Soldering & Surface Mount Technology

Advances in Pressure Sensing for Vapour Phase Soldering Process Monitoring

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Purpose: *To enable better productivity and assembling quality, the industry needs to provide precise control and measurements during assembling. In the paper, a special monitoring method is presented for Vapour Phase reflow Soldering (VPS) to enable improved process control and oven state identification.*

Design/methodology/approach: *The work presents the investigation of the workspace with dynamic and gage type pressure sensors in fusion with thermocouples. Different sensors were evaluated to find an appropriate type. The relation between the temperature and the pressure was investigated, according to the setup of the oven. The effect of inserting a PCB on the pressure of the vapour inside the oven was also investigated with the pressure/power functions.*

Findings (mandatory): *It was found, that the novel gage type sensors enable better precision than solutions seen in previous literature. The sensors are able to monitor the decreasing vapour concentration when a PCB is inserted to the workspace. It was found, that there is a suggested minimum power to sustain a well-developed vapour column for soldering in saturated vapour. An inflexion point highlights this in the pressure/power function, in accordance with the temperature/power curve.*

Originality/value (mandatory): *The research present original works with aspects of a novel sensor fusion concept and work space monitoring for better process control and improved soldering quality.*

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Keywords: Vapour phase soldering, pressure sensor, reflowing, soldering, heating power

1. INTRODUCTION

Vapour phase soldering (VPS) is an advanced reflow method in electronics assembling which is considered as an alternative to convection type solderinig (Dziurdzia et al. 2018). The oven used for VPS (see Fig 1) is a machine using the hot vapour of the Galden liquid (Galden datasheet, 2018) in order to transfer heat and melt the solder paste on the printed circuit board assembly during surface mounted assembly (Zabel, 2006), (Dusek et al. 2018), (Géczy et al. 2013). This soldering method provides high quality joints between the components and the board, rapid and uniform heating of the assembly (Suihkonen D. 2007), (Géczy et al. 2013), joints with less voids in the solder joints when vacuum is applied (Dusek et al 2008), (Munroe, C 2008), (Skwarek et al. 2013), and limited emission of the toxic gases are also important and positive aspects of the technology (Guene, E. 2016).

The VPS oven is based on a simple principle (Plotog et al 2010), (Branzei, M. 2012), where an external power source drives an electrical resistor (immersion heater) at the bottom of the oven to heat the Galden fluid which is stored in a reservoir. By reaching the boiling point, the vapour will start to distribute and ascend in the container above the reservoir (the workspace). At the top, a cooling system prevents any overflow of the medium and condenses it to the liquid state again, enabling it to pour back to the reservoir at the bottom.

To start the process of reflow soldering, with the basic principle of soldering in saturated vapours, the stabilization of temperature and saturation of vapour inside the oven is a basic requirement (Géczy et al. 2013).

For that matter, investigations are widespread in this topic, (Ankrom et al. 1989), (Plotog et al. 2010), (Géczy et al. 2013), with a general use of thermocouple based temperature detection on the PCB-s and inside the workspace as well (Livovsky and Pietrikova, 2017) (Illés and Harsányi, 2009). Temperature detection is also important on PCB level. (Vesely et al., 2018). Previously it was shown, that flow-based pressure measurements and static pressure measuring devices can be used (Géczy et al. 2013), for investigating the saturation of the vapour space more precisely, than solely relying on thermocouple measurements. However the previous results showed limitations both in revealing the dynamics of the vapour generation, and in the instrumentation used in during the process.

According to the findings of (Géczy et al. 2013), vapour column will saturate (reach its steady state) after a considerable time compared to the slow temperature saturation, thus, the pressure monitoring gives a more precise time for highlighting this steady state. This identification step is recommended before starting the process of soldering in saturated vapours. This paper focuses on further increasing the precision of pressure saturation identification with novel sensor devices. The vapour generation process is also investigated with the change of the heating power, and the resulting changes of the saturation time are also presented. With the method, more precise and faster oven control can be achieved, ultimately pointing to better soldering quality.

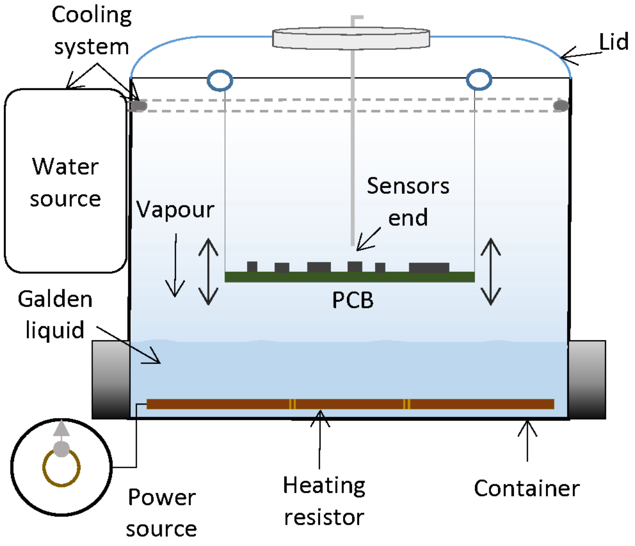

Fig 1. Typical cross section of a VPS Oven

Summing up, our main goal was to improve and develop the pressure measurement of the VPS from the following aspects:

- Control measurements for evaluating new sensors from the market.
- Pinpoint the time needed for steady workspace before and after immersing a PCB inside the oven.
- Effect of the power change on the pressure and the time of saturation.

2. EXPERIMENTAL

For the experiments, we use the vapour phase soldering machine with main unit formed from a stainless steel tank. The heater is positioned 10 mm from the bottom of the tank, and the heat transfer fluid must be filled in way to cover the heater resistor. The heater power is adjustable from an external power source. On the top of the tank, there is a removable lid; the cooling appliance is placed 1 cm under the lid. The measurements are based on initial investigations of (Géczy et al. 2013). The current extensions and novel aspects are the following: the heating power is varied from 250 W to 850 W in 100 W steps; HT170 type Galden is used with quantity of 1.3 dm^3 and a boiling point of ~170°C.

The sensors, their setup and their positioning are presented in the following subchapters.

2.1. Pressure measurements with gage type sensors

With the help of selected sensor output signals, the characteristics of the pressure change and the time needed for the system to set the steady state is measurable. In addition, the variations of the system can be monitored. The following sensors have been considered in this experiment (also shown in Figure 2) which are novel in such applications from the aspect of gage-type core:

-TBPDANS001PGUCV, (TBP) a gage type pressure sensor with a range of 0 psi to 1 psi, it is unamplified and compensated (TBP, Data Sheet. 2018).

-HSCDLNN060MGAA5, (HSC) amplified sensor, with the gage range from 0 mbar to 60 mbar (0.87 psi – similar range as TBP), (HSC, Data Sheet. 2018).

-ABPLANN001PG2A5, (ABP) is a piezoresistive silicon pressure sensor, it contains same range and characteristics of the TBP series, except the ABP is amplified and it is a board mount type component (ABP, Data Sheet. 2018).

- SDP1108-R (abbreviated later as SDP), differential dynamic pressure sensor, with high resolution (up to 0.05 Pa and accuracy up to 0.2% full scale (±1 Pa)) as a control sensor, also used in (Géczy et al. 2013). This serves as a control unit for our current investigations (SDP1108-R, Data Sheet. 2018).

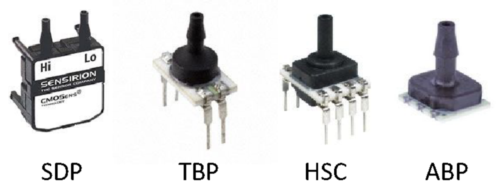

Fig 2. Pressure sensors used in our investigations

The sensors have been chosen with a focus on similar pressure ranges (see Table 1) to optimize readings and form a coherent setup. With the harmonized ranges, similar AD resolution becomes available from the side of DAQ for all sensors.

Tab1. The Ranges of the pressure sensors

Sensor	Ranges (Pascal)
TBP	0 - 6894
HSC	0 - 6000
ABP	0 - 6894
SDP	0 - 500

To execute efficient measurements with ABP, the support from a testboard (SEK002) and recorded data with Arduino Platform are needed - thus the acquired information are readable on a PC (see Fig 3).

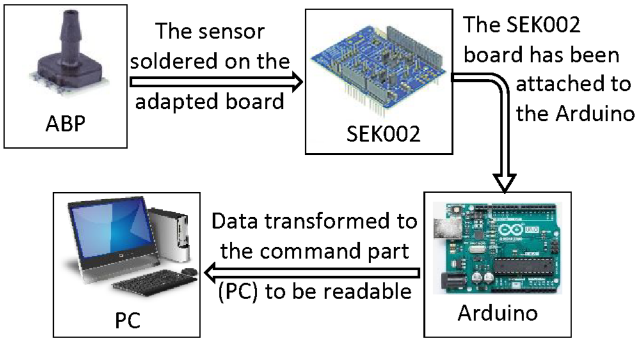

Fig 3. The system of ABP pressure sensor

SEK002 is a support board for humidity, temperature and pressure sensors, adapting with ABP, MPR, HDH and HPM series. The support board is working together with the classic Arduino Uno platform.

The other sensors are logged with MyPCLab type data loggers (DAQ) from Novus with 15-bit ADC configurations (see Fig 4).

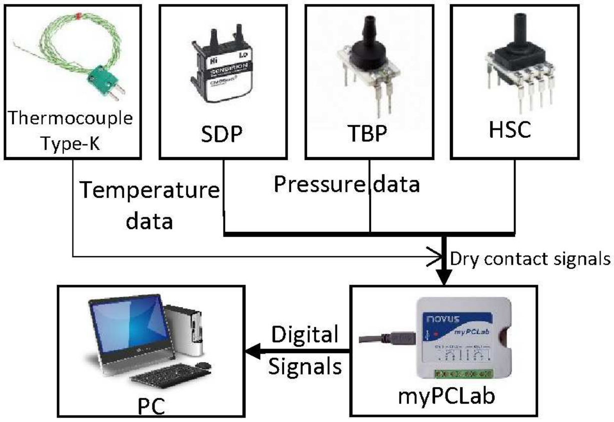

Fig 4. Sensors system connection with the myPCLab

TBP, HSC and ABP are gage type sensors, which are considered to be novel in the market in such form factors and resolutions. They can be applied to reveal hydrostatic pressure relations inside the vapour space. This value is calculated according to:

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

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.

The distribution of the vapour inside of the oven is very sensitive to any kind of perturbation (Illes et al. 2017). The measuring probes were developed from flexible, heat-resistant silicon hoses (1 mm Ø) combined with K-type thermocouples. The probes had 1 m overall length. The sensors and DAQ kits were left in ambient laboratory environment, the hose openings were applied approximately 1-1.5 cm above the boiling Galden. K-type thermocouples were positioned to measure the temperature at the "hot" end of the hose.

2.3. Pressure measurement within power change

Initial investigations proved that the temperature saturates in different time, when the power of heating changed. We aimed to change the power of heating combined with monitoring of the vapour concentration inside the process zone, to figure out the variations occurring for the pressure changes inside the working space of the oven.

The heating power has been modified regarding the following: 250W, 350W, 450W, 550W, 650W, 750W and 850W. The maximum of the heating power should not pass the cooling capacity (Considering a safety factor of 20% of cooling power.)

After initial tests, for the power related measurements, the single suitable pressure sensor was found to be (HSC).

3. RESULTS

3.1 Control measurements - pressure measurements with different sensors

For the first experiments, the different sensors were compared with each other with the same setup and the same initialization run of the oven. Figure 5 shows a raw comparison between the sensors and a temperature plot showing the setting of the system. The plots are transparent to reveal direct differences between them.

With combining the results of TBP, HSC, SDP and ABP (heating power at 850W) as seen in Figure 5, the sensors give similar outcomes regarding absolute maximums and peaks (showed in Tab.1). However, signal clarity was different.

According to the Figure 5, three phases can be differentiated: 1 – slow heating of the system, 2 – vapour generation, 3 – steady state. This is also presented in (Géczy et al. 2013).

SDP is giving a dynamic feedback on the buildup of the vapour – the second tall peak of SDP is a more accurate information on the steady state of the vapour space, than temperature. The slow ramp of temperature in Phase 2 will take long to interpret by a logical evaluator to make sure that the system has reached saturation, while SDP shows a peak. This signal can be considered as a control plot.

It is seen, that HSC type gage sensor with amplified input gives a defined characteristic which has a peak a bit later than the peak of SDP.

Due to its unamplified nature, TBP is considered to be noisy, even with appropriate interfacing to the DAQ system.

It can be stated, that the ABP sensor has the noisiest output plot, even with prepared, propriatery Arduino data acquisition system with SEK board. This suggests that without any further signal processing, it is not adequate for usage, compared to the other sensors. Use of TBP and ABP is not recommended compared to HSC due to the noisy signals, although they all exhibit similar characteristics. It was seen later, that ABP sensor in the setup is not able to follow up with changes caused by immersed PCBs, because of the inadequate density of data in short period.

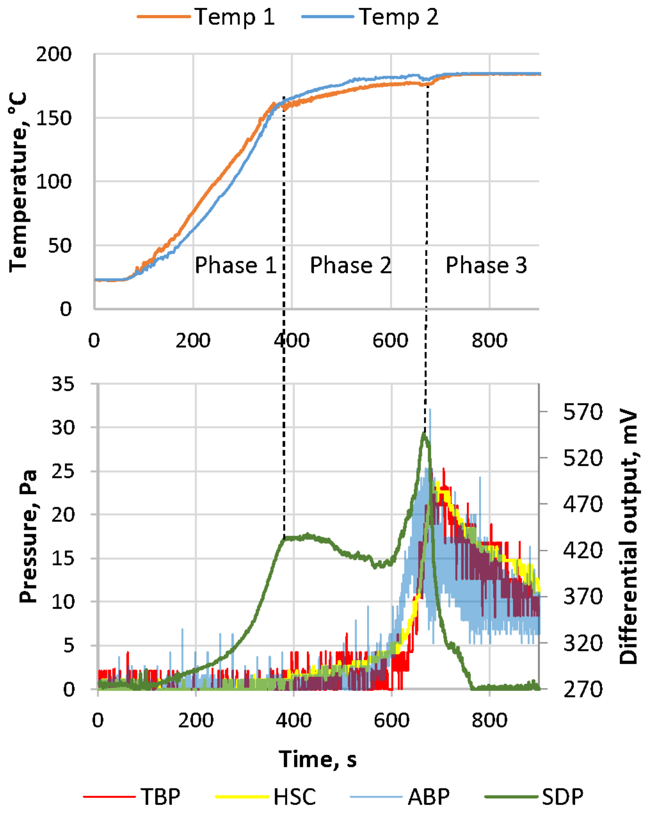

Fig 5. The three gage pressure sensors reading with the SDP measurement, compared with the temperatures measured at the hose openings.

It is an interesting finding, that the peaks of the gage-type sensors are happening, then the intense dynamics of SDP settles in a short time delay. This means, that actual hydrostatic maximum of the system is reached later, than the peak of the SDP sensor. This points to the novel finding, that the peaks of the gage type sensors point to a more precise representation of saturation s, where not the settling of the dynamic signal, but the peak of gage type sensors show the steady state. Previously (Géczy et al. 2013), it was shown that the peak of dynamic SDP gives a clearer representation of saturation compared to temperature measurements (which is still a valid point). Now the aspect was clarified further with the use of such sensitive gage type sensor devices.

Tab 2. The result of steady state time point with heating power 850W

Sensor	Time, s	Pressure, Pa	Pressure at the peak of SDP, Pa
ABP	677	24.2	17
HSC	678	23.9	14.7
TBP	679	24	12.6
SDP	667	-	-

Table 2 clears out the slight differences between the different sensors in time and absolute pressure values, where ABP HSC and TBP practically enables the steady state signaling of the system, addinig ~10 seconds to the peak of SDP. As it is seen in Table 2 (SDP is not directly compared, due to its flow-based nature) this can mean ~12 Pa, meaning that the fast buildup of the vapour height is still not finished at the peak of the SDP signal. A more precise pinpoint on the steady state enables better process control, and ultimately better soldering quality. The pressure values are helping to identify the height of the vapour blanket, according to the hydrostatic pressure equation (1). The calculated height is 12.8 cm, which is a good approximation of the work space height between the top level of the Galden and the bottom of the cooler circuit (12.5 cm). While the sensor probe opening is positioned 1 cm above the fluid, the result shows that the saturated vapour column might protrude 1 cm up into the zone of the cooler. This is at the XY location where the hose is positioned. (Around the XY centre of the oven, considering a traditional Cartesian coordinate system.)

At this point, it was found, that the most effective solution (regarding required hardware, further development of interfacing the sensors), that the HSC component will be used for further investigations.

It is shown, that all sensors (including gage type ones) show relaxation after reaching the peak, meaning that such small pressure is difficult to be sustained in the core of the sensor.

3.2 Result of stabilization after each reflow process phase

For the investigations of vapour recovery (stabilization) the following results are presented. In Figure 6, SDP and HSC, in Figure 7 HSC was used to show a full heating up period and a relaxation respectively. HSC is chosen because it gave the most accurate and stable results in Chapter 3.1. The first peak (according to Figure 6) appeared precisely when the temperature of the oven started increasing (1), which meant the beginning of the vaporization of the Galden. This is only shown with SDP type of sensors. The small pressure collapse (2) after the first peak, signs an opening of the oven lid – this small change reveal that pressure sensors can also monitor the closure and any intrusion of the system. The third point (3) occurred with the vapour saturation, point (4) is showing pressure plot relaxation mentioned in 3.1. When the board was immersed inside the oven, the structure of the vapour collapsed as some vapour was consumed by the condensation, for which the small dips in the process was signed – this is seen in continuation in Figure 7.

Any smaller peaks or dips in the signal between 1 and 4 (and after) are minor signatures of manual inspection and manipulation of the oven involving the movement of the lid.

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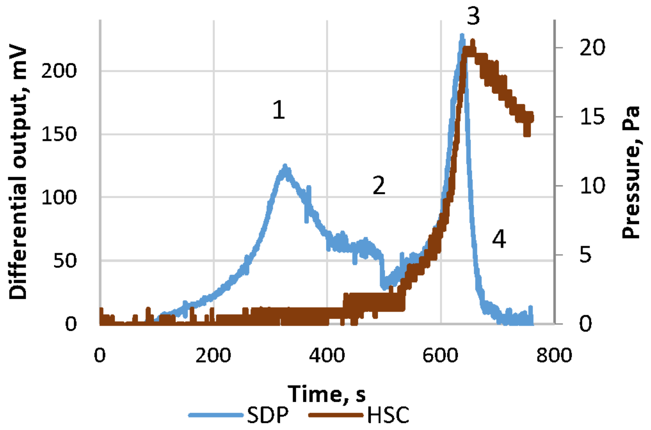

Fig 6. Dynamic pressure measurements

The PCB was immersed and taken out several times in the oven after the saturation to check the feedback of the pressure and the distribution of the vapour inside, with the help of the HSC sensor. This is concluded in Figure 7.

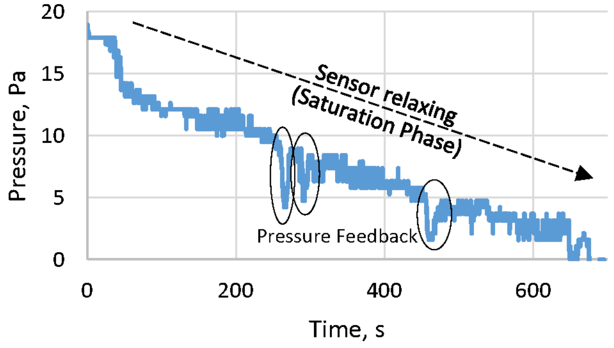

Fig 7. The change of pressure at the time of immersing the board by using the HSC sensor

After each immersion of the board in the VPS oven, there were dips of pressure recorded approximately between 4.7 Pa and 3.16 Pa, and it took between 10 s and 20 s for the system to recover to the full saturation again. That is shown in Figure 8, where the focus is on the third time of putting PCB into the oven (Fig 8).

The time needed from the vapour to get its distribution to the origin state is 14 s in this case and the pressure fall is 3.68 Pa.

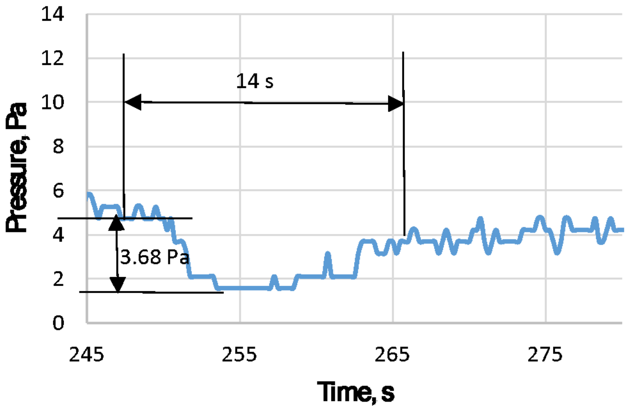

Fig 8. Sample of the system feedback when the board is immersed into the vapour

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After regaining saturation again it is getting more difficult in time to read out the same characteristics. The pressure values decreased directly in a slowly manner - this is seen in Figure 7, and this was mentioned in 3.1 previously. The cause of this phenomena is, that after the saturation the hydrostatic pressure, the vapour column will be constant, but the diaphragm of the sensor will be reacted to make the equilibria between atmospheric external pressure and the internal strain. This strain on the diaphragm is caused by the very low pressure of the vapours. The amount of pressure is small, compared to the given, relatively large total pressure range of the components. However this range is still a refined parameter, and is considered to be state of the art, from the aspect of commercial components. Another explanation can point to slight leaking of the setup (at the hose interfaces or at the package), or electrical-mechanical drifts caused in such low pressure values in the structure of the sensor device. This phenomena is remarkable with such low pressures (the measurement still uses ~0.3% of the full range.) This is still a limitation of the used devices, future developments in such components may help to avoid such measurement uncertainties.

The shown results has been measured with heating power equal to 650W, so the value may change when the power is changed, proved in Chapter 3.3 of this paper.

3.3 Result of pressure measurement with the changing of power

The use of the HSC pressure sensor with different heating power was investigated next. The results provide that the power of heating have an important role in the dynamics of the system saturation in the time aspect. Figure 9 shows a comparison between different heating powers and the signal of the pressure sensors regarding full heating up cycles.

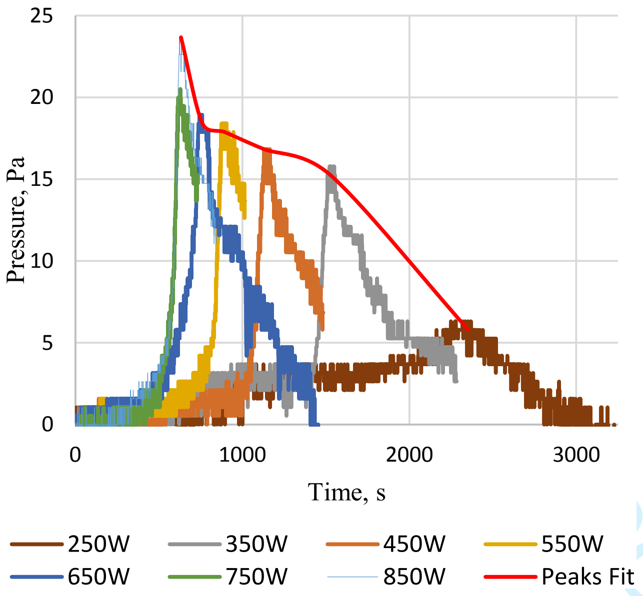

Fig 9. The characterization of the pressure at modification of the heating power

Tab 3. The variation of the Pressure and Time at the heating power sweep

Power, W	**Pressure, Pa**	**Time, s**	**height, m**
850	23.1	631	0.11
750	20.5	628	0.10
650	18.9	750	0.09
550	18.4	880	0.09
450	16.8	1135	0.08
350	15.2	1536	0.07

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250	5.7	2291	0.02

From Figure 10, it is apparent that time is exponentially decaying with the increase of the heating power, while the absolute pressure of the vapour column increases logarithmically (or in an exponential saturation manner) according to the increase of the power.

The first finding is in accordance with (Géczy et al. 2010), where the same characteristic was shown, but only with temperature measurements. The current finding with time/power relations extends on the previous results showing that the characteristic of the relation can be discussed with temperature and pressure sensors as well.

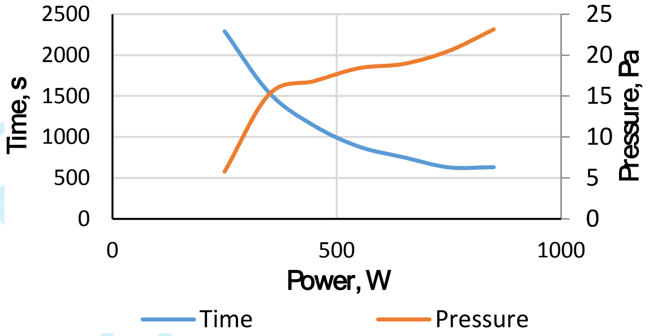

Fig 10. The peak of the pressure and the time saturation versus the change of heating power

The finding about pressure values with the increase of power can be discussed with the following assumptions. At small powers the system is not able to withhold a vapour column with usable height, while most of the power is lost at the non-adiabatic walls and ambient surroundings. However it seems (Fig 9 and Fig 10) that above 350 W, a stable peak is observed in the vapour column development, this is also reflected in the logarithmic type Pressure/Power plot, where the inflexion point is present at 350 W. This is the point, from where the system can withhold a stable vapour column. The saturation of the pressure (the limit of the saturation plot) is practically limited by the upper lid and the cooling circuit, shown in Figure 1. The slightly protruding end point at 850 W (Fig 10. pressure plot) can be due to either an overshoot of the cooling circuit in spatial direction with the vapour blanket or a dispersion in the wake of uncertainty of the measurement.

It is shown, that the method of pressure sensing in vapour work space is able to predict a proper power setting for a sustainable vapour column in a system.

4. CONCLUSION

In this paper the evaluation of a Vapour Phase Soldering oven was presented by further expanding knowledge on pressure sensing in the workspace of a VPS machine.

First the difference between the commercially available gage type sensors and previously used solutions were compared.

It was found that gage type sensors are in line with the previous measurements, where a specific dynamic pressure sensor clarified system saturation, compared to sole temperature measurements. It was found, that with gage type sensors, saturation can be shown with a more precise manner in time, but with the restriction of plot relaxation due to the limitations of the physical sensor devices.

It was also found, that the gage type sensor output can highlight the drop of pressure when a PCB is immersed into the vapours. The drop can be characterized with the decrease of hydrostatic pressure (practically the volume of the consumed vapours), and by the recovery of the sensor. The limitations of the gage sensor type is also revealed with the slowly decaying plots, after the process settles into steady state.

Finally, it was showed, that there is a suggested lower power limit to sustain a well-developed vapour column for soldering in saturated vapour. This is shown by the inflexion point of the Pressure/Power curve, in accordance with the Temperature/Power curve. The obtained results suggest, that defining a well suited vapour blanket with a given height for a given assembly, or overshooting the height limit of the cooler circuit might be also investigated with the proposed sensor application.

Future experiments will involve characterizations of vapour work space in function of the sensor position inside the chamber. The recovery of pressure after the drop during PCB immersion is also an aim for future investigations in function of powers, which might be able to compensate for fast vapour recovery. Future components with better sensitivity might provide more stable results for investigating steady state on a longer time period. The methods are totally compatible with novel paths of the industry, namely IoT and Industry 4.0 aspirations, where digitally interfaced sensors are used for more precise and flexible process control.

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