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AUTOMATED FILLING AND SEALING OF EMBEDDED HEAT PIPES

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ABSTRACT

High performance electronics cooling moves from utilizing modular heat pipes to fully integrated heat pipes. Filling and sealing of these non-tubular embedded heat pipes is a challenge, since traditional methods as evacuate, fill and pinch do not suffice. This paper presents a charging station that is able to fill and seal embedded heat pipes in a reliable manner. A small, low-cost charge component is connected to the heat pipe. This allows the fill head of the charging station to mount the heat pipe in an automated manner. The charging station uses specially designed zero dead volume valves to minimize internal fluid volumes and thus increase the fill accuracy. Inside the fill head, the internal fluid line for filling and the plunger performing a pressed plug seal alternate position during the charging process. Prototype testing shows that the charging station is able to charge heat pipes in around 5 minutes with a final fill accuracy of 1.5μl.

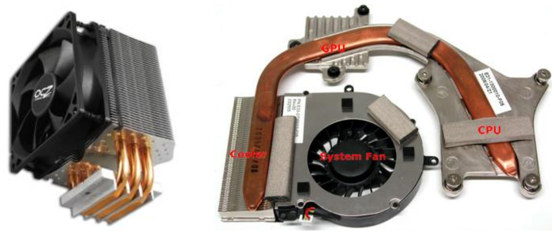
KEY WORDS*:* Heat pipes, Automated charging, Heat pipe filling station

1. INTRODUCTION

Thermal management plays an increasingly dominant role in the design process of electronic products. The increasing local heat fluxes constrain the design of electronic products. Nowadays, quite often traditional cooling methods, such as air cooling and single phase liquid cooling, no longer suffice due to the high power density.

1.1 Electronics cooling with heat pipes

Two-phase cooling techniques are an effective and reliable solution for high power density cooling. Especially interesting are heat pipes; as these are passive systems heat is transported in a very efficient manner. Heat pipes require no pump, power or moving parts to function and the temperature gradient across its length is extremely low; typical <10°C. By now the electronics industry has fully embraced the advantages of heat pipes in the thermal design of notebooks, game consoles and other high performance devices, as shown in Figure 1.



a) heat sink [OCZ]   b) notebook cooling [Tom]

Figure 1. Heat pipes in electronics cooling.

Figure 1 shows applications where heat pipes are build-in to either improve the spreading and/or transport of the heat from local hotspots. As shown, in most cases conventional tubular heat pipes are bent in the right shape and sometimes even flattened to get a good thermal connection. The use of a modular heat pipe to improve the cooling system is a very typical design solution.

1.2 Full integration of electronics cooling

This study focuses on the full integration of thermal management functions into the design process of electronic products. This will lead to more functionality and performance in a smaller form factor. In addition, by smart integration products can be realized at a lower cost; altogether leading to smaller, lighter and more affordable electronics products. A working demonstrator of this research was first presented in Wits (2006) and a comprehensive paper was presented at the IHPC 2007 (Wits, 2007) and published in Wits (2011).

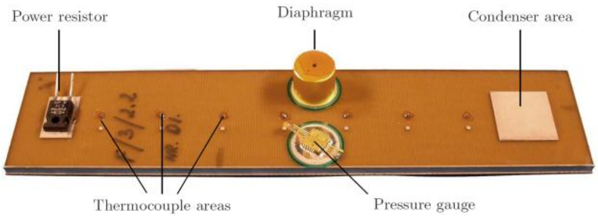


Figure 2. Heat pipe fully integrated into a PCB.

The working demonstrator consisted of a Printed Circuit Board (PCB) with a heat pipe designed as an integral part of the laminated board structure, as shown in Figure 2. Prototype measurements showed that the initial thermal performance of these heat pipe integrated PCBs was excellent; however, long term stability was an issue. This was likely due to the chosen approach of charging and sealing the heat pipe. To seal the heat pipe the design featured a diaphragm device filled with an airtight elastomeric barrier. Both evacuation and fluid filling was done through a (separate) needle.

1.3 Outline

This paper presents a new and reliable method to charge and seal non-conventional, integrated heat pipes. Typical for such heat pipes is that they are not modular as the examples of Figure 1; therefore, traditional evacuate, fill and pitch strategies cannot be applied. Integrated heat pipes are fully embedded into the electronics assembly, enabling direct access to local and even embedded hotspots. The next chapter describes the developed charging station, Chapter 3 describes the charging process and finally Chapter 4 describes the sealing method.

2. HEAT PIPE CHARGING STATION

To enable high speed filling and sealing of non-tubular, embedded heat pipes a special apparatus is developed. In literature several charging devices and procedures are described. In Faghri (1995) a device with interstage containers is described through where the working fluid is distilled into the heat pipe. For high-speed filling however usually the working fluid is injected into the heat pipe in its liquid form. For this, different methods are known. Probably most common is filling though a T-junction: one leg for evacuation, one leg for fluid injection and the last leg running to the heat pipe. In this case, sealing is usually done by pinching the tube from the outside. In practice, heat pipes charged using this method are usually overfilled and purged. By purging, unwanted Non-Condensable Gas (NCG) is blown out the heat pipe before permanent sealing. Due to the many valves and channels (and other reasons) it is difficult to reach a high accuracy; therefore, in practice heat pipes are often overfilled to about 10%.

To enable high-speed filling, the developed charging apparatus also injects the working fluid in its liquid phase. The complete station, as shown in Figure 3, is designed for high precision, automated and reliable filling of embedded heat pipes.

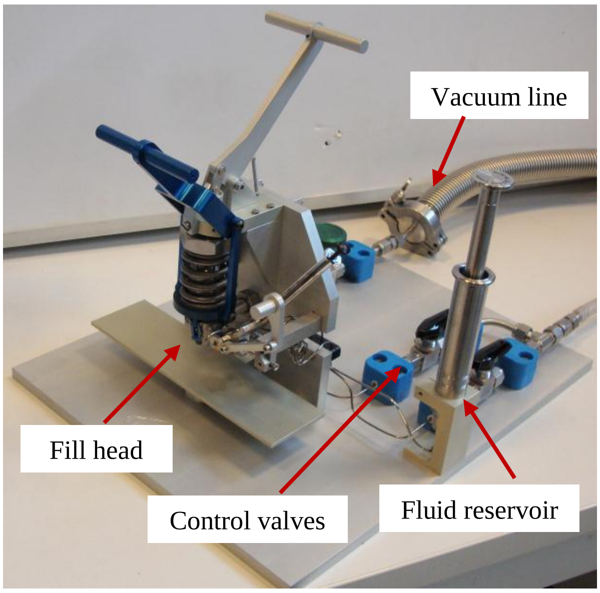
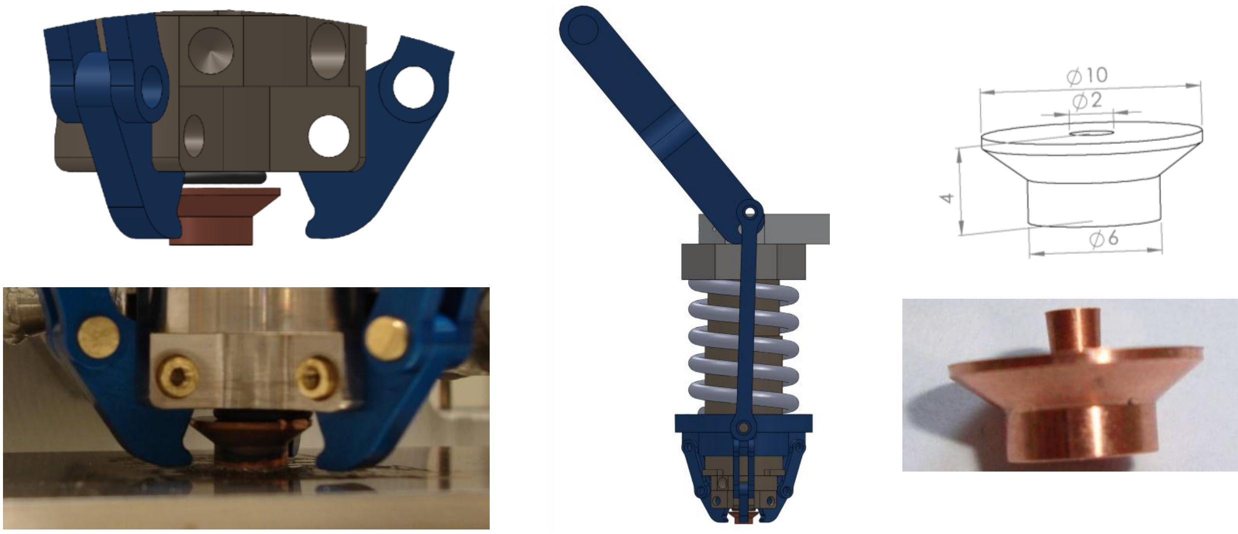


Figure 3. Heat pipe charging station.

Working fluid is transported from the fluid reservoir to the fill head using the control valves. Charging is done in 4 steps: mounting, evacuating, filling and sealing.

In the mounting phase, the heat pipe is clamped to the fill head. The clamp, clamp mechanism and charge component are shown in Figure 4. A specially design charge component is used for clamping. This part must be soldered, brazed or welded to the heat pipe prior to the charging process. The clamp mechanism automatically aligns the fill head to the charge component allowing for a quick and automated process.



a) clamp (open) b) clamp mechanism c) charge component

Figure 4. Mechanism connecting the fill head to the heat pipe.

The charging station is designed to guarantee a reliable temporary seal during the charging process. The clamp mechanism is calibrated to put sufficient pressure on the O-ring between the fill head and the component. Clamp forces are guided through the charge component only and not through the entire heat pipe and electronics assembly. In Figure 4c the charge component is depicted with an inserted pin. This pin is used to hermetically seal the heat pipe after filling (see Chapter 4). Since the charge component is required for every heat pipe, it is designed as a small, low-cost part measuring only Ø10x4mm.

3. HEAT PIPE CHARGING

Charging of heat pipes can be done in many ways (Peterson, 1994; Chi, 1976; Dunn, 1994), ranging from vaporizing a totally liquid filled heat pipe (large volume heat pipes) to filling heat pipes with supercritical vapor (micro-heat pipes). The most common technique is to evacuate the heat pipe after which it is filled through either the liquid or vapor phase. For high accuracy filling, charging is done through the vapor phase of the working fluid. Since vapor densities are relatively low compared to liquid densities it is much easier to meter the fluid entering the heat pipe accurately.

The main process steps in most charging procedures of low&high temperature heat pipes are

1. Baking out of the heat pipe internals
2. Working fluid purification; in parallel with 3&4
3. Flushing / cleaning sometimes operation in reflux mode (optional)
4. Evacuation
5. Working fluid insertion
6. Operating and venting of NCG (optional)

Baking out of the heat pipe internals can be done off-line and is not discussed in this paper. For working fluid purification the use of distilled water is chosen combined with a freeze-thaw cycle to remove any dissolved gasses (Chi, 1976). In this case, purified water is stored into the fluid reservoir and attached to the charging station. Cleaning is already implemented in the embedded heat pipe manufacturing process and is therefore not foreseen as a separate step during the charging process. This step can however be implemented when deemed necessary.

For this research critical focus is put on the design and trade-off of steps 4 (evacuation) and 5 (fluid insertion). The additional requirement of this research compared to conventional heat pipe filling is that filling is possible for a small series production line with a high accuracy. Typically for our application a 5% accuracy on a filling volume of around 300µl is demanded. Further, the formation of NCG and leak should be limited to 6% of the condenser volume for 25 years of heat pipe operation: 5% is reserved for leak during operational life time and 1% during filling.

Two possible sources of NCG are identified during filling. Firstly, the initial vacuum quality before liquid insertion and secondly the leak during filling through the O-rings and soldered connections. For both sources a maximum of 0.5% condenser volume of NCG is allowed. The vacuum level required to meet this requirement for the embedded

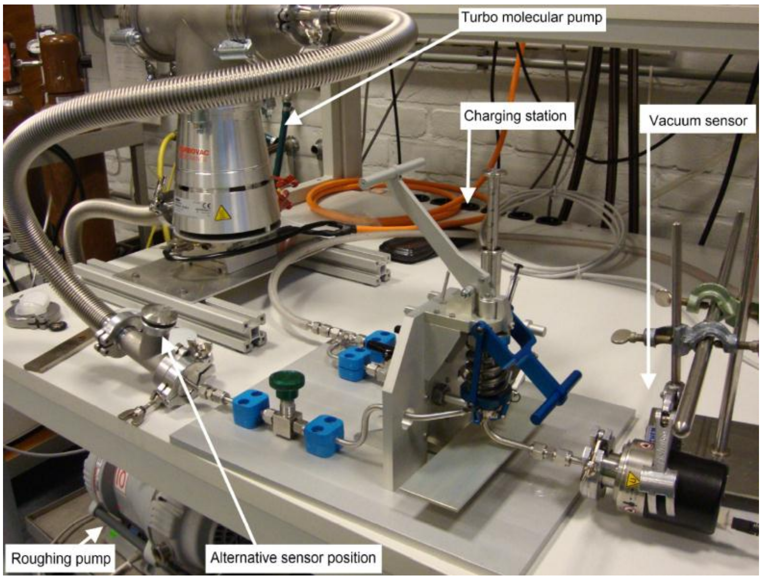


Figure 5. Vacuum test set-up.

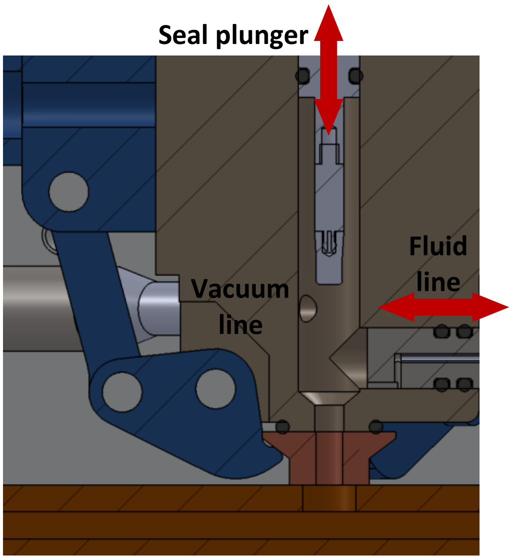


Figure 6. Fill head internals.

heat pipes as shown in Figure 2 is 0.18mbar assuming the baking out of the heat pipe materials is done in advance and off-line. The leak tightness for the filling system during filling is $2.1\cdot10^{-6}$ mbar·l/s assuming a charging time of 10 minutes.

3.1 Evacuation

The heat pipe is evacuated through the fill head after it is mounted to the charging station. The process time to reach the required vacuum level will be the most time consuming step for series production. The pump system of the charging station consists of a rough vacuum pump (BOC Edwards XDS10) connected in series with a turbo molecular pump (Oerlikon Leybold Turbvac TW 250S).

To estimate the required time for evacuation, tests have been performed with a vacuum sensor connected to the fill head (see Figure 5). The vacuum sensor is mounted to charging station using the same charge component as will be used to charge the heat pipe. The vacuum line runs through the fill head and charge component. The time to reach the required 0.18mbar is about 3½ minutes. In first instance this is acceptable for series production.

The vacuum level was also measured at the alternative position before the charging station to determine the pressure drop induced by the charging station. This proved to be about 2 decades. In a future design of the charging station, the design of channel and opening diameters, and charge component can be optimized to further reduce the required evacuation time.

Also, a leak test was performed using a helium mass spectrometer (Oerlikon Leybold UL200). Helium was sprayed around the charging station, but leaks were below the detection limit of $1\cdot10^{-10}$ mbar·l/s. Thus fulfilling the leak tight system requirement of $2.1\cdot10^{-6}$ mbar·l/s.

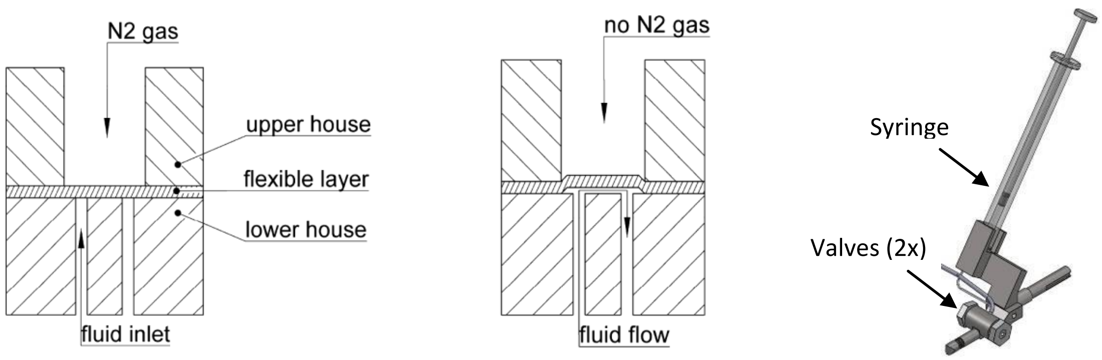
3.2 Working fluid insertion

After creating the required vacuum the pump system is disconnected from the charging station by closing the (green) valve. To start the fluid insertion phase, the fluid line is slid in horizontally (Figure 6). This way the fill opening is positioned above the charge component and the working fluid is dispensed directly into the heat pipe.

The driving requirement for the filling process is an accuracy of 5%; i.e. 15μl on a total of 300μl. Two main factors contribute to the filling error, namely the error of the metering device and dead volume inside the filling system. An accurate 500μl syringe is chosen as metering method with an error of less than 2% (6μl) of the syringe volume. The biggest source of error in filling accuracy for micro-heat pipes are dead volumes and the main contributors are normally the valves. The internal volume of the most accurate valve at the moment of writing is 16.5μl, which consumes already the whole accuracy budget available.

3.3 Zero dead volume valve

To tackle this problem two specially designed Zero Dead Volume Valves (ZDVVs) are incorporated into the design of the charging station. The ZDVV is derived from an expired patent by Hunkapiller, 1985. A schematic view, explaining the principle,



a) closed valve (schematic) b) open valve (schematic) c) implemented valves

Figure 7. Working principle of the zero dead volume valve.

is given in Figure 7. The valve consists of 3 components: a lower house, a flexible layer and an upper house. The small channels inside the lower house are used for fluid pumping. The flexible layer enables opening and closing of the valve. The ZDVV is closed pneumatically by applying a gas pressure, in this case nitrogen, above the flexible layer (Figure 7a). Opening is done by releasing the nitrogen pressure. Fluid inside the small inlet channel can now be pumped into outlet channel (Figure 7b). The ZDVV can also function as a pressure relief valve.

By operating 2 ZDVVs in series the error in fill accuracy is reduced to the volume uncertainty in the connection lines between the 2 ZDVVs and the heat pipe, indicated in grey in Figure 8. These connection lines have capillary dimensions and by heating them it can be assured that they only contain a minimum of vapor. In the figure, S2 refers to the fluid reservoir and S1 refers to the accurate 500µl syringe. By operation the nitrogen pressure valves V2 & V3, the working fluid can be transported from S2 to S1, accurately metered and finally transported from S1 into the heat pipe.

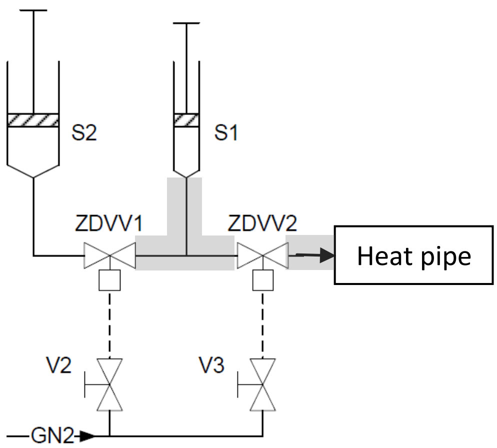


Figure 8. Operational filling scheme.

3.4 Fill accuracy

The fill accuracy is verified by filling a number of test tubes (see Figure 9) connected to the fill head. The inserted mass is verified by measuring before and after filling with an accurate mass balance.

Measurement results show that on average 99.5% of the intended fill volume was actually inserted into the test specimens. For the intended heat pipe application this means a fill accuracy of 1.5µl, well below the required specifications.

Figure 9. Test items for fill accuracy testing.

4. HEAT PIPE SEALING

To prevent unwanted gases entering the heat pipe, a permanent seal has to be made after the pipe is fully charged. Traditionally, heat pipes are sealed by pinching the fill tube. This is an efficient way for conventional tubular heat pipes. However, for embedded heat pipes or vapor chambers this method is not very suitable. Due to a lack of alternatives sometimes a small protruding tube is connected and used for charging and sealing.

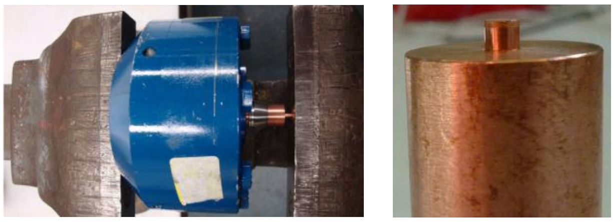
As mentioned, 5% of the condenser volume is allowed as leak during the operational life time of 25 years. For the intended application this means the maximum leak rate of the heat pipe seal is $4.3 \cdot 10^{-11}$ mbar·l/s. Next to this requirement, the seal procedure should not impede the filling process and series production.

As mentioned before, this research explores another method of sealing, namely the pressed plug seal. Here, the seal is formed by forcing a plug into a housing, in this case the charge component. Similar to the traditional pinched tube, this forms a cold weld seal. After forcing down the plug, soldering or welding can improve the long-term reliability of the seal. Inside the fill head, the fluid line is first slid back to make room for the plunger that forces down the plug (see Figure 6).

There are a number of advantages of using this method. The combination of a plug and housing is more compact than a protruding tube. Also, the process of sealing by inserting a plug is better controlled and industrialized. The cost of the charge component is negligible to the system cost. Finally, as the charge component can be positioned and soldered automatically as many other electronics components, the proposed method is very suitable for integration with common electronics manufacturing processes.

4.1 Seal test results

A number of experiments have been done to prove and optimize the pressed plug seal concept. The plugs are tapered and the internal diameter of the charge component was set to 2mm for evacuation and filling requirements. Copper is chosen for both the plug and charge component. The plugs are pressed into the hole using a workbench and a load cell was used to measure the insertion force (see Figure 10a). After insertion, the seals were tested for leakage right away and also 4 days later.



a) workbench and load cell b) test specimen

Figure 10. Pressed plug seal experiment.

The insertion length varied from 0.2-2.6mm, but this proved to be no clear indicator of a good seal. The insertion force was however critical and had to be over 100N to guarantee a hermetic seal. This threshold was also used to engineer the plunger.

Pressurized helium leak tests show that the concept of heat pipe sealing by means of inserting a plug into a compact counterpart is robust and reliable. Combined with a cost efficient process integration, this makes for an overall attractive solution.

5. CONCLUSIONS

This paper presents a new apparatus for quick, accurate and reliable filling of non-tubular embedded heat pipes. The charging station uses specially designed zero dead volume valves to minimize internal fluid volumes. A small, low-cost charge component is connected to the heat pipe. It allows the fill head to be mounted to the heat pipe in an automated and reliable manner. Inside the fill head the fluid line and plunger alternate position during the charging and sealing processes.

Prototype testing shows that the charging station, for which a patent is pending, performs well. Sealed heat pipes are leak tight well below their requirements. Heat pipe charging can now be done in an automated manner within about 5 minutes with a final fill accuracy of 1.5μl.

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