Smart Integration of Thermal Management Systems for Electronics Cooling

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1 Introduction

Electronics cooling is currently receiving more and more attention, since power densities have increased significantly over the years. Interesting cooling technologies thermally surpassing traditional applications are among others: jet impingement cooling and two-phase cooling (e.g. heat pipes and vapor chambers). Both cooling technologies seem very promising since they are capable of cooling large power densities.

This study focuses on the application and implementation of such advanced cooling technologies on a system level. The goal is to develop cooling technologies capable of managing multiple high-power components simultaneously on a regular Printed Circuit Board (PCB) structure. By observing thermal criteria early in the conceptual design phase and on a system level, smart integration is researched. Cost efficiency is strived for by producing the thermal management system with current electronics manufacturing techniques only.

1.1 Background

This research project was part of a Dutch transnational research project focusing on integrated technology for the design and manufacturing of antennae systems. Amongst the consortium members were the Netherlands Institute for Radio Astronomy, Thales Netherlands B.V. and the University of Twente. The project’s specific goal was to research and develop integrated technology for the design and manufacturing of mass-market, low-cost, complex electronic products. The vision was to improve system performance and simultaneously reduce cost by clever integration of new technologies for the next generation of current electronic products.

1.2 Research Proposition

At the start of the project, break-through practical implementations for cooling were sought after. Within the discipline of thermal management already a lot of research is targeted at improving the cooling capacity. The number of recent publications on both jet and two-phase cooling are overwhelming. In order to force one giant leap instead of an incremental step forward in terms of for thermal management systems, two challenging research propositions were formulated:

1. Instead of transporting the heat to the cooling fluid as is done conventionally, **focus on bringing the cooling fluid to the heat source.**
2. Instead of just applying another technology to increase cooling performance, **integrate the cooling system for zero extra cost.**

These propositions were an incentive to force a paradigm shift and be inventive.

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2 Integrated Design Approach

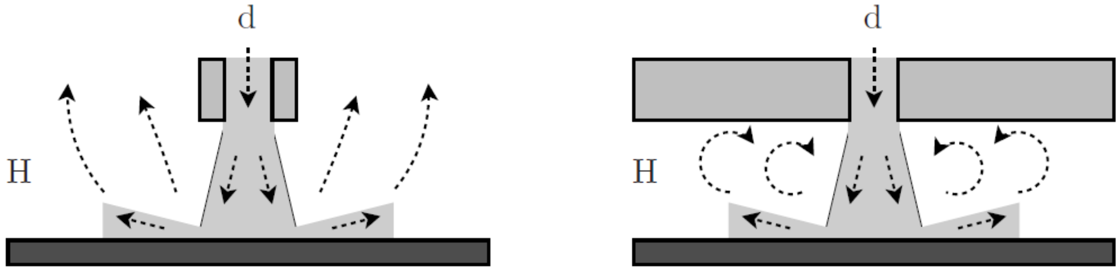
Major improvements and innovation are accomplished during the conceptual design phase. After a concept is selected the design process becomes much more rigid and big changes can no longer be implemented. This is especially true for large enterprises with many engineers working on products collaboratively. Interesting to note it the fact that cooling is usually regarded as a support function that needs to be addressed towards the end of the design process. By considering thermal aspects at in the very beginning of the design phase (the conceptual stage), previously unseen levels of product integration are targeted directly.

To improve thermal management on a system level and thereby strengthening the next generation of electronic products, two potentially interesting cooling technologies were identified by a market scan: **jet impingement cooling** and **two-phase cooling**. The former technology increases cooling performance by jetting a fluid onto a surface locally breaking through the stationary boundary layer and thereby improving heat transfer coefficients. The latter technology uses a fluid's phase change behavior to increase performance, as during evaporation and condensation large quantities of heat are either absorbed or released, respectively. Both technologies are widely researched and are commercially available as modular building blocks (e.g. add-on cooling devices).

Technology assimilation and thorough understanding of the working principles led to believe that PCB manufacturing technology can facilitate these cooling principles as an integral part of the product. By a structured integrated design approach targeting thermal criteria early in the conceptual stage, cooling technologies are integrated directly into the electronics product.

3 Jet Impingement Cooling

Research on convective cooling had long ago already discovered that by impinging or jetting a fluid onto a surface much higher heat transfer coefficients can be obtained. Two possible jet configurations are unconfined and confined jets, as shown in Figure 1. For both cases, the ratio of H over d is significant for the jet performance.



(a) unconfined (b) confined

Figure 1: Two possible jet configurations.

Usually (laboratory) set-ups involve mounting a device encompassing the jet nozzle on the electronic component to be cooled. This modular approach does not result in the far-reaching level of integration that is sought for; therefore, another design has to be developed. In theory, any fluid can be used; however, using (filtered) air clearly has an advantage. It is available abundantly and does not damage electronics as for instance water does.

3.1 Concept solution

Research, so far, has always concentrated on issuing a jet on an electronic component from the top side. From a design perspective this is certainly not mandatory. When trying to redesign the electronic component according to the integrated design theories and the aforementioned research propositions such that all engineering disciplines benefit from the new design, it was discovered that by jetting from the bottom side a far more compact solution is possible. This is illustrated in Figure 2.

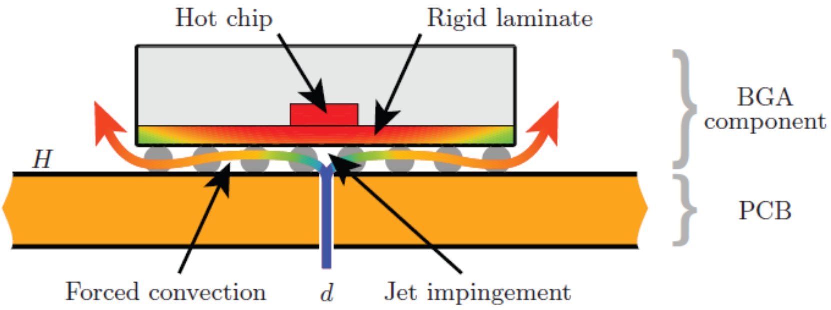
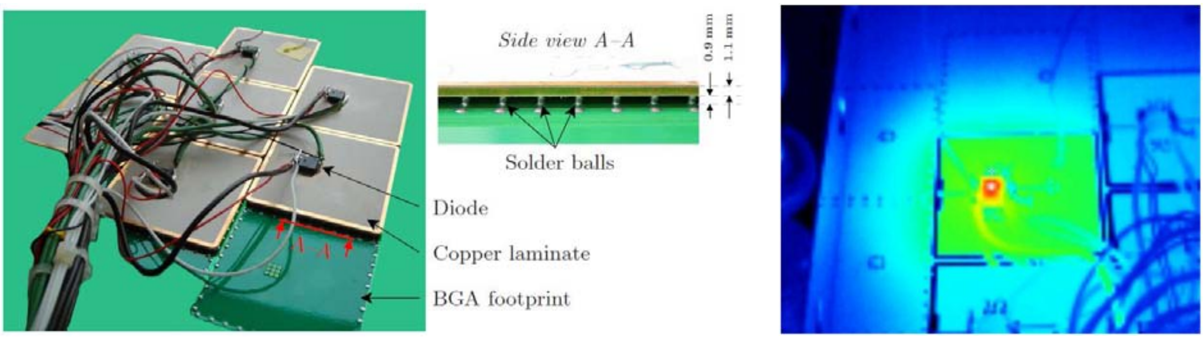


Figure 2: Concept design of integrated jet cooling for electronics.

The design of the electronic component – in this case a Ball Grid Array (BGA) component – remains the same; no new technologies are needed for this part. Also, for the design of the PCB very little changes. In fact, only a hole or multiple holes need to be drilled directly underneath the electronic component. Note that, the heat sink that is usually mounted on top of the electronic component is no longer required. The solder balls of the BGA actually work as a heat exchanger with the added benefit of having a jet in the center.

3.2 Technology demonstrator

The technology demonstrator that was developed to validate this concept solution is shown in Figure 3(a). The diodes and wires were to simulate power dissipations and measure the thermal performances. Coolant air was injected from the bottom side underneath the components. Figure 3(b) shows a thermal image that was taken during the one of the measurements. The experiments demonstrated that the concept is viable and multiple components can be cooled simultaneously. The ability to cool many components simultaneously and independently is a very important design aspect of this solution.



a) prototype b) thermal image

Figure 3: Implementation of the technology demonstrator.

3.3 Experimental Results

To determine the thermal benefit of the developed prototypes, they were measured both unpressurized and pressurized. The former is equivalent to the case of natural convection, whereas the latter introduces both forced convection through the confined channel and the theoretically dominant impinging jet effect. By subtracting both measurements from each other the thermal benefit can be determined.

The measurement set-up was limited to a continuous volumetric air input flow of about 1350 l/h. The ambient jet air temperature was 21°C. In all cases, the air velocity increased as the pressure was increased and as a result heat transfer improved. Hence, more power could be dissipated at a lower junction temperature. Figure 4 shows the temperature profile of a small package (15x15mm) for increasing amounts of dissipated power with a single jet of 2mm in diameter. After increasing the power input, sufficient time was taken to record a steady junction temperature. As the maximum allowable temperature was reached, the measurement was stopped and the apparatus was allowed to cool down. Subsequently, the air pressure was increased and a similar measurement was started.

The top black measurement line in Figure 4 indicates no air flow, hence the Reynolds number equals zero. As the air pressure was increased, according to the green arrow, more power could be dissipated. At the final measurement, indicated by the bottom black line, the pressure was increased to 8,500Pa (U ≈ 115m/s). This measurement corresponds to the top right measurement point in Figure 4, where a Reynolds number of approximately 15,258 was observed. Also, the maximum allowed junction temperature of 150°C specified for many electronic components is indicated in the figure by the dashed red line.

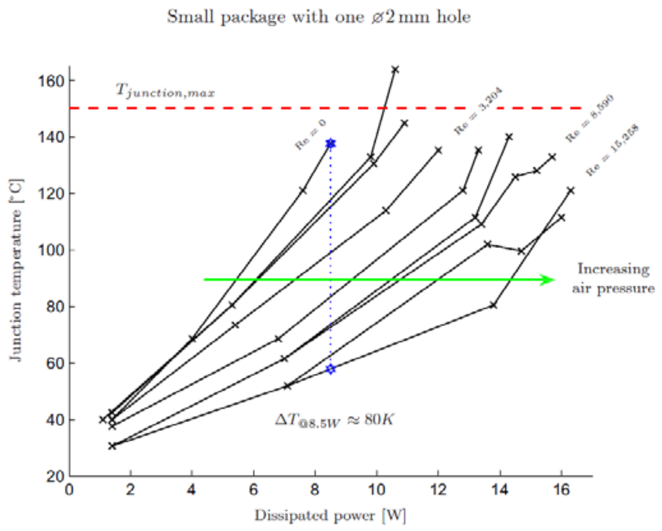
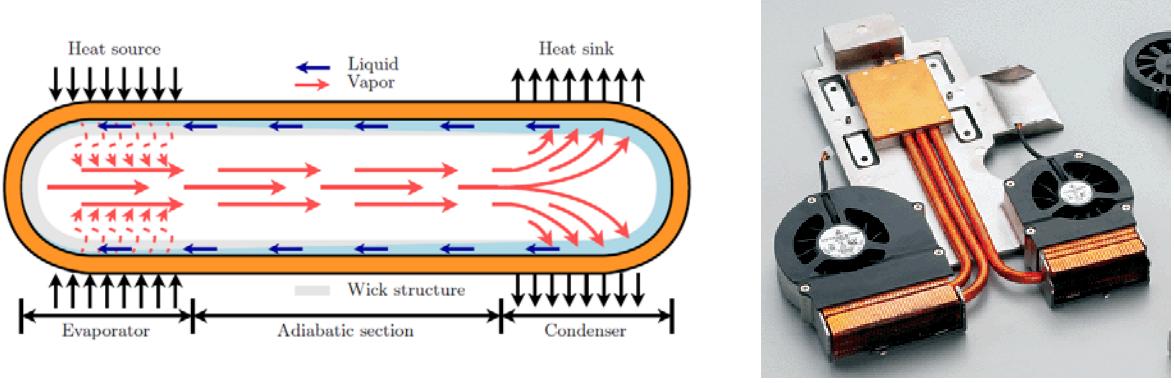


Figure 4: Junction temperature for increasing power dissipations.

The thermal benefit – determined by the difference between the natural convection measurement and a pressurized measurement – is indicated by the dotted blue line in Figure 4. It shows that a temperature decrease of about 80K can be realized at 8.5W of power dissipation. At higher dissipated values, directly injected cooling also clearly demonstrates its merit, as the apparatus can operate safely, without reaching crucial thermal criteria.

4 Two-phase Cooling

The application of two-phase cooling is gaining interest for many industrial fields. The usual form is a heat pipe can best be described as a hollow tube with a fluid inside, as shown in Figure 5(a). For electronics cooling this fluid is usually water. On one side of the heat pipe the fluid absorbs high amounts of heat by evaporation. This heat is released again on the other side by condensing. Most engineering effort is required to design the capillary wick structure to return the condensed working fluid to the evaporator.



a) working principle *b) notebook assembly **

Figure 5: Heat pipe technology.

** http://www.chaunchoung.com.my/info-pipe.htm*

A well-known example where heat pipe technology has really made an impact is shown in Figure 5(b). For notebook computers the heat dissipated by the CPU and hard drive is transported efficiently to the exterior of the notebook. Next to great thermal performance, the small form factor and good reliability made heat pipes excellent candidates for this industry.

Usually heat pipes complement the cooling system as add-on devices, similar to heat sinks. The bottleneck with this is that a high degree of integration is not achievable and additional assembly cost occurs during the production phase. Hence, as for jet cooling, also in this case further integration between electronics, mechanics and thermal management was researched according to the integrated design theories and the research propositions.

4.1 Concept solution

Instead of accepting the heat pipe as an add-on device, a redesign of the electronic board structure makes it possible to integrate a custom-made heat pipe directly into the PCB. This concept is illustrated in Figure 6. Dissipated heat from the resistor or any other electronic component can be transported efficiently though the board itself. At the resistor location no external, protruding heat transport device needs to be attached. The wick structure is formed by capillary microgrooves that are deposited on the top and bottom layers on the PCB. After the heat is transported and released at the condenser end, the microgrooves pump the liquid back to the evaporator end, where the cycle continues.

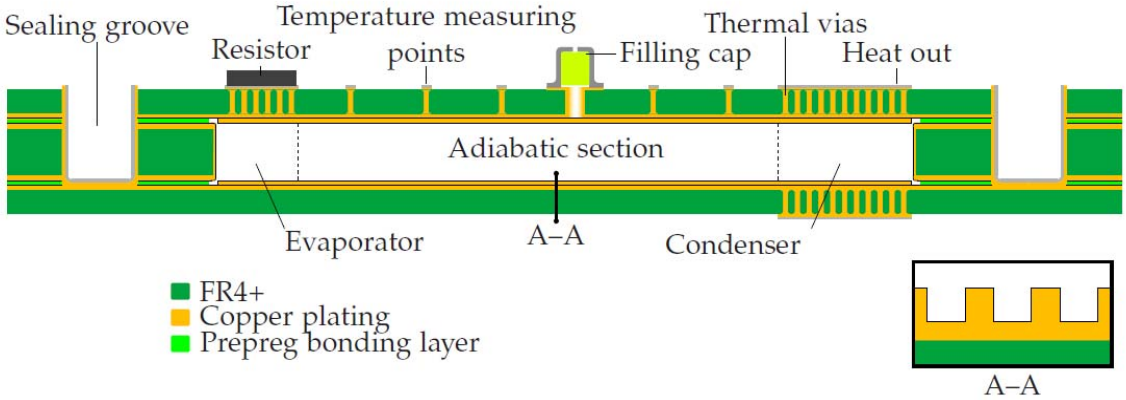
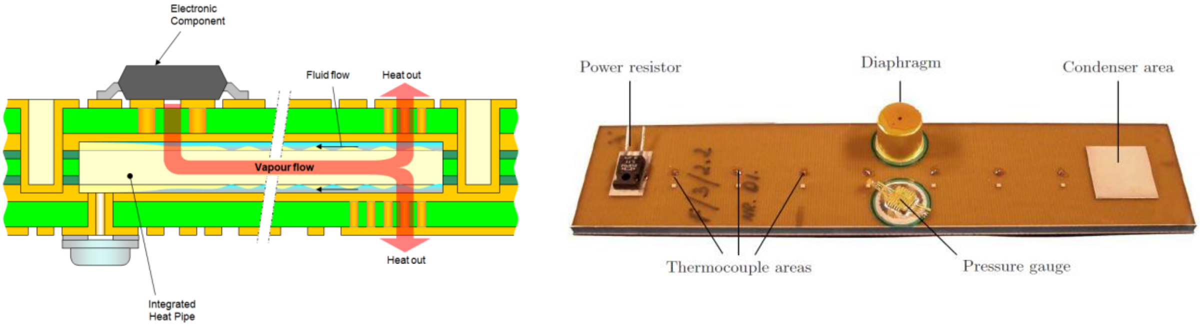


Figure 6: Concept design for integrated heat pipe technology.

As thermal criteria are now integrated into the PCB structure, its design and design rules must be updated. However, from a production perspective no new technologies are introduced. Drilling, machining, depositing copper and stacking board layers are already well understood PCB manufacturing steps. As most cost occurs during the initial PCB's design phase, in production the integrated thermal management system comes add virtually zero extra cost.

4.2 Technology demonstrator

Figure 7 shows the technology demonstrator that was constructed to validate the integrated heat pipe concept. Figure 7(a) shows a schematic overview of how the prototype operates, whereas Figure 7(b) presents the actual prototype. In fact many prototypes were manufactured to test different geometries and layouts. Also in this case, the experimental investigation showed excellent results for cooling of the mounted components. Exceptional heat transport capability can be realized directly inside a PCB structure. Also, multiple components can be cooled simultaneously by the same heat pipe. As the board clearance without heat sink is relative low, many can be mounted in a compact space. This is an ideal solution to cool high-power electronics in a small form factor.

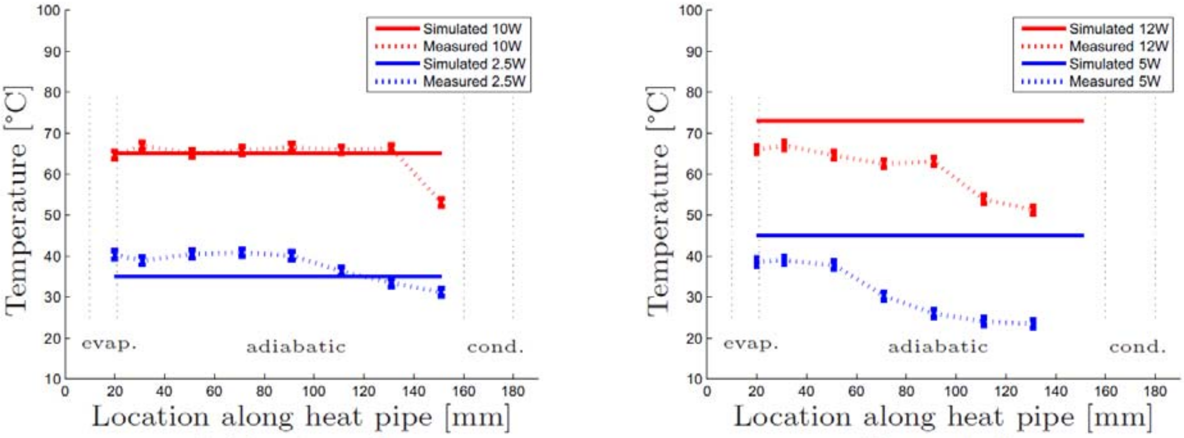


a) schematic overview b) prototype

Figure 7: Implementation of the technology demonstrator.

4.3 Experimental Results

Figure 8 illustrates the temperature distribution along the heat pipe length when subjected to a thermal dissipation of 2.5 and 10W horizontally, and 5 and 12W vertically. In all cases, the solid lines represent the simulated predictions, whereas the dotted lines indicate the measurement results. Note that, in the vertical case, the last thermocouple did not function.



(a) horizontal (b) vertical

Figure 8: Temperature distribution along the heat pipe length.

Especially in the horizontal mode, the heat pipe is able to transport the heat with a low temperature gradient along its length; vertically this behavior was recorded less. For both cases, at even higher dissipated values the evaporator temperature would rise unacceptably, indicating local evaporator dry-out.

During the measurements the ambient temperature was approximately 25°C. The heat pipe operating temperature is mainly determined by the amount of dissipated power and the thermal resistance value at the condenser side, where the heat is extracted from the heat pipe. As the heat pipe operates with a low thermal gradient across its length, the equivalent thermal conductivity is extremely high.

The temperature drop in the condenser region is an indication of the presence of non-condensable gases. During the filling process, either the vacuum quality was held insufficiently or leakage occurred when the working fluid (water) was inserted. Hence, charging must be done in a more reliable manner. Power losses through the insulation also cause premature condensation. This explains the difference between the vertical and horizontal case, as vertically heat is dissipated better by natural convection. Also, the build-up of non-condensable gases in the top of the heat pipe – in the vertical case this is the condenser region – might attribute to the premature condensation.

5 Conclusions

The current state of the art for thermal management systems is evolving continuously, due to the rapid evolution of electronic products worldwide. A bigger demand for cooling capacity is required for virtually any new electronic product. The evolving state of the art however primarily focuses on increasing the cooling power or heat transfer coefficient. As aforementioned, very little research is targeted directly towards integration of engineering disciplines at the very beginning of the design phase in order to find more compact solutions.

The integrated jet cooler makes very efficient use of the manufactured connection between the electronic board and the electronic component. This connection now integrates functionalities for multiple engineering disciplines and the otherwise mandatory heat sink can be omitted. Next to the cost savings, this also results in a lighter and more compact product.

The heat pipe is also designed integrally into the board structure; hence, otherwise mandatory assembly and handling aspects of external thermal management systems can be omitted. This potentially offers huge cost savings and, in addition, with less handling, production will be more reliable as well. Also in this case, a higher form of integration is achieved. The integrated heat pipe also makes use of established manufacturing techniques. For PCBs these already rely on mass-production techniques.

According to the formulated research propositions of Section 1.2 cooling fluids are literally brought closer to the heat source and in mass production thermal management is integrable for virtually zero extra manufacturing cost. Both results demonstrate the high level of integration that is achievable between electronic, mechanic and thermal design criteria. Subsequently, the final product will cost less. Additionally, it will be smaller and lighter.

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