) Resolving No solder joint issue thru understanding of basic principle in solder and heat transfer, ECS Transactions, 44(1), pp. 991–1001. doi: 10.1149/1.3694421.
[5] Versteeg, H. K., & Malalasekera, W. (2010). An introduction to computational fluid dynamics: the finite volume method.
[6] Information on http://www.mcm.edu.cn/