Cooling of chips and the principle of Heat Pipes

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***Abstract*—Different methods to cool large computers with thousands of cores were analysed. The main contribution is the presentation and evaluation of heat pipes. Therefore a testing configuration was set up. For a 25 W heat source a theoretical temperature difference of $\Delta T = 10,01K$ was calculated. This value fits very well within the limits of errors with the measured $\Delta T = (8 \pm 2)K$. It is shown as well that there are some points that could be optimized in the future to improve the capabilities of heat pipes in supercomputers.**

I. Introduction

Today supercomputers become faster and faster. But by increasing the performance, the power demand raises as well. That's why those computer generate a lot of heat. The K computer, number 3 of the world's supercomputers, for example needs a 12660 kW power supply for its 705024 cores [1]. There are different approaches to transfer this huge heat away. The classical cooling with fans is improper due to the high heat resistance of air. Using oil or water cooling is possible but has disadvantages as well [2]. A further idea is to use heat pipes which transfer a lot of heat without the need of an additional power supply. The main contribution of this work is to show the heat pipe principle, how much heat can be transmitted and which factors in the heat-transport-chain can be optimized.

II. Theoretical Principle of Heat Pipes

The abstract structure of a heat pipe is shown in Fig. 1. In the evaporator area the working fluid which is in equilibrium with its own vapour is heated and vaporized. Due to the thermal expansion and the pressure difference to the condenser area, the vaporized working fluid moves through the adiabatic section. At the other end of the heat pipe the vapour condenses again and the working fluid gets back to the heat source through thin tubes driven by the capillary force [3].

So, important for the heat transport capability are the following two factors: surface tension and geometry of the heat pipe case. The higher the surface tension, the higher the driving potential and heat transport capability [3]. For thermal control of electronic devices heat pipes are often made of copper or aluminium and they use water, methanol or acetone as working fluids [5].

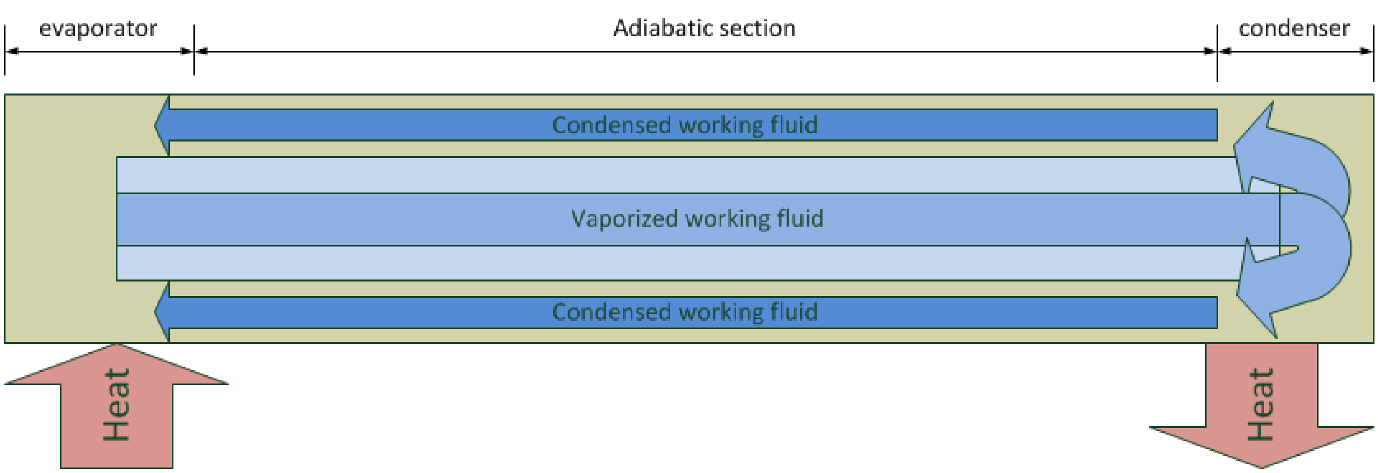

Fig. 1. Schematic heat pipe [4]

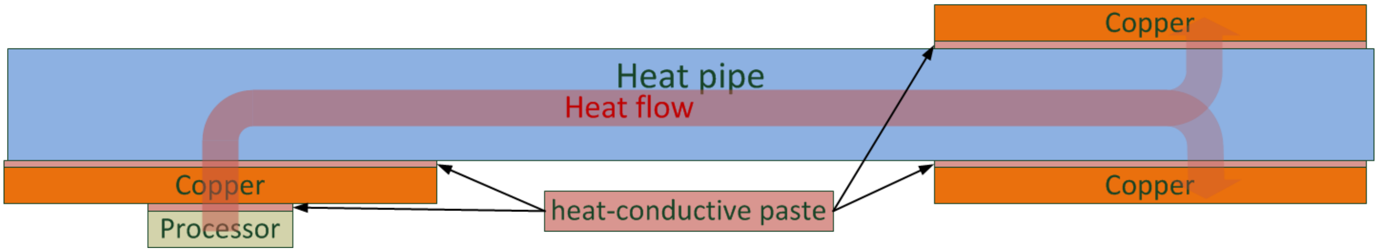

Fig. 2. Heat pipe configuration

These substances are chosen because of their well-fitting working points. Due to the geometry of most electrical devices flat heat pipes are more commonly used here [4].

III. Performance of Heat Pipes

Heat flow and performance of a heat pipe can be understood by calculating the heat reduction from the chip to the end of the heat pipe. An example configuration is shown in Fig. 2.

Like Ohm's law for elictrical current, the temperature difference (ΔT in [K]) can be calculated as the product of the thermal resistance (R in [K/W]) and heat flow ($\dot{Q}$ in [W]). Thermal resistance is a material capability which is given by:

$$R = \frac{l}{\lambda \cdot A}. \tag{1}$$

The l stands for length, the A for area and λ is the material's conductivity in $[\frac{W}{m \cdot K}]$.

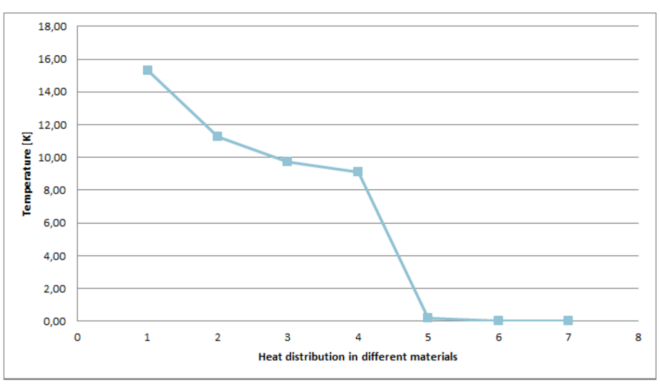

Fig. 3. Heat reduction over all parts of the heat-transport-chain 1) Chip, 2, 4, 6) Heat-conductive paste, 3, 7) Copper, 5) Heatpipe

Fig 3 shows the relative heat reduction for the settings described in Fig. 2 with a 50 W heat source. Meassurements, heat conductivity and heat resistance values are based on an example set-up of an AMD Opteron and a Flat Cool Pipe from Amec Thermasol. It is easy to see that the biggest temperature differences are caused by the heat-conductive paste. Although it is very thin, the conductivity is up to 100 times smaller than that of copper [6] [7], so the thermal resistance is increased. In order to verify the producers' data sheet for the Flat Cool Pipe from Amec Thermasol the settings shown in Fig. 4 were used.

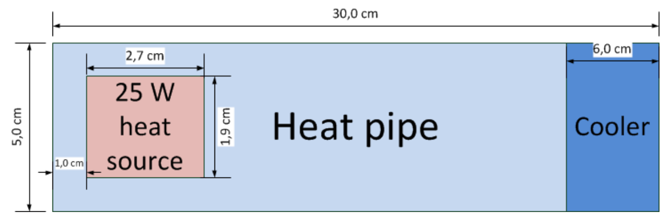

Fig. 4. Settings for the verifying experiment

A. Theoretical Performance

To calculate the relative temperature difference between the heat source and the cooler, the collective heat resistance is required. Like a series connection in an electric circuit, the particular resistances, shown in table I, add up to $R_{collective} = 0,400347\frac{K}{W}$.

TABLE I
MATERIAL CAPABILITIES [7] [8]

material	length [cm]	heat resistance [K/W]
heat-conductive paste 1	0.5	0,167
heat pipe	29	0,2
heat-conductive paste 2	0.5	0,033

Now it is possible to calculate the temperature difference by

$$\Delta T = \dot{Q} \cdot R_{collective} = 10,01K. \tag{2}$$

Fig. 6 shows the relative heat distribution over the distance. As also shown in fig. 3 again the heat-conductive paste is the cause of the biggest thermal difference. This calculation does not include the heat pipe's thermal emission into the air.

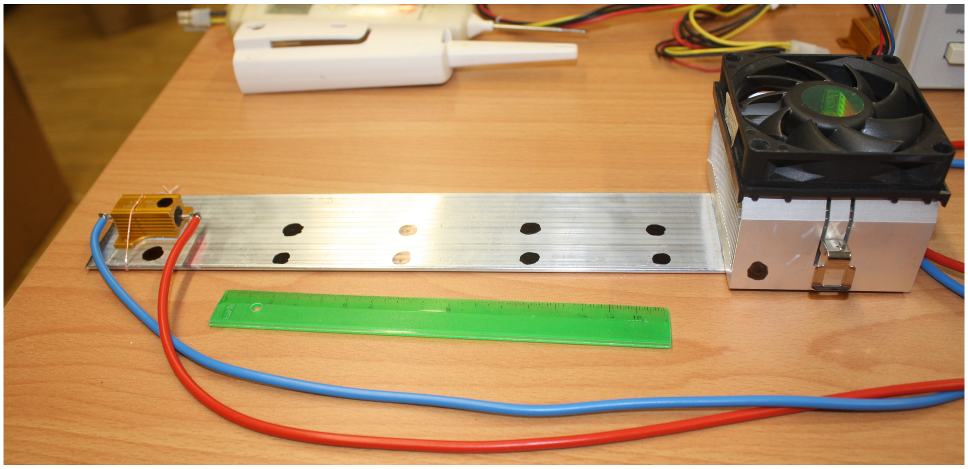

Fig. 5. experiment build up

B. Evaluation

To evaluate this calculation an installation of this settings is shown in fig. 5. The black dots are painted every 5 cm for thermal measurements with a Pyrometer which uses thermal radiation to detect temperatures [9]. This thermometer works with the assumption of an emissivity $\epsilon = 0.95$ which is similar to a black body emissivity of 1.

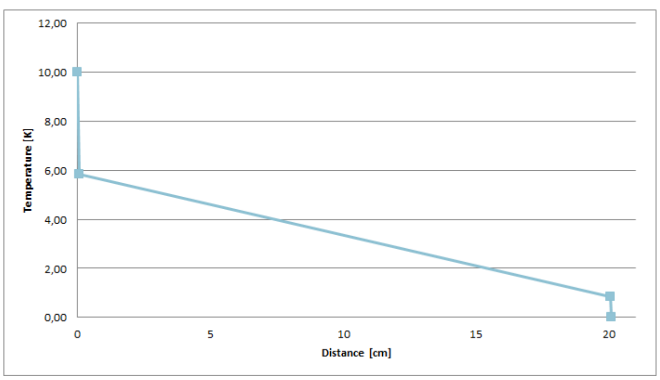

Fig. 6. Relative heat distribution across the heat pipe (calculated)

All in all, five series of measurements were taken; at the beginning (t = 0s), after 1, 4, 10 and 15 minutes. The individual results are shown in fig. 7. These results comply with the theoretical assumptions within the limits of errors and the information given by the manufacturer. After 15 minutes the temperature difference has evened out at $\Delta T = (8 \pm 2)K$. The large error margins are the result of the weakness in the infra red measuring method used here. Another interesting fact is that no significant vertical heat distribution was recognized, even although the width of the heat source was less than half

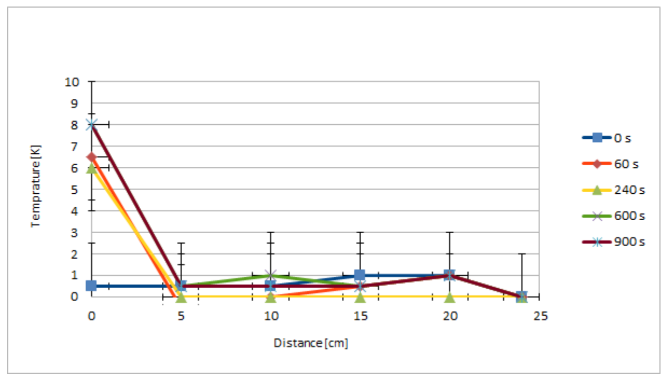

Fig. 7. Relative heat distribution across the heat pipe

the width of the heat pipe. The faster cooling of the heat pipe is probably the result of thermal emission into the air and the workbench. This emission would cause a rise of the air temperature and also would warm up the printed circuit board (PCB) in a computer.

IV. Optimization

As seen before there are several possibilities to improve the cooling behaviour. The heat pipe itself works solid and is qualified to be used in large computer clusters. There are to different weak spots in the cooling. On the one hand the high heat resistances of air and heat-conductive paste which appear at every crossing between to elements. On the other hand the heat flux into the PCB and the air.
The first problem can be decreased be very plane surfaces, so that the thickness of the gap can be minimized. in this context the heat distribution in solids is also important. As seen in fig. 2 the chip itself is a lot of smaller than the box. And although copper has good heat

dissipation capabilities, there is a heat gradient which causes a higher temperature in the middle and colder edges.
The second problem is not visible at itself on the first view. But heat pipes are used to carry heat from the sources away in order to save other components on the PCB for overheating. But if there is a non negligible heat flux into the PCB this effect decrease a lot. While warmer air is much easier to handle via fans for PCBs it is not that simple. Here is a extra heat isolation layer necessary. However there will be always pins which pipe besides current also heat into the PCB. So this effect can not be completely eliminated. All in all it shows that a cooling without any additional power supply is not that simple.

V. Conclusion

Heat pipes per se are a good idea to cool supercomputers. They can achieve a thousand times higher heat flux than an equal sized copper block [6] [8]. These theoretical values were confirmed by several experiments.
But there are still some weak spots. So it is barely possible to go without any kind of fan or a comparable cooling system which blows out warm air and cools PCBs per convection.

Acknowledgment

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