Abstract

Purpose: With the spreading of Vapour Phase Soldering (VPS) technology it is important to understand and optimize the process itself. The paper presents a novel approach on the process zone characterization for direct feedback on the state of vapour, for better monitoring, control and understanding of the process.

Design/methodology/approach: The simple model of condensation heating shows the importance of vapour concentration during condensation soldering. Different pressure sensors were applied in an experimental VPS station, where the hardware setup is focused for the current experiments. Static and dynamic pressure values are analyzed and correlated with additional thermal measurements.

Findings: The results reveal the dynamics of the vapour blanket generation. The correlated measurements show different stages of the process initialization, highlighting better accuracy than sole temperature measurements of saturated vapour identification. It is possible to trace the height of the available saturated vapour blanket with static pressure measurements.

Originality/value: The methods provide a completely novel approach from the aspect of process zone state variables and parameter characterization, focusing on pressure measurements.

Practical implications: The VPS process may benefit from the more precise saturation detection, giving better control on the heat transfer, enabling more efficient production with the reduction of idle time, and resulting in better soldering quality.

Social implications: Reducing the idle time of the VPS stations may result in better efficiency and smaller power consumption, reducing the environmental impact of the method.

Keywords: vapour phase soldering; VPS; thermal profiling, pressure profiling, Galden

1. Introduction to the technology of Vapour Phase Soldering

Vapour Phase Soldering (VPS) is a reflow soldering method, which is generally considered as an emerging alternative of the conventional reflow technologies. During the process, a heat transfer fluid is heated in the bottom of a closed tank. Due to the continuous heating, the fluid initially starts to boil, forming a vapour blanket inside the tank. The saturated vapour does not exceed the volume of the tank - a cooler appliance condenses the excess at the top. The assembled board, prepared for soldering is then immersed into the vapour blanket, which then condenses on the surface of the board. This condensation provides the required energy to melt the solder alloy. The board is lifted out of the vapour, when the process is over. During the process, soldering temperatures are defined by the boiling point of applied fluid. This material nowadays is usually Galden type perfluoropolyether (PFPE) polymer fluid (Bassi, 2011.) composed of ether chain (1) structure:

$$\begin{array}{l} CF_3-(OCFCF_2)_n-(OCF_2)_m-OCF_3 \\ \qquad\qquad | \\ \qquad\quad CF_3 \end{array} \qquad (1)$$

where the exact m,n ratio is handled by the manufacturer. The charbon-fluorine bonds give an optimal stability for the continuous stress on the fluid (Avataneo, *et al.* 2009.) during the heating and cooling periods of the VPS process. Each available Galden type has a fixed boiling point; however after continuous use the Galden may have a notable drift in this parameter due to the continuous thermal stresses.

The process of VPS was invented in the seventies (Pfahl and Ammann, 1975.) and the technology was constantly revised and improved later in the eighties. Different variations of VPS oven constructions were investigated (Wenger, 1987); different types of fluids (and their vapours) were compared (Lea, 1989.) for VPS application. The technology has lost its role in surface mount technology during the time, while the applied chemicals released Chlorofluorocarbon (CFC) gas by-products. Later this soldering technology was banned (Leicht and Thumm, 2008.) due to the caused environmental hazard according to the Montreal Protocol. VPS technology was re-introduced after Galden fluid emerged to the market (Sprovieri, 2002. and Munroe, 2008.) as a possible substitute of the previously applied chemicals.

Fig. 1 shows an example for a simple VPS station construction, where the inner space is highlighted with a grid and the actual process zone is defined between the liquid level and the circular cooler.

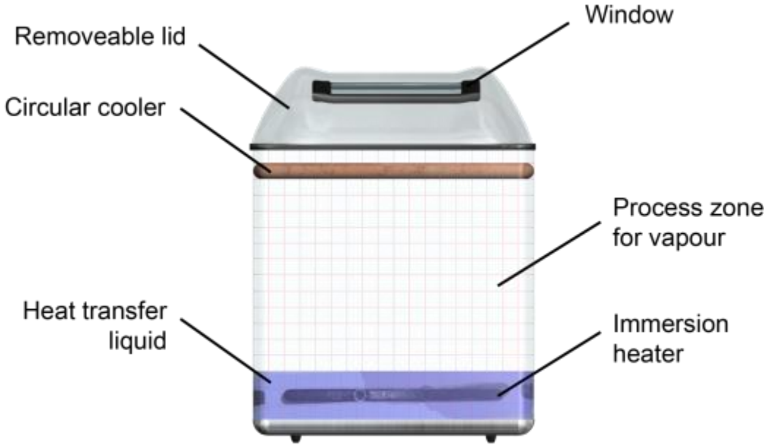

Figure 1 An example for a simple VPS station

The common VPS system adjusts vapour level inside the soldering chamber only with controlled power applied to the heating of Galden. The boiling point temperature (saturation temperature) of the applied fluid may be programmed into the control unit of a soldering station with a defined temperature value. Also the boiling point may be recognized with temperature profiling, where a time consuming recognition phase must be implemented to the workflow principles of the VPS system. During recognition phase, the fluid is heated, until it reaches the point where the temperature cannot increase further. This recognition reduces the possible error of pre-set temperature values caused by boiling point drift, in the same time increases the idle time of the machine and the whole production line.

Several investigations are in progress aiming to find the possibilities and limitations of the technology in comparison to the conventional reflow methods. The main advantages of the VPS process are the uniform, rapid heating (and heat recovery) of the goods where the temperature is limited to a maximum (Lee, 2002., Munroe, 2008. and Suihkonen, 2007.); the inert atmosphere and the condensed film layer keeping oxygen and other gases from direct contact of the solder paste, preventing oxidation. The principle of condensation heating allows large components with high mass to heat up evenly (Thumm, 2010.) without the effect of shadowing.

Considerable disadvantages include rapid heat flow with higher heat transfer rate (Leider, 2002.), which may cause damage in the solder goods. Also the process may result in tombstoned components; minor voiding or solder beading (Lee, 2002.) due to the condensed film layer. Wicking (Strauss, 1998. and Zabel, 2011.), puddle formation on the top of the board (impeding further condensation and heat transfer), popcorn effect, and delamination of plastic packaging (Lee and Earmme, 1998. and Huang *et al.*, 1998.) may also be a considerable problem. Without proper cooling down phase of the soldering profile, cracks and reduced shear strength (Krammer and Garami, 2010.) may also be observable on the solder joints.

With preheating (Strauss, 1998.) spluttering paste, tombstone effect, and damaged components can be avoided, also the dwell time in the vapour can be reduced. Additional cooling can also be applied to the soldering level inside the process zone to modify the profile. With appropriate heating of the fluid, non-saturated vapour can be achieved, where the vapour concentration and heat transfer efficiency has a gradient along the vertical axis, where the saturated vapour is only developed to a certain height. This so called “Soft VPS” (S-VPS) method was introduced by IBL Loettechnik GmbH, where the boards are descended into different heights of the non-saturated vapour blanket. Non-linear VPS soldering temperature profiles can be created with S-VPS, to match the requirements of the pastes. Asscon came up with an addition of a vacuum chamber module to the VPS process, where the gases (voids) are drawn out from the molten solder by vacuum (Zabel and Duck, 2009.) after reflowing the paste. According to recent research results, solder joints produced with VPS have been found (Pietriková and Durisin, 2009., Krammer and Garami, 2011., Gatza and Evans, 2012.) to have near equivalent quality like the ones created with conventional reflow technologies.

Industry standards for process zone characterization involve solely thermocouple probes (chromel-alumel, K-types). The probes are used for temperature monitoring inside the commercially available soldering stations. Lam used copper-constantan T-type thermocouples for temperature profiling of the VPS tank (D.M. Lam, 2012.), heat distribution was also observed by thermovision cameras (Plotog *et al.*, 2010., D.M. Lam, 2012.) inside the process zone. Also Platinum (Pt) Resistive Thermal Devices (RTDs) were used for temperature monitoring (Géczy, *et al.*, 2010.) along the Z axis. The characterization of Galden vapour blanket was extended with the measurement of vapour propagation with optical probe, floating polymer pillow (Géczy, *et al.*, 2010.) and investigation of the condensed droplets (Illyefalvi-Vitéz, *et al.*, 2010.) inside the vapour space.

Besides the temperature an additional parameter is suggested for monitoring: the concentration of the vapour/air mixture. The literature does not refer to any concentration- or pressure measurement related solution of process zone monitoring; investigating these relations is still an untapped area. This paper presents the results and a suggested model of the pressure measurement application inside an experimental, custom built vapour phase station.

2. Principles of the VPS Process

If an ambient temperature body is immersed to a process space where the vapour of a heat transfer fluid is present, the vapour condenses on the surface of body. The condensate surrounds the body with a fluid film. The condensate film transfers the released latent heat to the body. The latent heat energy transferred by the condensation of the Galden fluid can be calculated with (2):

$$Q = m \cdot L \qquad (2)$$

where Q is the energy of the phase change [J], m is the mass of the condensed fluid [kg] and L is the specific latent heat of the fluid [J/kg]. For continuous heating of the body by the filmwise condensate, permanent vapour source is needed, because the condensation itself reduces the vapour concentration in the surroundings of the body. The reduced amount of vapour must be compensated by re-developing vapour from the boiling fluid. When the film starts to cool down by heat transfer to the board, new vapour immediately condenses and heats the film again.

The film thickness of the condensate is critically dependent on the surface condition of the body, the material properties of the heat transfer fluid and the process temperature. The thickness value can be approximated as 0.2-0.3 mm in the case of commercially used Galden fluids. The whole process continues until the body reaches the saturation temperature (the boiling point of the vapour). The overall thermal distribution inside the process zone can be described by the heat equation (Cheng, *et al*.,2012.):

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c} \cdot \nabla^2 T \qquad (3)$$

where T is the temperature [K], t is the time [s], λ is the thermal conductivity coefficient of the given material [W/m·K], ρ is the density of the given material [kg/m^3], c is the specific heat capacity of the given material [J/kg·K]. The ideal gas law (4) gives the correlation between vapour concentration and vapour pressure:

$$P = R \cdot T \cdot C \qquad (4)$$

where P is pressure of the vapour [Pa], R is the ideal gas constant [8.314 J/kg·K], T is the temperature [K], C is the molar concentration [mol/m^3]:

$$C = \frac{n}{V} \qquad (5)$$

where n is the number of moles, V is the given volume. The energy in a given vapour space after the start of the evaporation can be calculated (6) as a mixture of air and Galden vapour:

$$E = (c_a \cdot m_a + c_G \cdot m_G) \cdot T \qquad (6)$$

where E is the energy, m is the mass of the available material, a is the index of air and G is the index of Galden for the mass and the specific heat capacity. By increasing the amount of Galden vapour and with reduction of the air from the vapour space, the energy of the vapour space (7) changes:

$$\frac{\partial E}{\partial t} = c_G \cdot T_G \cdot \frac{\partial m_G}{\partial t} - c_a \cdot T \cdot \frac{\partial m_a}{\partial t} \qquad (7)$$

The energy change causes the following (8) temperature change:

$$\frac{\partial T}{\partial t} = \frac{1}{c_a \cdot m_a + c_G \cdot m_G} \cdot \frac{\partial E}{\partial t} \qquad (8)$$

The molecular weight of the Galden vapour is around twenty times more than the molecular weight of the air, so the temperature saturation of the vapour space is much faster than the concentration saturation of Galden vapour. It can be calculated with (8) that temperature is nearing its saturation at around 20-25% concentration of the saturation level. The previously described correlations (4-8) emphasize that concentration of the available vapour is a crucial criterion for the process and the condensation itself, while the rate of heat and energy transfer is governed by the amount of available vapour for condensation. The measurement of absolute concentration and dynamic concentration change is possible with proper application of pressure sensors according to (4), so direct vapour concentration monitoring gives a feedback on the state of the process zone.

3. Experimental setup

A VPS system was constructed for experimental purpose. The system is used in laboratory environment and its construction is based on the common design approach of commercial batch type VPS machines. The main advantage of the system is its flexibility. Different sample holder baskets with rails, thermocouple ladders (along the Z axis), 2D thermocouple grids (along XY axes), probes and hoses can be attached to the system. The sub-parts can be modified to suit various measurements according to dedicated experimental investigations.

The main unit is a closed stainless steel tank. A heater (⌀10 mm stainless steel tube, ceramic filler and ⌀1 mm heater filament with ~25 Ω resistance) is positioned 10 mm from the bottom of the tank. The heat transfer fluid is then filled in the bottom of the tank, directly onto the heater. The power of the heater can be controlled by voltage from an external power source. The cooling appliance is constructed from a copper tube, aligned 1 cm under the top edge of the tank and led outside through the removable lid. Ambient temperature water is circulated inside the tube with an external pump. Fig. 1 is also based on our experimental unit, highlighting the process zone. Fig. 2 reveals the block diagram of the setup, showing the tank from the top. The batched sensor probes are connected to a data acquisition system, which is logging the data on a PC to MS Excel format.

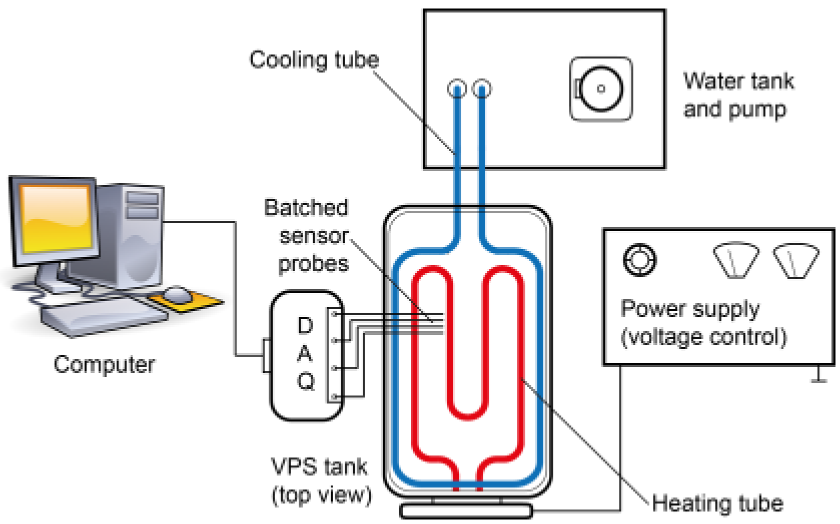

Figure 2 Block diagram of the experimental setup

It was important to set up a parameter space for the experimental station where each measurement is based on the same initial conditions. 1.3 dm^3 HT170 type Galden was filled to the VPS tank, with a boiling point of 170 °C. The heating power of the system was set to ~550 W, while the cooling power of the appliance at the top of the tank was fixed to ~50 W.

For each heating up measurement, the whole system had to be heated up, and then cooled back to the ambient conditions. The full cycle of heating up and cooling down is around 3-4 hours compared to the time window (~20 minutes) of the examined period. It was important to choose a lower temperature Galden, achieving faster and more efficient heating up cycles. This way the time of a full heating up/cooling down measurement cycle can be reduced dramatically compared to fluids with higher boiling points. HT170 is also relevant from the aspect of lead-free soldering, while special pastes (such as low melting point Sn-Bi alloys with 138 °C melting point) are recommended to be soldered in HT170 type Galden fluids. Our method is also compatible with any other Galden types, such as LS230, where the material parameters are also well known, and the temperature is suited for more conventional lead-free pastes (e.g. SAC305 alloy with 217 °C melting point).

Two pressure measurement sensor types were applied to the experimental VPS system, to highlight the dynamic and the static behaviour of the vapour. The dynamic measurements can identify the development and the dynamic progression of the saturated vapour blanket during heating up; the static measurements can reveal the hydrostatic height of the vapour blanket with saturated concentration. All sensors are based on differential principles showing *gauge* type outputs, which present the difference between the *atmospheric* and the *absolute* pressure (Benedict, 1977.) in the system. To achieve gauge measurement, one port of the differential manometer must be left open for ambient atmosphere. Sensirion

SDP1108 (SDP) amplified dynamic sensors were used for dynamic measurements. According to its data sheet, SDP has ±0,05 Pa tolerance and square root characteristics, offering precise measurements in the lowest range of the sensor. SDP is based on a thermal sensor core, requiring minimal air flow (dynamic characteristic) for an active output. With the development of the vapour blanket and the rise of the pressure, the air inside the probes is pushed through the sensor core out to the ambient space. Therefore it is possible to characterize the dynamic changes of the pressure with the mass of the airflow through the core. A Fluke 922 (F922) manometer was used for dynamic and static measurements. This device is ideal for depth/static pressure measurements, while it is based on membrane core, enabling the hydrostatic pressure sensing of a liquid or vapour column at a given depth, with proper coupling. The sensor has 1 Pa resolution with an accuracy of ±1% of measurement + 1 Pa.

The sensors cannot withstand the heat inside the process zone, so coupling between the sensors and the process zones were implemented with silicone hoses. Three silicone hoses with the length of 1 m were attached together to form a measurement probe – one hose is attached to the SDP, the other is to the F922, the third one is an auxiliary port for any additional sensors and to maintain the symmetry of the construction. Each hose is attached to each input (+) port. Reference ports (-) are left open to the ambient space. This way atmospheric pressure is compensated, which is required due to the non-hermetic sealing of the process zone. The end of the probe is illustrated with Fig. 3, where a K-Type thermocouple is positioned between the hoses, and the welded hot spot is positioned just below the openings.

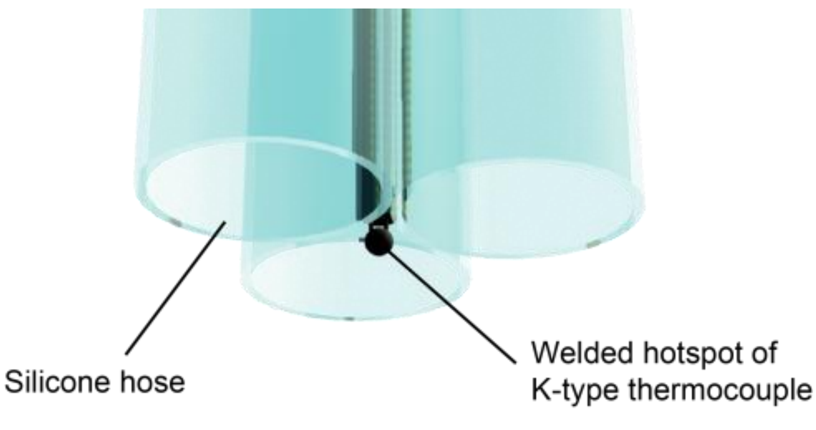

Figure 3 Pressure sensing probe with three silicone hoses and a K-type thermocouple

The K-Type thermocouple has an acceptable ± 1 °C tolerance, and the small welded spot (with ~0.5 mm diameter); its relatively small thermal capacity allows fast response for rapid temperature changes. The submersible insertion of the probe is shown in Fig. 4. The end of the probe is positioned 1.5 cm above the boiling Galden. This height was defined as a fix position for soldering in the process zone. Reference ports are also positioned in the same height outside the system. According to the technical sheet of the sensors, the 1 m length of the hose cause nearly 2% deviation of the measured values, which was compensated afterwards the data acquisition. It was considered, that the temperature of the sensor elements may rise due to the coupling. Additional thermal measurements (with the same K-Type thermocouples) showed, that there is no significant temperature coupling to the sensor ports from the hoses.

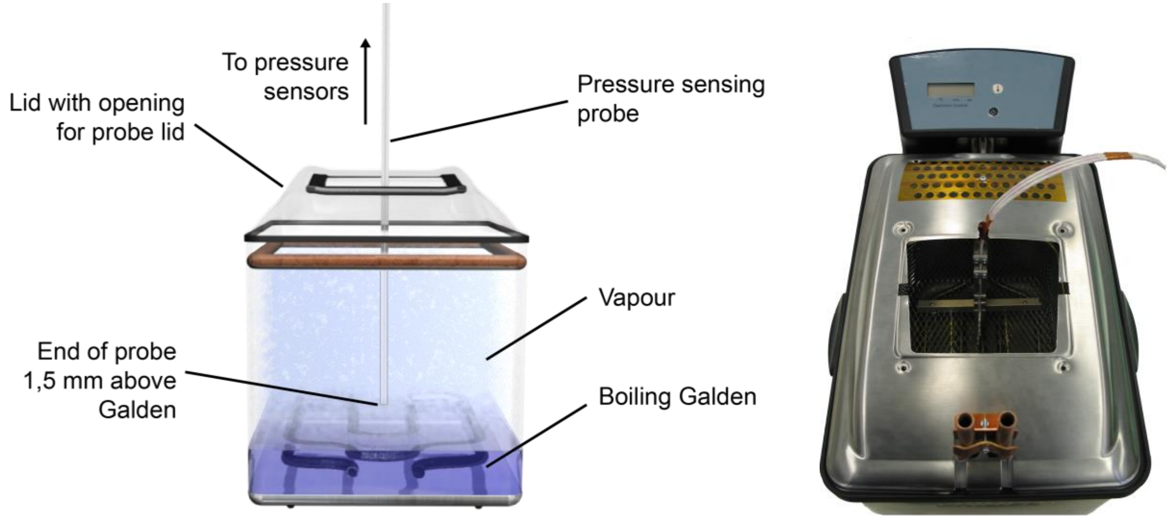

Figure 4 Schematic front view of VPS station, with submersible insertion of probe into the vapour blanket (left); The station from a top perspective – without the window element (right);

4. Results

The main aim was to monitor the dynamic and static relations of concentration with the pressure sensors. First the dynamic changes of the pressure were characterized with the SDP sensor. The flow values of the sensor output are presented in SCCM (Standard Cubic Centimeters per Minute). The first peak (Fig. 5) of the dynamic plot highlights a relatively slower change compared to the second peak. During the rise of the first peak, the layer of vapour blanket is starting to fill up the bottom of the tank. The rapid rise of the second peak highlights the boundary of the saturation, where the saturated blanket passes through the level of the probe. For better recognition of the different phases of vapour development, the measured temperature profile was correlated with the dynamic plot.

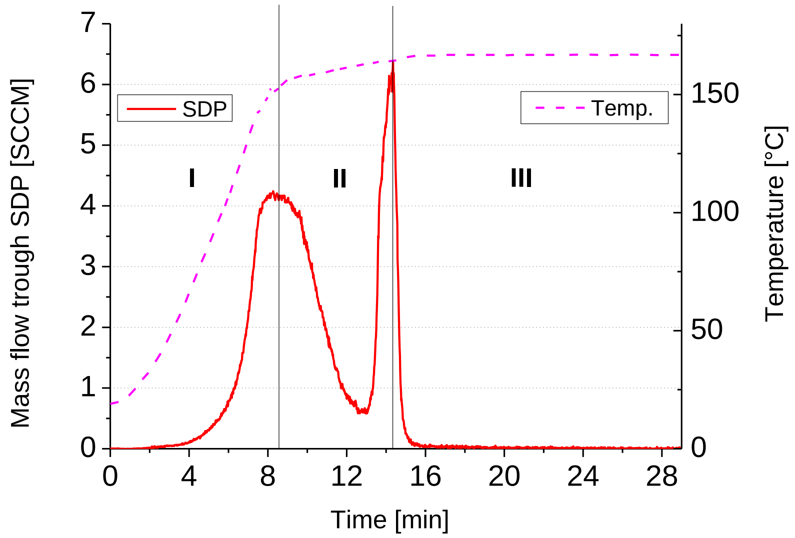

Figure 5 Dynamic pressure measurements combined with temperature measurements; 3 different stages highlighted (I-II-III)

Three stages of the process were identified during the period. Each stage was defined by the peaks in the dynamic plot of the mass flow, which were also in correlation with the break points of the temperature profile. The first stage (I) shows that temperature is increasing from the start, while vapour generation has just started after 2 minutes, according to the dynamic output of the pressure sensor. The temperature is nearing its saturation when the process reaches the second stage. The second stage (II) shows that temperature rise has slowed down considerably, and the amount of flow is decreasing in the pressure sensor. This means that vapour generation has slowed down in the vertical direction. The phenomenon can be described with to the horizontal spreading of the generated vapour which must take place before the fast vertical rise of the saturated vapour. According to our previous work (Illés and Géczy, 2012.), it is assumed, that just above the fluid level, the vertical propagation of the vapour is slowed down, until the saturated vapour covers the whole surface of the liquid horizontally. According to our simulations, this phenomenon can be reduced by applying more homogenous heating. Then the following rapid increase in the flow indicates the rise of the saturated vapour at the end of the second stage. The system settles to steady state in the third phase (III).

The results show that heat transfer in saturated vapour is only recommended at (III) while the vapour concentration is not reaching its saturation until that point. Sole temperature monitoring of the process zone may not reflect the actual amount of vapour available for condensation – thus affecting the intended heat transfer on the board and on the solder joints, also affecting the intended soldering profiles. With the inaccuracy of the thermocouples

(±1 °C) it is possible to indicate a pre-set value of temperature saturation during the second (II) stage, and the boiling point drift also makes it more difficult to identify the saturation in the proper time. If the control of the VPS system is relying on saturation temperature recognition routines, the time of the recognition phase (which is an idle time from the aspect of the machine and the production) may also be reduced with the direct indication of vapour concentration saturation. The fast response of the dynamic sensor output works like a trigger signal for the indication of the saturation boundary and the start of the third stage. The settling of the dynamic pressure also identifies the end of the saturated blanket generation and the steady state of the process zone, which becomes ready for soldering in saturated vapour.

During the measurement cycle, the output of F922 manometer was logged manually. Fig. 6 presents the logged values from the output of F922, and also a simulation data. A tool for the simulation of the process zone was presented in (Illés and Géczy, 2012.), where the initial parameters of the process were synchronized with the simulation tool. The plot of the simulated (calculated) pressure was derived from a selected cell of the simulation geometry, where the probe was positioned during measurement.

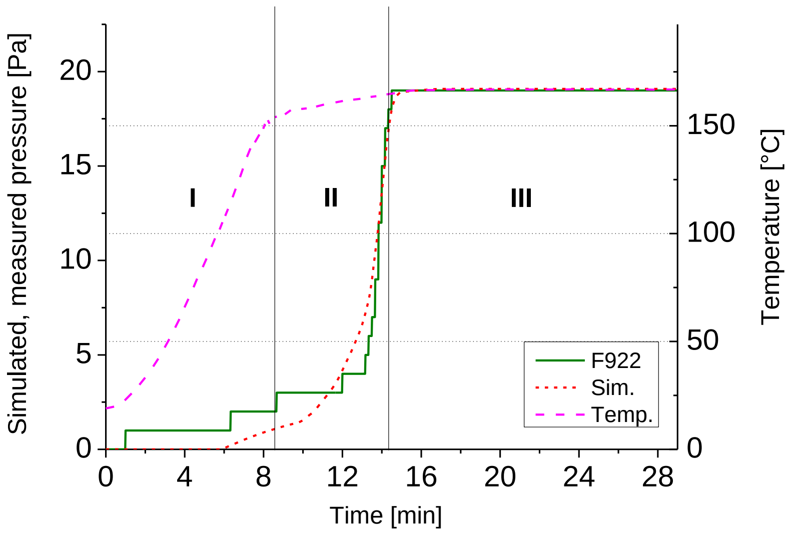

Figure 6 Fitting simulation data to the measurement

The saturation point and the pressure plot measured by F922 is consistent with the tendencies and recognized stages of Fig. 6, F922 is able to measure actual pressure values for a numerical characterization of the pressure inside the process zone. The pressure values are far from the saturation in (II), while temperature has almost reached its maximum. (This was predicted from the energy change, described by (8).) F922 is also able to highlight the transition between the (II) and (III) stages. The simulation tool is in good correlation with the measurement to predict the same transition with an acceptable transient effect. The validated simulation of a custom process zone is also offering a tool of process optimization, where the steady-state can be predicted even in the designing period of a conceptual VPS system, at given initial parameters.

Several measurements were conducted, where the measured temperature and flow variations were within the tolerance of the sensors. Small deviations were observable in the time values of each stage, but these values may also depend on the small variations of initial temperature (which had also some deviation according to practical causes). The tendencies and correlations show the same phenomena.

Static pressure is an important parameter from the aspect of the vapour blanket height monitoring and setting for special applications, such as S-VPS. Multiple fixed measurement points are needed in different heights to trace the progress of the saturated vapour blanket, by using the principles of temperature measurement. The measured data can be interpolated between the temperature measurement points, but without significant increase of the measurement point density along the vertical axis, the method will not give an accurate approximation of the height. The other problem of temperature measurement was discussed above, while the temperature saturation is not in direct correlation with Galden vapour concentration saturation. With implementing one pressure probe at one given height above the Galden fluid, the height of the saturated vapour can be traced, by measuring the hydrostatic pressure of the saturated vapour column above the fix measurement point. For evaluation of the method, static conditions in steady state were analyzed with F922, after the saturated vapour layer had reached the top of the tank (this state of the process zone was already set during the heating up measurements.). For each measurement, the probe was submersed into the corresponding depth of the blanket.

For the calculations of the static pressure, the hydrostatic pressure equation (9) was used:

$$P = \rho \cdot g \cdot h \qquad (9)$$

where ρ is the density [kg/m^3], h is the height [m] of the hydrostatic column, g is the standard gravity [m/s^2]. The concentration of the Galden vapour is ~19 kg/m^3 around the saturation, g is 9.81 m/s^2. For each consecutive measurement the probe was submersed 1 cm deeper into the saturated blanket starting from 1 cm below the cooler height at the top of the process zone. Fig. 7 presents the calculated and the measured data as well.

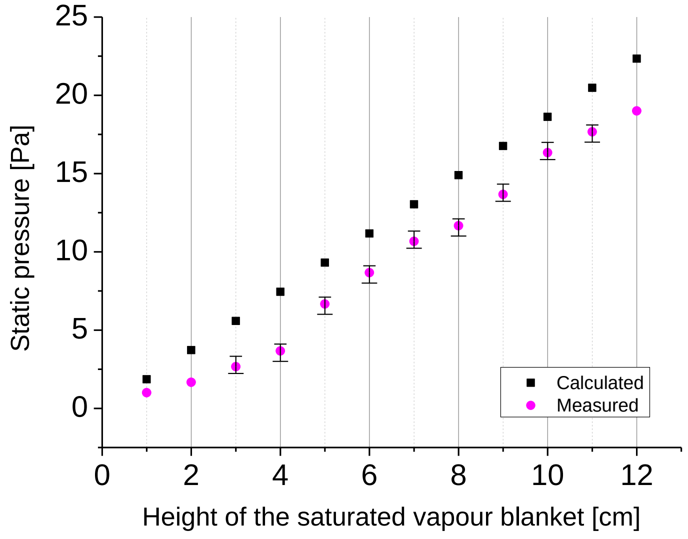

Figure 7 Steady-state static pressure values at different vapour blanket heights

The measurement results are averages of three data samples at the same height. The offset between measured and calculated values (also presented on Fig. 7) was higher than the absolute error of F922 (±1% + 1 Pa). This can be explained with the imprecision of manual probe fitting and also with the extremely low pressure level compared to the full range of the sensor (0.45% of the 0-4000 Pa measuring range). However the measurement confirmed that the tendency of the measured values is consistent with the tendency of calculated pressure values of the vapour layer. To compensate the offset for better practical utilization of the data, measurement results were compensated with the mean of the offset, giving an acceptable fit afterwards on the original data. The 11.9 % average error was reduced to 2.4 %, which is an acceptable value. Even without compensation, the height of a vapour blanket can be approximated with 1.4 cm tolerance. The approximation becomes more precise (0.2 cm tolerance) after the compensation of the average offset.

With the method, it is possible to approximate the saturated vapour blanket height with the measurement of hydrostatic pressure in one dedicated point of the tank. Also the accurate height setting may help to set different vapour concentration profiles for non-conventional VPS heat transfer (such as S-VPS custom soldering profiles). It was already concluded, that relying solely on temperature measurements will not provide an accurate saturation tracing of the vapour. Also similar vertical resolution could be achieved only if temperature sensors would be positioned with one sensor per 1.4 cm distance across the vertical axis. This precision would unreasonably increase the sensor count and the corresponding processing requirements for the VPS system controller.

5. Conclusions

A novel method was developed for a Vapour Phase Soldering system, where the two main parameters of the process zone were investigated; temperature and vapour concentration.

With pressure measurements it is possible to monitor the vapour concentration inside the process zone. With the measurement results we have defined three stages (I, II and III) of the initial heating up of the process zone. It was concluded, that only the third stage (the steady-state of the process zone) is ready for soldering in saturated vapour. The results of the measurements with different sensors showed the same boundary of the saturation. A simulation of saturated vapour dynamics was also correlated with the measurement results. All three methods for dynamic behavior monitoring are able to highlight the boundary of the steady state, allowing a fast and precise process zone condition description. The idle time of the VPS systems can be reduced with the method, also improving the efficiency of the assembly. The verified static pressure measurements during steady state offer a simple technique for the characterization of saturated vapour blanket height, which can simplify and help to improve the accuracy of process zone monitoring for special VPS applications. The method gives a more accurate solution of height tracing than temperature measurement at different points; the tolerance of the measurement at one dedicated measurement point was ~1.4 cm which was further reduced to ~0.2 cm with a compensation step. The presented approach may help to improve the overall process and current constructions of VPS stations working only with temperature sensors.

Future work is required to reveal the dynamics and the static concentration relations of the vapour blanket in special VPS methods, where non-saturated vapour is utilized for soldering. In addition, the presented approach is also applicable to optimization of other processes, where vapour concentration measurements can be used for monitoring the process atmosphere of condensation heat transfer.

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