Development of New Model Reflow Oven for Lead-Free Soldering

by Motohiro Yamane [*], Nobuaki Orita [*2], Koichi Miyazaki [*2] and Weiming Zhou [*2]

ABSTRACT The main issue with regard to improving the heating ability of reflow ovens is to minimize the temperature difference ΔT among the various parts of the printed circuit board (PCB) during the reflow soldering process. We need to control temperature within a much narrower process margin when we use lead-free soldering. Accordingly, our development target in this work is to achieve a significant increase in heat transfer coefficient α, fundamental to the heating performance of a reflow oven. We have developed a new model of reflow oven for lead-free soldering with a much higher heating ability by redesigning the hot air blowing unit, specifically by changing the design of the hot air panel. We were able to achieve this target in only five months by using process diagnostic techniques such as direct measurement of heat transfer coefficient and flow visualization, which we have developed and used for various applications.

1. INTRODUCTION

As the process and equipment for lead-free soldering have become more widely used, the characteristics required of reflow ovens for lead-free soldering have become clearer and more advanced.

The status quo for lead-free surface mounting technology is:

a) An Sn/Ag-based composition with a high melting point has become the de facto standard as the lead-free material. This is because problems are still encountered with materials of Sn/Zn-based composition, which have lower melting points.

b) It is difficult to improve the heat-resistance of any parts in the short term. In practice, most parts have to be mounted under conventional reflow temperature conditions due to the parts that have low heat-resistance.

c) The problems relating to the solder material and heat-resistance of the parts should therefore be overcome by improving the characteristics of the reflow oven.

The main issue with regard to improving the heating ability of reflow ovens is to minimize the temperature difference ΔT among the various parts of the printed circuit board (PCB) during the reflow soldering process. This is equivalent to improving the basic heating ability of the hot air.

2. REQUIRED PROPERTIES AND TARGET FOR REFLOW OVEN IMPROVEMENT

Heating ability, which is fundamental to the performance of reflow ovens can be estimated by the accuracy with which it conforms to the required temperature profile. Figure 1 shows a typical temperature profile for the lead-free soldering process. Assume that the upper temperature limit, based on the heat-resistance of the parts, is 240°C, the process window for Sn/Ag/Cu-based solders will be 20°C. Again, assuming that the lower temperature limit, based on the melting point of the solder is 230°C, the allowable ΔT is less than 10°C, which is narrower by 25 % than that of conventional Sn/Pb-based solder. The temperature control within this narrow process margin must be achieved.

The following is the main issues in improving reflow oven properties:

1) improving ΔT by improving heat transfer coefficient α of the hot air;
2) improving cooling ability;
3) improving flux collection; and
4) reducing N_2 consumption (for N_2 atmosphere ovens)

The most fundamental of these issues is improving heat transfer coefficient α, but improving cooling capacity is also important when we consider a lead-free process. This is because we have to control the high temperature exposure time according to the heat-resistance of the parts.

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[*] Industrial Equipment Dept., Electronic Components Div., Electronic Mounting and Components Co.

[*2] Production Engineering Development Center, Plant & Facilities Div.

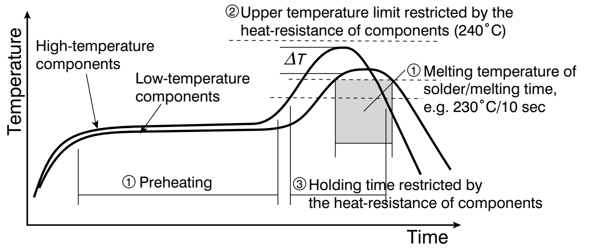


Figure 1 Typical temperature profile for lead-free soldering.

3. IMPROVING BASIC HEATING ABILITY

Basically there are three mechanisms of heat transfer: 1) conduction, in which heat is transferred by contact between a high-temperature body and a low-temperature body; 2) convection, in which heat is conveyed by moving fluid; and 3) radiation, in which heat energy is converted to electromagnetic waves and transferred without any transfer medium. Of these mechanisms the two that we can control in terms of the heating ability of a reflow oven are convection and radiation. Conventional SALAMANDER reflow ovens have achieved the desired heating ability by using both forced convection heating via impinging jets and radiation heating via a far infrared (IR) heater. In this development, however, heat radiation has not been used as a measure of improving the heating ability. We focused purely on redesigning the jets, in order to achieve the improvement target. There are two reasons for this: 1) it is not efficient to use an IR heater when we want to heat the PCB uniformly because the IR heater tends to heat those parts with smaller heat capacity more rapidly; and 2) it is not desirable to insert a body with a higher temperature than the upper limit of the allowable temperature range of the parts. Under forced air convection heating, the PCB will not be heated beyond the temperature of the hot air, which is “more friendly” on the parts.

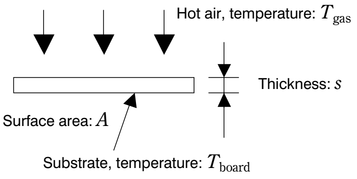


Figure 2 Heating model of PCB by convection.

Now consider the heating model shown in Figure 2, where a PCB with a surface area of A (m^2), and a thickness of s (m) is heated by hot air at a constant temperature of T_{gas} (°C). Assuming that the temperature of the PCB is T_{board} (°C), the amount of heat conveyed from the hot air to the PCB per unit time Q (W) will be

$$Q=\alpha A(T_{gas}-T_{board})=\rho A s C_p\frac{\partial T_{board}}{\partial t} \qquad (1)$$

where,
α: heat transfer coefficient (W/m^2/K)
ρ: density of the PCB (kg/m^3)
C_p: mean specific heat capacity (J/kg/K).

Heat transfer coefficient α is not a constant, but takes a value determined by the kind of fluid and the status of the flow. This α is the index of heating ability and is determined by designing the status of the flow impinging on the PCB, and this can be designed, by modifying the shape, size, diameter and the pitch of the blowing nozzles. The greater the jet velocity, the higher α will be, but jet velocity must be so limited that the parts will not be dislodged during the reflow process.

Equation (1) above is a first-order differential equation and can be solved analytically by

$$T_{board}=T_0+T_{gas}\left[1-\exp\left(-\frac{\alpha}{\rho s C_p}t\right)\right] \qquad (2)$$

where,
T_0: temperature of the PCB (°C) at the time $t=0$.

The coefficient of t in the exponent ($\alpha/\rho s C_p$) represents the response speed of PCB temperature. That is, the greater α and the less the specific heat capacity C_p, the more quickly the PCB will be heated. By using this characteristic, namely, by passing a PCB the various parts of which have different heat capacity and measuring the difference ΔT between the maximum and minimum peak temperatures, we can evaluate the heating ability of the reflow oven. We can emulate a surface-mounted PCB by using a stainless steel substrate and partially changing its thickness.

Figure 3 shows the simulated result of the temperature of a PCB heated by two main heating zones for various values of the heat transfer coefficient. The horizontal axis represents the time (s) and the vertical axis represents PCB temperature (°C). The blue line represents the temperature of a PCB with a thickness of 1 mm, the red line represents the temperature of a PCB with a thickness of 2 mm, and the gray line represents the gas temperature. We have assumed that the board stays 25 seconds in one zone before moving to the next, and that the board is to be preheated to 190°C for the 1-mm part and 180°C for the 2-mm part.

The gas temperature in the first zone is to be set so that the temperature of the 1-mm part at the exit of the first zone is 240°C, and the gas temperature in the second zone is 240°C, which means that only the 2-mm part is heated in the second zone. The difference in temperature ΔT at the exit of the second zone is 11.0°C for a heat transfer coefficient α of 110 W/m^2/K. ΔT can be reduced to 7.2°C for a heat transfer coefficient α of 150 W/m^2/K. Our target in this development was keep ΔT below 10°C.

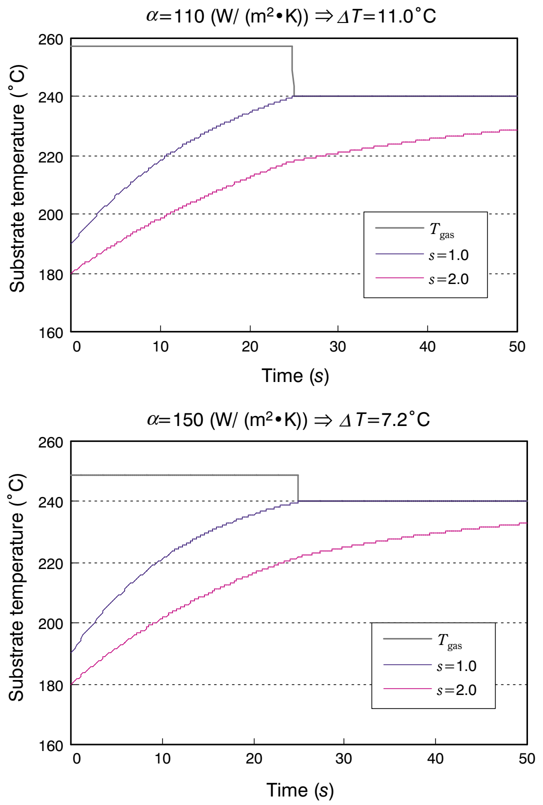


Figure 3 **Relationship between heat transfer coefficient α and temperature difference ΔT.**

4. MEASURES FOR IMPROVING HEAT TRANSFER COEFFICIENT α

As shown above, improving the heating ability is equivalent to improving the heat transfer coefficient, but under the constraint of jet velocity it is not good to raise the volume of the hot air flow excessively. We have to take into account how to design the flow from impinging jets so that the heat is transferred effectively. The main measure we took was to redesign the hot air blowing unit, specifically by changing the design of the hot air nozzle arrangement-- nozzle diameter and nozzle pitch -- in order to obtain more efficient heat transfer. The first step was to examine the relationship between the hot air nozzle arrangement and the heat transfer coefficient by means of model experiments (see Figure 4). Hot nitrogen is blown via four nozzles of various diameters and pitches on to PCBs provided with thermocouples. The rate of nitrogen flow is controlled by a mass flow controller so that the jet velocity on the PCB stays constant for any nozzle arrangement. The heat transfer coefficient can be calculated by the heat-up time of the board.

Figure 5 shows a summary of these experiments. We found that the heat transfer coefficient was inversely proportional to the ratio of nozzle pitch to nozzle diameter, that is, the more the nozzle pitch is decreased and the nozzle diameter is increased, the higher the heat transfer coefficient will be.

This is equivalent to increasing the volume hot air rate of flow per unit area of the PCB.

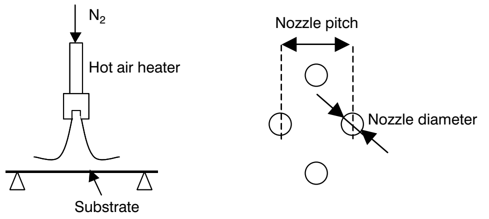


Figure 4 **Schematic representation of heating model experiment.**

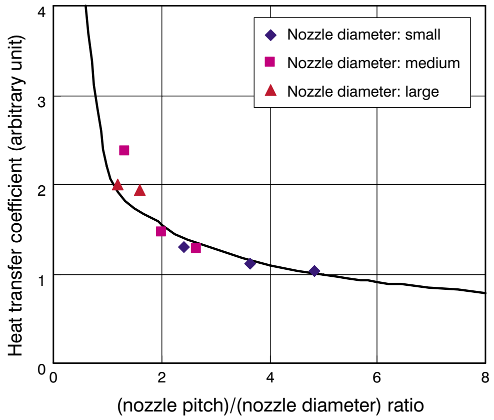


Figure 5 **Relationship between (nozzle pitch)/(nozzle diameter) ratio and heat transfer coefficient.**

Let us now consider the balance between blowing and suction on the panel in an actual reflow oven. The relationship derived above only takes into account the heat transfer coefficient of the blowing nozzles. In order to get a uniform flow of hot gas on the PCB from a large area of blowing nozzles, we need to have an equally large area of suction apertures, but this results in the loss of heating ability at the suction area. We therefore present a new design of blowing panel, in which the suction means has been changed from slits to pipes, arranged between the blowing nozzles. This achieved a good blowing/suction balance without losing heating ability.

5. EVALUATION OF HOT AIR BLOWING PANEL

To evaluate the heating ability and status of flow for the newly designed blowing panel, we first carried out the heating model experiments described above, and then scaled up to a one-zone experimental unit to analyze the full-scale panel. More specifically, we applied process diagnostic techniques, including 1) direct measurement of the heat transfer coefficient, 2) evaluation of uniform heating ability by thermal imaging camera, and 3) flow visualization using the smoke method, all of which have been used in various applications in our section. It is noteworthy that we were able to minimize both the time and the money required for development. Detail of the techniques are as follows.

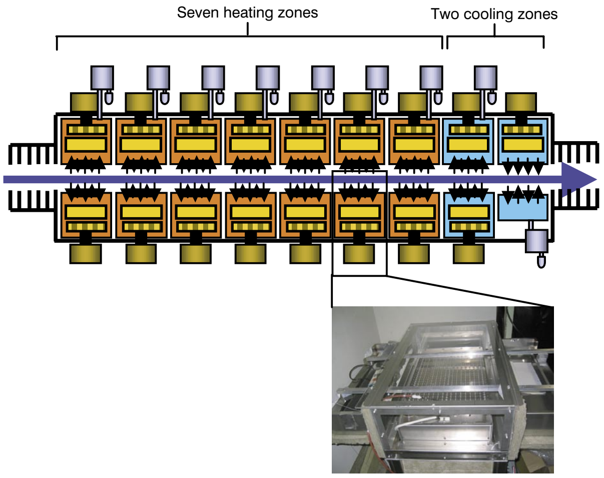


Photo 1 One-zone experimental machine.

5.1 Direct Measurement of Heat Transfer Coefficient

The heat transfer coefficient can be calculated from measured results for the temperature of the PCB and of the atmosphere. We used a blank PCB made of stainless steel and provided with two thermocouples, which was conveyed manually through the one-zone experimental unit and heated at 200°C. We compared a number of panel designs by changing the panel installed in the unit. Figure 6 shows some of the measured results. We adopted the pipe suction type panel having the highest heating ability as the basic design for the production model.

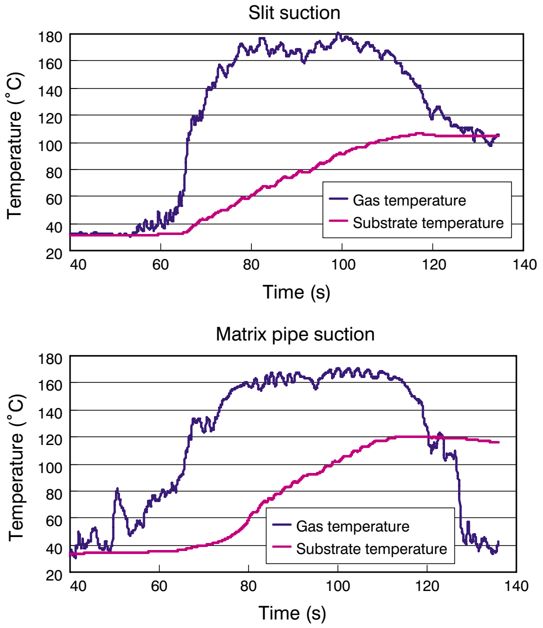


Figure 6 Measured results for PCB temperature and gas temperature.

5.2 Evaluation of Uniform Heating Ability by Thermal Imaging Camera

The experimental setup of evaluating is shown in Photo 2. The central part of the lid of the one-zone experimental unit was made of quartz glass. After heating the unit to a specified temperature, we inserted blank PCBs, and took thermal images at 0, 10, 20, and 30 sec. Figure 7 shows some of the images taken in this way. It can be seen that the newly designed panel with matrix pipe suction has a superior ability to heat the PCB uniformly that is superior to that of the conventional design with slit suction.

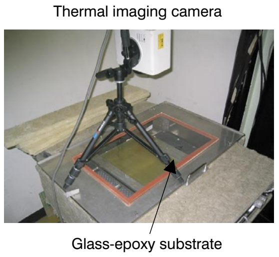
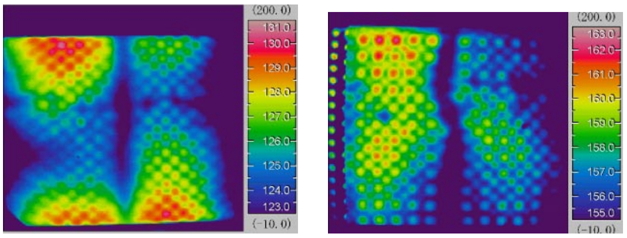


Photo 2 Thermal imaging by thermal imaging camera.



Slit suction **Matrix pipe suction**

Figure 7 Typical thermal image 30 sec after PCB insertion.

5.3 Flow Visualization Using Smoke Method

To visualize the jet flow using the smoke method, we made the top and sidewall of the one-zone experimental unit from acrylic material. We first introduced the smoke from a blowing nozzle and illuminated by a sheet laser beam created by a polygon mirror, and then took images with a CCD camera. Photo 4 shows a typical image taken in this experiment. Based on the results of the visualization, together with in-depth investigation of the jet velocity measured by a wind velocity probe and a 3-dimensional micro stage, we have concluded that the jets from the blowing nozzles change direction near the PCB pass line and are sucked into the suction nozzles efficiently. This means that the hot air that has cooled inside the oven after heating the PCB is retrieved immediately, and also that there is no interference between the jets blown from the top panel and those from the bottom panel in each zone. Consequently, we can set the temperatures of the top and bottom panels independently. This has the advantage of raising the temperature of the soldering joint without heating the body of the parts themselves. We can also achieve lower consumption of the nitrogen used in controlling oxygen concentration than in the conventional reflow oven because the flow of the jets does not fluctuate even if there are PCBs on the board pass line. We therefore conclude that the structure that creates this phenomenon is efficient on the whole.

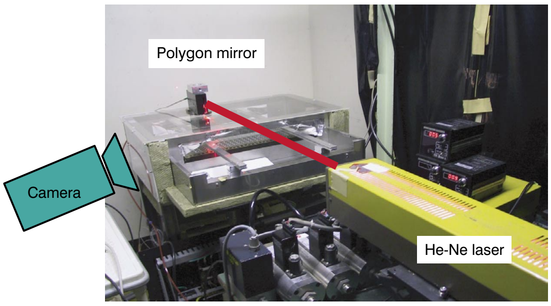


Photo 3 Setup for flow visualization experiment.

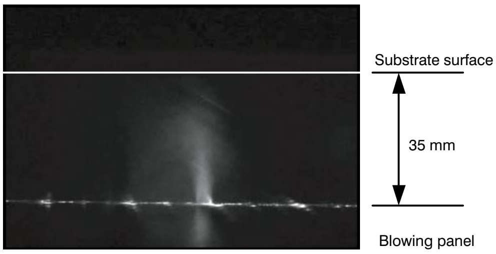


Photo 4 Flow visualization by smoke method.

6. NEW DESIGN OF BLOWING PANEL

We have determined a new design for the hot air blowing panel, as shown in Photo 5, based on the model experiments and evaluation procedures described in Section 5. The main difference with respect to the conventional design is the modification of the suction means: from slits to pipes arrayed between the blowing nozzles. The overall heat transfer coefficient of the panel was significantly increased by this modification compared to the previous design which loses heating ability at the suction slit.

There is an additional row of blowing nozzles at both the entrance and the exit of the zone (see Photo 6). These rows work as a sealing region which prevents zone-to-zone interference. We have confirmed the efficiency of these rows by flow visualization (see Photo 7).

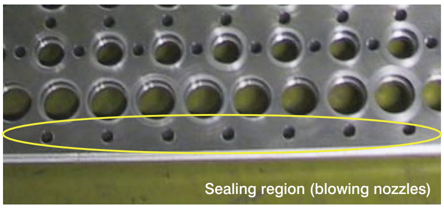
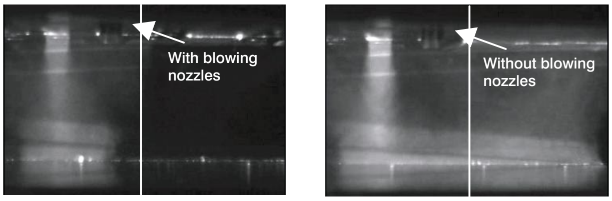


Photo 6 Sealing region (row of blowing nozzles) on the newly designed panel.



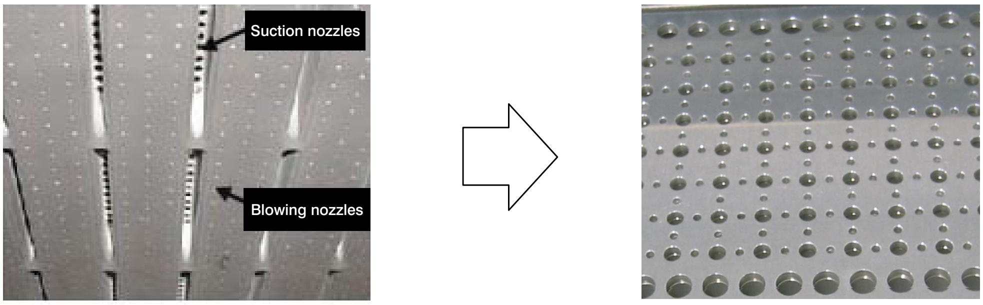
Zone-to-zone interference is not seen   Zone-to-zone interference is seen

Photo 7 Effects of the providing sealing region.

7. CONCLUSION

We were able to achieve the developmental target of achieving a significantly increased heating efficiency by adopting a newly designed hot air blowing panel without changing the main features of Furukawa's lead-free reflow soldering system, i.e., forced heat convection through impinging jets. Work for the future would include 1) continued improvement of basic heating ability, 2) improvement of the heating ability between parts for boards with high-density mounting, and 3) stabilization of atmospheric control inside the reflow oven (reduction of nitrogen consumption). In order to continue presenting the market with reflow ovens of ever higher performance, we will not only apply the process diagnostic techniques we have developed but also create more sophisticated flow visualization (for high temperature, large area, etc.) and computer simulation of flow analysis.

The new model reflow oven is now under a final investigation in detail preparing for mass production at



Conventional design (slit suction)
SUS sheet, ΔT=11°C /Substrate, ΔT=13.5°C

New design (pipe suction)
SUS sheet, ΔT=8.7°C/Substrate, ΔT=9.6°C

Photo 5 Newly designed panel.

Furukawa Electronics (Suzhou) Co., Ltd., China. The cost advantages of transferring the manufacturing activities to China is significant.

We must anticipate the trend to lead-free soldering and continue to develop reflow ovens of higher-performance and lower-cost. Finally we would like to express our deep appreciation for the support of numerous people, both within and outside Furukawa Electric.

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