INVESTIGATIONS INTO THE PROCESS OF VAPOUR PHASE SOLDERING

PHD THESIS-BOOKLET

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Motivation

The majority of the electronic circuits are assembled with Surface Mount Technology (SMT) today and reflow soldering is a common joining method in SMT assembling. During the reflow soldering process, the solder paste (which is a suspension of selected solder alloy powder and selected flux material) is deposited onto the solder pads of a PCB with stencil printing. After stencil printing, discrete components of the circuits are placed onto the solder deposits at their proper positions automatically. Then the manufacturing continues with heat transfer: the key step of reflow soldering. During the heating period the solder alloy melts, while during the cooling period, the alloy solidifies again forming mechanical and electrical joint between the terminals of the components and the pads of the PCB. Reflow soldering is usually done with ovens using infra-red radiation, convection or vapour phase (condensation) heat transfer. These ovens can be inline machines for mass production or standalone batch type stations for smaller scale manufacturing or laboratory work.

Vapour phase soldering utilizes the effect of condensation of hot vapour to heat up the prepared assembly. During the process a special heat transfer fluid (Galden fluid) is heated in the bottom of a tank until its boiling temperature (150-250 °C). The vapour is heavier than air, so a blanket of vapour develops just above the surface of the fluid. This blanket is the heat transfer medium. The assembled circuit is then immersed into the hot vapour blanket, where the vapour condenses on the cold, ambient temperature surface, giving its latent heat to the assembly in order to melt the alloy. Condensation stops when the assembly reaches the maximum temperature: the boiling temperature of the fluid. In the end the assembly is lifted out of the process zone for cooling.

The method was introduced in the 70’s [1] but it was banished for a long time because the use of harmful materials inside the ovens (such as CFC heat transfer fluids) [2]. The method was later re-introduced after the development of Galden, which is an inert perfluoropolyether (PFPE) type heat transfer fluid [3]. VPS is getting more attention with the domination of lead-free solder alloys. The solder joints produced with VPS were found to be nearly equivalent [4, 5] with the quality of the conventionally produced solder joints, so the method is considered as an optional alternative possibility for the industry as well. The use of VPS is also advantageous from the aspect of smaller volume production, where economic, energy saving and environment friendly aspects of the method are exceptional.
With the study of the literature I have concluded, that the description of the technology is mainly based on empiric observations. The modelling of VPS is lacking scientific depth or details. In my work I have focused on these aspects: investigation and modelling of the process.

**Problems of the Field Requiring Novel Solutions**

The common literature of VPS praises the even heating on the surfaces of the given assembly prepared for soldering [6, 7]. With even heat transfer the main problems of radiation and convection type ovens could be avoided: shadowing effects [8] and local temperature maximums [9]. This problem is avoided in the case of VPS due to the fact that the maximum of the temperature is limited to the boiling temperature of the applied fluid. To obtain even heat transfer, even vapour concentration and even temperature distribution is required in the process zone. The literature offers simple solutions for the characterization of the process zone, both qualitatively and quantitatively. The descriptions found in the oven manuals and the solutions found in the commercially available ovens themselves are suited to understand the practical utilization of the machines. The literature also lacks any thorough description of the typical VPS process zones, and does not serve with a complete model of the process itself [10, 11, 12].

The literature misses the description of the measurement techniques of the process and its state variables. It does not take into account of the advantages or disadvantages of the possible measurement methods. The root causes and related effects of process zone inhomogeneities are also roughly neglected by the literature.

The authors do not take the vapour concentration (one of the most important state variables in the thermodynamics of the field) into consideration, they do not investigate the dynamic changes of the vapour, and they lack any theoretical or practical characterization of the vapour blanket. To provide a complete characterization of the vapour concentration, novel approaches must be investigated and applied. The combination of electronic measurement technologies and the use of pressure sensors may enable new opportunities to characterize the pressure and concentration directly. It is important to define the saturation value of concentration, which can serve as a threshold value and can help detecting the steady state inside the process zone.

No complete solution is given by the literature for the modelling or simulation possibilities of the VPS method. With proper boundary conditions, a thermodynamic process simulation would give a complete volumetric description of the main state
variables (temperature, pressure) inside the process zone. Dynamic simulated mapping in three dimensions may also give detailed results, which could hardly be achieved by practical measurement methods. With a properly verified simulation tool, the investigation of a VPS oven may become possible at the constructional design phase, which can also influence decisions even during the design phase of a new oven.

When the condensing fluid wets the surface of the PCB filmwise condensation occurs on the top and bottom side of the board which is immersed into the saturated vapour \[11\]. To describe the filmwise condensation the literature offers examples \[11,13,14\] which are originating from the Nusselt formula \[11\], but are specified for the horizontal cases of the phenomenon. The authors are not giving any scientifically thorough description about the condensation process on the PCB, so it would be important to define a proper and practically simple thermodynamic model, which would give a precise approximation of the heat transfer coefficient during the heating of the PCB. So it is important to investigate the applicability of the general models and the correction factors for the case of VPS. The goal is a description for the overall heat transfer coefficient which enables calculation of the PCB heating. The literature defines the values of the coefficient in a loose range (between 100-400 and 400-700 W/m²K). Such model may be able to refine these empirical values \[8,11\]. With the help of the model, a fast calculation could be presented approximating the PCB temperature in time, in other words, the soldering profile.
Research Objectives

After a research on the literature I have set the following points as milestones of my research:

- developing a physical model of the VPS system with a complex measurement system, where the main time and location dependent state variables (temperature, concentration) can be determined flexibly inside the process zone. The model can then serve as a verification tool for further research;
- defining a proper saturation threshold with temperature and pressure measurements inside the process zone, which will indicate the steady state of the system in time for the standard VPS method;
- characterization of the process zone, where a multi-physics simulation enables full characterization of the main state variables inside the process zone, also enabling the optimization of the actual workspace;
- developing an explicit heat transfer model based on the theory of filmwise condensation, which will describe the heat transfer coefficient of the process, will describe the heating of the immersed PCB, will approximate the thermal conditions and will help to determine the requirements for actual reflow soldering.
Methodology

I have started my research with the development of a physical model station, an experimental VPS oven. An immersion heater heats the Galden heat transfer fluid in the bottom of a tank. The heating is based on a power supply, controlling the voltage on the heater. The boiling Galden forms the vapour blanket, the heat transfer medium itself. I have prepared a cooling circuit at the top of the tank, which enables condensation of the excessive vapour.

During the measurements I have used Galden HT170 type fluid, which has a relatively low – 170 °C boiling temperature. Thus the long measurement cycles could be shortened effectively. From the aspect of the method HT170 is commutable with the common LS230 type fluid, which is often used in lead-free soldering.

For the temperature measurements I have used Pt500 type resistance temperature detectors, which were fixed on stands with low thermal capacitance. For the pressure measurements I have used differential pressure sensors, which detects relative pressure and the dynamic behaviour of the investigated medium. For the static measurements I have used a membrane-based sensor device, for the dynamic measurements I have used a thermal sensing core based flow detector (pressure sensor) device.

For the data acquisition I have developed a system based on data logger cards, which are able to record the input data with a computer program.

I have defined the geometry for the simulation with Excel software. The input parameters and boundary conditions were defined according to literature data and my measurement results. To run the simulation software and evaluate the results, I have used Matlab. The verification of the simulation was done according to my measurements.

To describe filmwise condensation I have wrote a Matlab software. I have used my own measurements (conducted in the physical model station) and their results for verification.
Novel Scientific Results

Thesis I/1: I have shown that the developed physical model system enables complex measurement possibilities for a novel, quantitative, multi-parameter description of physical processes during vapour phase soldering, also enabling optimization from the energy consumption and efficiency of the method.

Discussion: I have measured the temperature with Pt500 RTD sensors and K-type thermocouples. For positioning the measurement devices in the right dimensions a fixture and a probe was developed with low thermal capacitance to minimize any additional transients in the measurement results. I have investigated the precision and applicability of the following methods:

- temperature measurement with ceramic based, RTDs;
- temperature measurement with NiCr-NiAl K-type thermocouples;
- pressure sensing with static and dynamic pressure sensors;
- additional methods (such as optical and buoy-based measurements).

With the physical model and the measurement techniques I have concluded, that in any point of the process zone, the time required to reach the maximal temperature decreases exponentially with the increase of the input power. I propose an optimal heating power in the physical model, which is expedient from the aspect of soldering cycle time reduction. On the other hand it should be lower than 5 W/cm² in order to minimize the degradation of the heat transfer fluid.

It can be concluded from the results that the acceleration of the heating can be obtained with the increase of heating power. This effect is limited by the thermal degradation of the Galden fluid, which is caused by high power density at a given surface of the heater.

Related publications: L4, R6, R7, R8, R9, R10
Thesis point I/2: I have identified the physical sub-processes of the vapour phase soldering process according to the following phases: in the first phase the identification of the saturated vapour is not possible from the measurement of the rising pressure; in the second phase vapour development significantly rises, saturated vapour appears above the surface of the fluid and the saturated vapour blanket is getting thicker; in the third phase saturated vapour fills the vapour space (the process zone) completely and the dynamic behaviour settles. In the beginning of the third phase, reaching the saturation boundary, the system sets into steady state, and is ready for soldering.

Thesis point I/3: I have proved that one pressure- and temperature measurement point is enough for the exact characterization of the saturated vapour space with the measurements of the introduced sensor system.

Discussion: I have extended the method presented in I/1 with extensive investigations on the pressure and concentration state variables. During the investigations it is possible to measure the hydrostatic pressure inside the process zone, while the dense vapour pushes out the air from the tank.

The examination of the hydrostatic pressure was carried out with a differential manometer, the examination of the pressure changes was carried out with a differential volume-flow pressure sensor based on a thermal core, which is able to measure the dynamic flow inside the process zone.

From the results I have concluded that the state of the process zone can be separated to three stages in time, after the initialization of the heating. The first stage finishes before the saturated vapour blanket becomes observable from the pressure increase. The second stage (the “dynamic development” stage) is characterized with significant vapour development. The saturated vapour blanket appears and grows higher. This blanket does not fill the tank vertically yet; the concentration and pressure of the vapour are decreasing as the along the Z axis from the bottom to the top. The third stage is the steady state of the system. I define the saturation boundary at the cease of the dynamic behaviour, where the system settles to steady state. In the steady state – where the state variables have no dynamic behaviour – the static pressure shows a variable tendency in space: it is increasing along the Z axis from the top to the bottom.

I conclude that with the knowledge of the state variable functions (in time and space) one measurement point is enough to obtain the height of the saturated vapour blanket.
The methods and the results of Thesis group I. enable flexible verification of modelling and simulation results.

*Related publications: L2, R2, R5*
Thesis Point II: With the time- and spatial analysis of the vapour temperature- and concentration distribution I have verified that the inhomogeneities of an auxiliary vapour phase soldering oven are caused by constructional details.

With the analysis of temperature and concentration distribution inside the developed vapour space I have defined the optimal process zone of the oven.

I have proved that the optimal process zone is significantly smaller than the whole vapour space.

Discussion: The used simulation software calculates with the heat and mass transfer processes inside the investigated system.

With the analysis of the simulation results I have pointed out that in the process zone of an arbitrary vapour phase soldering oven the state variables of the vapour are not entirely homogeneous in space even in steady state, due to the construction of the process zone. According to the simulation results I have defined a recommended optimal process volume, where the inhomogeneities can be neglected, and the heating of the given board can be considered uniform. Thus I have defined the maximum size of the applicable PCB for the given process zone. (I define the boundaries of the optimal space where the concentration of the vapour derives with 5% from the saturation concentration.)

The temperature and pressure/concentration state variables can be defined with simulation at any point of the process zone.

With the method the settling time of the system can be predicted during the development phase of the oven, enabling the investigation of the effects caused by the constructional changes.

Related publications: L3, R3, K1
**Thesis Point III/1:** With the special, improved models of the filmwise condensation on horizontal plates, I have defined a novel thermodynamic modelling method for the description of heat transfer on a Printed Circuit Board during soldering in saturated vapour.

Discussion: I have started the investigation from widely accepted models from the literature [11, 13-18] but the novel approach combines the heat transfer coefficient calculation from both the top and the bottom side of the PCB. This way it becomes possible to calculate the temperature of the PCBs during soldering with 20% maximum and 7% average error, which is acceptable according to the literature.

The combined method is based on the classical Nusselt approach on thermodynamic modelling of filmwise condensation and incorporates different heat transfer coefficients obtained from refinements found in the literature. For the top side, the modelling approach of Nimmo-Leppert [13], Leider [11] and Bejan [14] was considered. For the bottom side, the modelling approach of Gerstmann-Griffith [15] was applied. My method incorporates both the correction factors of Roshenow and Drew [16-18]. With the method it is possible to obtain the dynamic heat transfer coefficient of the vapour phase soldering.

The fast calculations allow such industrial utilization of the method (e.g. soldering profile setting), where the complex multi-physical simulations are not applicable due to the extended calculation time.

*Related publications: L1, R1, R4*
**Thesis point III/2:** I have defined a dynamic heat transfer coefficient for a PCB soldered in saturated vapour, with the thermodynamic method presented in III/1:

\[
\overline{h_{L_{\text{VPS}}}} = 1.079 \cdot \frac{k_i}{L} \left( \frac{h_{b_i} \cdot \rho_i \cdot (\rho_i - \rho_v) \cdot g \cdot L^3}{(T_{\text{sat}} - T_b) \cdot h_{b_i} \cdot k_i} \right)^{\frac{1}{3}} + \left( \frac{0.90 \cdot k_i \cdot (Ra')^{\frac{1}{6}} \sqrt{g \cdot (\rho_i - \rho_v)}}{1 + 1.1 \cdot (Ra')^{\frac{1}{6}} \cdot \sqrt{0.8}} \right)
\]

where

\[Ra' = \frac{g \cdot \rho_i \cdot (\rho_i - \rho_v) \cdot h_{b_i} \cdot \left( \frac{0.8}{g \cdot (\rho_i - \rho_v)} \right)}{\mu_i \cdot \Delta T \cdot k_i} \left( \frac{0.8}{g \cdot (\rho_i - \rho_v)} \right)
\]

Discussion: With the heat transfer coefficient, the maximum error from the calculation results of III/1 was reduced to 8.4%, the average error was reduced to 1.9%.

It is also concluded, that according to the obtained heat transfer coefficient, during the simple method of Vapour Phase Soldering, the overall values of the coefficient can be considered in the window of ~300-800 W/m²K.

*Related publications: L1, R1*

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Index subscripts</th>
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<tbody>
<tr>
<td><strong>T</strong></td>
<td>Temperature, K</td>
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<tr>
<td><strong>Q</strong></td>
<td>Thermal Energy, J</td>
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<tr>
<td><strong>h</strong></td>
<td>Heat Transfer Coefficient, W/m²-K</td>
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<tr>
<td><strong>A</strong></td>
<td>Surface of the Body, m²</td>
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<tr>
<td><strong>t</strong></td>
<td>Time, s</td>
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<tr>
<td><strong>L</strong></td>
<td>Characteristic Length, m</td>
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<tr>
<td><strong>k</strong></td>
<td>Heat Conductance, W/m-K</td>
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<td><strong>h_{hv}</strong></td>
<td>Latent Heat of Vaporization, kJ/kg</td>
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<tr>
<td><strong>ρ</strong></td>
<td>Density, kg/m³</td>
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<tr>
<td><strong>g</strong></td>
<td>Gravitational Coefficient, m/s²</td>
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<tr>
<td><strong>μ</strong></td>
<td>Dynamic Viscosity, kg/m·s</td>
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<tr>
<td><strong>Nu</strong></td>
<td>Dimensionless Nusselt Number</td>
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Practical Utilization of the Results

With the results and methods of Thesis group I. it becomes possible to follow the different state variables (temperature and vapour concentration) of the process zone dynamically. The presented methods offer more flexible approaches and more detailed results than the solutions found in current industrial ovens. The flexibility of the data acquisition system enables easy connection to a computer, which is still not a common approach in the case of commercial ovens. The results of the power investigations reveal optimization possibilities for the energy consumption. The results help to prepare and conduct various verification methods in the case of modelling and simulation. The investigated methods help to identify and define the height of the saturated vapour blanket in one measurement point, which is a considerable improvement and simplification upon the multi-point approach of the industrial solutions. With the presented methods it is possible to define the settling time of the system (the steady state of the process zone); the idle-time of maximum Galden temperature recognition routines (experienced in the commercially available ovens) can be reduced with an in-situ measurement. This helps to improve the utilization during the full working time of the machine. This way the summarized energy-requirements of the oven can be reduced, emphasizing the role of this technology within environmental-friendly green-technologies.

The results of Thesis group II. can be utilized at the advance design phase of a vapour phase soldering oven, where the system can be characterized with the given initial boundary condition. It is possible to analyze different constructional concepts of a VPS during design phase in the level of virtual modelling. It is possible to define an optimal workspace volume in a custom VPS oven, which may help to avoid inhomogeneous heat transfer, also improving the quality of soldering.

The results of Thesis group III. clean up a considerable shortcoming of the available literature in the topic. From the practical point of view, the method can help to predict a given soldering profile, thus helping the on-the-fly soldering profile setting – which is a valuable added value from industrial aspects. Better control and overview on the soldering profiles may help creating better quality solder joints and ultimately, more reliable electronic devices.

The scientific content of the first two thesis points is connected to the "Talent care and cultivation in the scientific workshops of BME/Új tehetséggondozó programok és kutatások a Műegyetem tudományos műhelyeiben" project. The results of the thesis points are evaluated and utilized in the project which is funded by TÁMOP-4.2.2.B-10/1-2010-0009 grant.
List of Publications

Publications Related to Thesis Points

International, peer reviewed journal papers, written in foreign (English) language


International, peer-reviewed conference papers, written in foreign (English) language

[R1] A. Géczy, B. Illés, Zs. Illyefalvi-Vitéz, „Modeling of condensation heating during Vapour Phase Soldering“, 36th International Spring Seminar on Electronics Technology, IEEE-ISSE2013, Alba Iulia, Románia 2013.05.08-2013.05.12.,


Hungarian conference papers, written in foreign (English) language

A. Géczy, B. Illés, Zs. Illyefalvi-Vitéz: Investigating the process zone of a Vapour Phase Soldering oven, Proceedings of the TAMOP PhD Workshop, TAMOP-4.2.2/B-10/1-2010-0009, Budapest, Magyarország, 2012.03.09. 4. o. Paper 3.

Additional Publications

International, peer-reviewed journal papers, written in foreign (English) language

B. Illés, A. Géczy, „Investigating the dynamic changes of the vapour concentration in a vapour phase soldering oven by simplified condensation modeling”, Applied Thermal Engineering, 59:(1-2) pp. 94-100. 2013. (IF: 2.064)

International, peer-reviewed conference papers, written in foreign (English) language


Hungarian papers, written in Hungarian language


References

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