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Numerical simulation of condensate layer formation during vapour phase soldering

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HIGHLIGHTS

- Refined numerical model of VPS is developed with dynamic condensate layer.
- Condensate layer changes have considerable effect on the heating during VPS process.
- Considerable temperature gradient can form on the assembly during the VPS process.
- Suggested to fit the soldering profile to the demands of the bottom of the assembly.

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ABSTRACT

This paper presents a modelling approach of the condensate layer formation on the surface of printed circuit boards during Vapour Phase Soldering (VPS) process. The condensate layer formation model is an extension to a previously developed board level condensation model, which calculates the mass of the condensed material on the surface of the soldered printed circuit board. The condensate layer formation model applies combined transport mechanisms including convective mass transport due to the hydrostatic pressure difference in the layer and the gravity force; conductive and convective energy transport. The model can describe the dynamic formation and change of the condensate layer after the immersion of the soldered assembly into the saturated vapour space and can calculate the mass and energy transport in the formed condensate layer. This way the effect of the condensate layer changes on the heating of the soldered assembly can be investigated. It was shown that the numerical modelling of the VPS process becomes more accurate with application of dynamic condensate layer instead of a static description.

1. Introduction

The Vapour Phase Soldering (VPS) or condensation soldering is an emerging reflow soldering technology in electronics industry, which could be a future alternative of forced convection and infrared reflow methods. During the VPS process a special heat transfer liquid (called Galden™) is boiled in a closed tank until a saturated vapour space is generated. After the saturation the prepared assembly is immersed into the vapour space, the vapour condenses and forms a continuous condensate layer on the surface of the assembly. The condensate layer – which heats the assembly above the melting point of the applied solder alloy – is heated by the latent heat of condensation and the heat from the surrounding medium (vapour). The Galden liquid [1] is composed of perfluoropolyether substance (PFPE):

$$\begin{array}{l} CF_3-(OCFCF_2)_n-(OCF_2)_m-OCF_3 \\ \qquad\qquad | \\ \qquad\quad\; CF_3 \end{array}$$

where the flexible ether chain structure is closed with strong carbon–fluorine bonds providing stability. Galden liquid is produced with various boiling points (from 150 °C up to 240 °C) fitting the melting point of the applied solder alloy.

The condensation heating or cooling is a widely applied technology due to its high efficiency which makes this technology suitable for heating of facilities via heat pumps [2] and for cooling of electronics appliances via heat pipes [3]. In addition, the

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Nomenclature

v	velocity, m/s
ρ	density, kg/m^3
P_h	hydrostatic pressure, Pa
g	gravity acceleration, m/s^2
t	time, s
T	temperature, K
q_m	mass flow, kg/s
υ	kinematic viscosity, m^2/s
λ	specific thermal cond., W/m.K
C_S	specific heat capacity, J/kg K
h	height of condensate, m
A	surface, m^2
σ	surface tension, N/m
θ	decline angle of the board, rad
n	indexing of the mesh
Δx, Δy, Δz	resolution of the mesh, mm
$\bar{r}$	local vector
Δt	time step, s

Abbreviations:

l	liquid
v	vapour
f	flowing
d	dropping

condensation plays an important role not only in direct condensational applications but in other various applications, such as the ventilation pipes of deeply buried tunnels [4] or in the technologies of CO_2 separation from steam [5]. From the point of soldering technology the most important advantages of VPS method are the almost uniform heating and the elimination of overheating since the maximum temperature during the soldering is equal with the boiling point of the applied heat transfer liquid [6,7]. Vapour phase soldering also eliminates the shadowing effect in the case of small size components what is a frequent problem during the forced convection reflow soldering. During the VPS process oxidation of the solder joints is also avoided due to the inert atmosphere in the VPS tank and the condensate film layer on the assembly [8].

Without proper control, the major disadvantage of the VPS process is the high heating gradient, while the heat transfer coefficient of the vapour can be much higher than in a forced convection oven [9]. This can result in soldering failures such as tombstoning, solder cracking, solder beading [10], solder voiding [11]; popcorn cracks of the packages and delamination of packages and Printed Circuit Boards (PCBs) [12]. Nowadays, there are a lot of technical innovations to reduce the previously mentioned soldering failures such as application of vacuum atmosphere [13] and soft vapour technology [14]. There are also some examples for the characterization of the VPS process parameters (concentration and temperature of the vapour) through measurements and simulations. Lam and Plotog worked with simple thermal profiling [15] and thermo-vision camera [16] to describe the temperature distribution inside the VPS tank. Vapour saturation and condensed droplet formation were also examined with floating polymer pillows and by optical probes [6].

In our previous studies we have examined and modelled the vapour space saturation [17] and the condensation process [18]. During these studies the Galden layer was considered to be static with a given 250 μm thickness and without any motion and convection effect in the layer. According to the optical investigations of the VPS process by Illyefalvi-Vitéz et al. [8], the concept of static condensate layer is not enough accurate approximation. During the VPS process the flow of Galden liquid is observable with changing velocity on the top side of the soldered PCB. The concept of constantly varying condensate layer is also supported by the results of highly changing vapour concentration during the VPS process which has a high impact on condensation [18]. However, in the literature of the VPS method there is no example where the dynamic changes of the condensate layer is examined. Therefore in this research we have concentrated to the dynamics of the condensate layer, such as the formation of the layer, the motion of the layer and the convective temperature transport effects. During this study the simple VPS process was investigated without soft vapour or vacuum application, in order to study how the dynamic changes of the condensate layer influence the heating efficiency and homogeneity of the VPS process.

2. Condensate layer formation model

This condensate layer formation model extends our previous board level condensation model which calculates the condensate mass on the surface of the soldered PCB according to the present values of vapour concentration and temperature (presented in Refs. [17,18]). In this study we have concentrated only to the physics of the condensate layer.

While the basic position of the PCB during the VPS process is horizontal, the concept of the condensate layer formation is the following: at the beginning of the process condensation starts on both sides of the PCB. For the top side we can apply the most advanced Bejan model [19] (for upward facing plate with free edges), which supposes zero condensate layer height with zero hydrostatic pressure at the top edges of the plate. This causes pressure differences in the condensate layer which triggers the motion of the Galden liquid towards the edges of the plate. Due to the surface tension the Galden liquid flows from the upside to the down side of the plate. Dropping of the Galden liquid does not occur until the force from the surface tension can hold the weight of the condensate. The down-flowing Galden liquid causes hydrostatic pressure difference at the bottom edges of the plate which induces movement of the layer. According to Gerstmann and Griffith, this results in a "wavy structure" of the condensate layer on the bottom side of the plate [20]. A schematic of the condensate layer model can be seen in Fig. 1.

2.1. Physical description of the condensate layer formation

The governing equations of the condensate layer are given below. The continuity equation for incompressible fluids can be used since the pressure change has no effect on the density:

$$\frac{\partial \upsilon_x}{\partial x}+\frac{\partial \upsilon_y}{\partial y}+\frac{\partial \upsilon_z}{\partial z}=0 \tag{2}$$

The Navier–Stokes equation for incompressible fluids is adopted here to close governing equations:

$$\frac{\partial \upsilon_x}{\partial t}=g_x-\frac{1}{\rho_l}\frac{\partial p_h}{\partial x}+\upsilon\left(\frac{\partial^2 \upsilon_x}{\partial x^2}+\frac{\partial^2 \upsilon_x}{\partial y^2}+\frac{\partial^2 \upsilon_x}{\partial z^2}\right)-\left(\upsilon_x\frac{\partial \upsilon_x}{\partial x}+\upsilon_y\frac{\partial \upsilon_x}{\partial y}+\upsilon_z\frac{\partial \upsilon_x}{\partial z}\right) \tag{3}$$

where v is the velocity [m/s], υ is the kinematic viscosity [m^2/s] of the Galden liquid, P_h is the hydrostatic pressure [Pa], ρ_l is the densities of the Galden liquid [kg/m^3] and g is the gravity