Temperature Prediction on Flexible Printed Circuit Board in Reflow Oven Soldering for Motherboard Application

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Abstract. Flexible printed circuit boards (FPCBs) appoint an interest in current electronics devices with unique capabilities in the form of flexibility, lightweight, and thin thickness. In this paper, the proposed of that utilises FPCB as a substrate for motherboards is investigated. Assembly surface variation temperature in the reflow soldering process is a crucial factor to address the feasibility of substrate for surface mount technology (SMT) applications. For thin FPCB, higher Reynold number (Re) would not give the significant effect of heat transfer on assembly surface temperature. Although the primary focus is in a continuous reflow oven, FPCB findings could enhance the information for other FPCB applications such as designing the soldering thermal profile.

1. Introduction
Flexible printed circuit boards (FPCBs) are referred to as an alternative to a rigid printed circuit board (PCB) for electronic applications since it would have an excellent physical aspect of lightweight, flexibility and twistability. FPCB simplifies a potent of space-efficient design, enhance the inside system presence, reduce weight and installation cost. Over recent years, numerous electronic devices were adapted FPCBs, but in the application as SMT and motherboards are still scarce. Although the FPCB could be very thin in comparison with rigid PCB, the heat transfer performance during reflow soldering process is the primary concern in use as SMT motherboard.

In the microelectronic industry, a reflow oven is widely used in contact to attach surface mount components (SMCs) and devices (SMDs) to PCB. The use of the adjective “reflow” with the noun “oven” stems from its hardware being developed and used to fabricate solder interconnects[1]. Prior preparatory steps before the reflow soldering process, a screen printing of solder paste on the copper pad through a stencil or foil. Subsequently, the SMCs insertion on the printed solder paste is through automated component placement machine. Next, the contacting of solder SMCs and copper paste takes place, when PCB passes through the reflow zone (pre-heating, soaking, soldering and cooling). On top selective reflow oven type, continuous type of single or combination of forced convection and infrared (IR) is more preferred for the manufacturing [2]. The air flow in the continuous type of reflow oven required forced air convection for temperature field distribution uniformity within the space.

The understandings of thermal reflow profile are benefits to soldering process control. The defined profiles may influence the solder joint microstructure aspect, such as the thickness of the intermetallic compound (IMC) [3]. Hence, various aspects of reflow oven study had been reported by the scholars. An extensive investigation using experimental and simulation of the reflow oven include oven space heat transfer [4] and gas flow characterisation [5] and the nozzle-matrix convection reflow oven [4-6] were reported in the previous studies.
Some partial effect of the rigid PCB (RPCB) on continuous reflow oven was examined by [7]. However, the need for further investigation of the effect forced convection velocity towards new FPCB material. Then, the study aims to investigate the temperature prediction on FPCB towards feasibility for electronic motherboards application. Also, thermal impact of reflow soldering process on FPCB assembly, respectively still not available in the literature. The developed method has potential to be used for precise prediction in oven space as well for designing thermal profile to obtain minimal temperature deviation on assemblies.

2. Experimentation
A ready-to-use FPCB was chosen for this study. The FPCB is formed in single-sided consisting of single polyimide and single copper layer with an overall thickness of 53 µm. The complete dimensions and materials of FPCB [8] and epoxy capacitor mould are denoted in Table 1. The gained properties were used in simulation purpose.

| Material | Dimensions (mm) | Density, (kg/m³) | Thermal conductivity, k (W/[mK]) | Specific heat, Cₚ (J/kgK) |
|----------|----------------|-----------------|-------------------------------|--------------------------|
| FPCB     | 110 x 80       | 3839            | 0.3                           | 421                      |
| Mold     | 4.0 x 4.2      | 1820            | 0.6                           | 236                      |

For this study, the soldering process was implemented in the continuous type of BTU Paragon 150 oven. In a particular zone, is equipped with a nozzle-matrix system to form the jet streams as shown in Figure 1. The nozzle-matrix system which uses a centrifugal blower to force heated air toward the assemblies. On top of that, a reflow oven is made up of an entrance, eight heating zones, two cooling zones, and an exit section. The heater is installed on each of top and bottom blower in heating zones. The view of the heater structure is shown in Figure 1a. The soldering agent gas (air) was heated via the heating coil and passed though the small diameter nozzles before contacting the assemblies. The nozzle configuration is in Figure 1b, then the gas pass through the recirculation delivery area to complete the cycle.

According to JEDEC JSTD-020D standard [9], reflow soldering profile typically consists of two regions: the heating region comprises a preheating, soak, and reflow zone, and cooling zone as shown in Table 2. The duration of soaking and reflow-soldering were fall in 60-120 and 60-150 s, respectively. Also, the peak setting for SAC solder material should in 230-240 °C, whereas in the ramp up and ramp down reflow zone temperature was set to be less than 3 °C/s. For this study, duration of 60 s; preheating, 60 s; soaking and 124 s; reflow soldering were considered.
3. Numerical analysis

3.1. Fluid Flow Model

The governing equation is subjected to single-phase flow model, and FLUENT 18 is employed to solve it using velocity and Cartesian spatial coordinate in differential control volume which written in the non-dimensional form [10].

a) Single phase

Eq. (1) denoted the incompressible continuity equation.

$$\frac{\partial \rho u_i}{\partial x_i} = 0$$  \hspace{1cm} (1)

where $u_i$ is the velocity component in $x_i$ direction (for $i=1,2,3$ reflects to three perpendicular axis)

While, Eq. 2 is the momentum equation with neglecting buoyancy terms as the following:

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i$$  \hspace{1cm} (2)
Denoted, ρ is the fluid density, τj is the viscous stress tensor, u_i is the velocity component in x_j direction, P is the pressure, g is the gravitational acceleration and F is external body force in the i-direction. Neglecting of buoyancy terms is defined under forced convection from blower to the oven space.

Considering of thermal in the oven space, the energy equation is denoted as Eq. (3),

\[
\frac{\partial}{\partial t} (\rho C_p T) + \frac{\partial}{\partial x_i} \left( \rho u_i C_p T \right) = - \frac{\partial}{\partial x_i} \left( \rho u_i \frac{C_p}{\lambda} \frac{\partial T}{\partial x_i} \right)
\]

where \( C_p, T \) and \( \lambda \) mentioned the specific heat, temperature and thermal conductivity of hot air, respectively.

Flow typically begins at the top and bottom nozzle matrix into oven space, becomes turbulent due to proportional flow is directive on each other correspond to fluid-fluid configuration interaction as jet impingement. As above judgement on flow, Re obtained is the turbulent regime. From the turbulent CFD codes, the standard k-epsilon (SKE) model is selected and performs well in non-large adverse pressure gradient [11] and consist of two transport equation as follows:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_k} \frac{\partial \varepsilon}{\partial x_j} \right] + G_k - \rho \varepsilon
\]

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1k} \frac{\varepsilon}{k} (G_k + C_{3k} G_b) - C_{2k} \rho \varepsilon^2
\]

where \( G_k \) is the turbulent production term due to mean velocity gradients. The negative term using energy dissipation. The closure constant, \( C_{1k} = 1.44, C_{2k} = 1.92, C_{\mu} = 0.09; \sigma_k = 1.0; \sigma_\varepsilon = 1.3 \) are the used parameter value.

The air properties defined according to the ideal gas equation and for the calculation of the density as follows:

\[
\rho = \frac{R}{T}
\]

where R is a specific gas constant.

3.2. Modelling strategy
The 3D assembly model of the fluid domain was modelled by SpaceClaim in ANSYS workbench version 18. The half geometry of an actual single zone oven was generated with the dimensions of 290 mm × 305 mm × 90 mm, while the solid assembly model was deducted from the domain as depicted in Figure 2. Figure 2 also illustrated the important boundaries including inlet, outlet, enclosure and capacitor. The model was meshed with 870 000 hexahedral and tetrahedral elements at assembly. For verification accuracy purpose, grid independence test were done as in Table 3.

In FLUENT, 3-dimensional, incompressible and unsteady turbulent type of flow was used. A user-defined function (UDF) script was written in C++ language in order to develop closely to the actual oven atmosphere. The density of air was set to follow the ideal gas properties. Giving in Eq. (7), through which air, ρ is the density, v is the velocity applied as follows.; \( \mu \) is the dynamic viscosity and D is the nozzle diameter. The boundary setting conditions for the fluid domain were

1) At the enclosure of FPCB walls: \( \vec{v} = 0 \) (no slip condition).
2) At the inlet: \( \vec{v} = \vec{v}_{\text{inlet}} \) (inlet flow velocity) with the oven space temperature profile using user define function.
3) At the outlet: Pressure = 0 atm (ambient condition)
\[ Re = \frac{\rho v D}{\mu} \]  
(7)

**Figure 2.** Fluid domain

| Case at 10s | A   | B       | C       | D       | E       |
|-------------|------|---------|---------|---------|---------|
| Fluid elements | 702836 | 781853 | 866928 | 1034758 | 1314649 |
| Temperature (K) at 10 s | 319.31 | 326.80 | 328.25 | 326.30 | 328.60 |
| Deviation from case E (%) | 2.9  | 0.6  | 0.1  | 0.7  | -       |

The operation mode was run as denoted in Table 4. Different parameters of turbulent flow at Re of (36,611 – 44,088) was carried out with the similar mesh and FLUENT setting for forced convection study.

| Table 4. Operating conditions for FPCB reflow soldering |
|--------------------------------------------------------|
| Soldering Agent | Blower pressure (IWC) | \( Re \) (at 25°C) |
|-----------------|-----------------------|-------------------|
| Air             | 0.5                   | 33,260            |
|                 | 1.0                   | 40,221            |
|                 | 1.2                   | 44,088            |

4. Result and discussions

4.1 Heat transfer performance

The flow induced into reflow oven space could be varied as denoted in Figure 3. The dominant velocity of the jet stream was triggered using blower frequency that in inch water column (IWC). Criteria for
selecting the blower IWC would reflect to processing requirement, by means of board assembly soldering quality and throughput. The range of 0.5 to 1.5 IWC were selected as occupy by oven blower correspond to give uniform velocity on the top and bottom side. Uniformity of forced convection flow induced, is enable to reduce the adverse pressure gradient on oven space. As such explained, a higher IWC lead to induce more heat flux to the oven space, hence alleviate the surface temperature.

Figure 3. Measured nozzle outlet velocity against blower pressure

Figure 4 shows the board assembly temperature at different zones in a reflow oven. The used initial condition was mimic of situations where the FPCB left the components deposit machine at room temperature. At 10s in preheating, the temperature gradient was up to 15-20 °C at the pushing slope rate of 1.8°C/s. It can be explained that the thermal exchange for FPCB to initially absorb the heat flux from oven space reaching the substrate. Also, heat on the capacitor was high only in moving direction. In the soaking zone, the maximum temperature difference across the assembly board was within 3 C. As predicted, the uniformity or thermal equilibrium was observed at the wetting time, 230 s. For this period, the linear temperature relationship between the assembly surface and molten solder could benefited into a good interconnection. While in 350 s, the gradient of 8 °C can be identified while FPCB was entering the cooling zone process. The implication of proper cooling slope might inhibit the thermal shock towards component and molten solder.
Figure 4. Zone temperature a) Initial entering (0s) b) pre-heating zone c) soaking zone d) wetting and e) cooling zones in a reflow oven

4.2 Flow characteristics
The complex flow patterns within the array of nozzle jet of the reflow oven in x and z-axis direction are shown in Figure 5. The temperature distribution as mentioned above is governed by the flow field and heat transfer of the oven space. From the flow patterns generated, it has the similarity on those represented by Weigand and Spring [12], which highlights the three types of interactions attribute to nozzle inlet jet stream. To that, the first type of interaction (denoted as 1) is jet-to-jet interactions after approaching the board level surface. A homogenous and gapless heat transfer to the FPCB is observed. While in second type interaction lied (denoted as 2) is the cross-flow interaction when the jet stream is not asymmetrical. The third type of interaction could explain the interaction of neighbouring jet stream in mixing domain upon approach to the board level, which depends on the spacing between each inlet nozzle.
4.3 Effect of Re

The effect of Re is investigated in the preheating zone. The findings of temperature contours for Re of 33, 260, 40,221 and 44,088 are shown in Figure 6. The comparison was made by the similar speed of FPCB on conveyor speed (1.2 cm/s). Based on the results, the all assembly board surface temperature show the gradient temperature less than 2 °C, with low inconsistency for ensuring uniform heat for a capacitor that attached to it. At this point, successiveness of reflow soldering was incorporated with surface gradient temperature even for RPCB or dealing with FPCB. With higher Re, flow the air from nozzle becomes more vigorous, subsequently produced a higher heat transfer effect on the FPCB surface.

In contrast, the thin thickness of FPCB was not able to capture higher heat flux at the oven space when higher Re was achieved. The discrepancy of heat transfer coefficient, h more or less 5% across the assembly surface where the oven space is dominant with the turbulent flow with wide spreading in all axis. These findings suggest that for thin motherboard as FPCB, Reynold number must be considered in order to predict the surface local temperature. Moreover, the 1.0 IWC or Re at 40,200 was found to suit for low-density components placements.
Figure 6. Change of maximum temperature and heat transfer coefficient with Re

5. Conclusion
The current paper has outlined the study on the temperature prediction of FPCB as a substrate for computer motherboard application and performed using FLUENT codes. The predictions model shows the good agreement with oven configuration with minimum deviation. The comparisons were done on different PCB and noticed that FPCB is feasible to have a suitable surface temperature during the reflow soldering process. Even in higher Re, FPCB surface temperature remains almost similar. Although the current findings only focused on board level, the results can be contributed to the advancement of FPCB assemblies.

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