Sommerakademie Leysin
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Different Methods of Cooling

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Contents

1. Abstract

Today there are thousands of data centers and supercomputers which run weather simulations, store our data (clouds), provide information, host websites etc. The energy consumption of those large computers raised enormously in the past two decades (see figure 1 and 2) due to the increasing demand of computing power and storage. One data center can consume up to 30 MW[1] of electricity and up to 40% are used for cooling. But this part can be reduced to about 5% depending on the location of the data center. This paper is meant for people, who are interested in this topic and who want to get an overview over the different ways to cool large servers. We will have a look at the heat output of different systems and then go into details of every step of the heat transport from the hardware to the ambient.

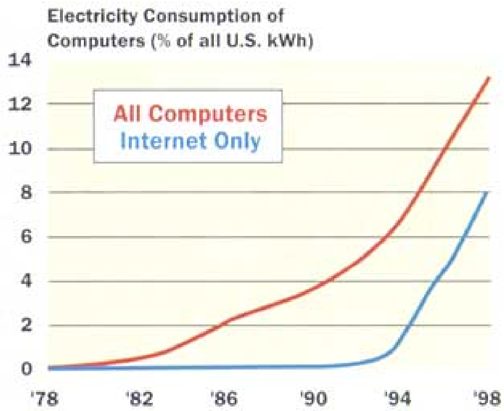


Figure 1: continuously raising demand

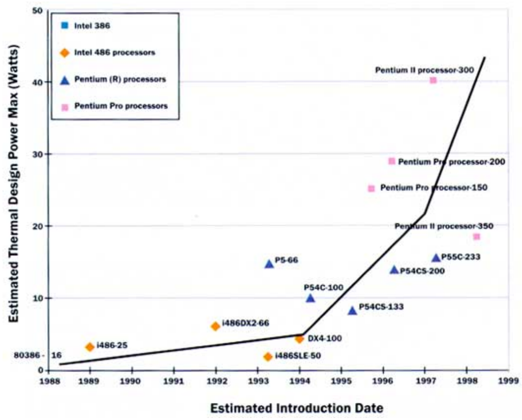


Figure 2: Heat output of CPUs

2. General questions

There are some questions that one might think of when looking at this topic.

Why should a computer be cooled at all?

Due to the Joule Effect components in an electric circuit always[2] are heated up. All kinds of processors and computer hardware consist of those circuits. This means every chip produces heat which needs to be transported away. If that doesn't happen, at first the calculations in the processor will fail more often due to physical effects, which means it works less effectively. If the temperature rises above 100 °C some parts of the chips may start burning or melting which leads to the destruction of the hardware (see figure 3). To prevent hardware damage complex processors are equipped with a control software which will lower the frequency of work steps (see figure 4). This leads to a lower heat output but at the cost of performance.

[1] e.g. Facebook server in Sweden
[2] at least if they are not superconducting

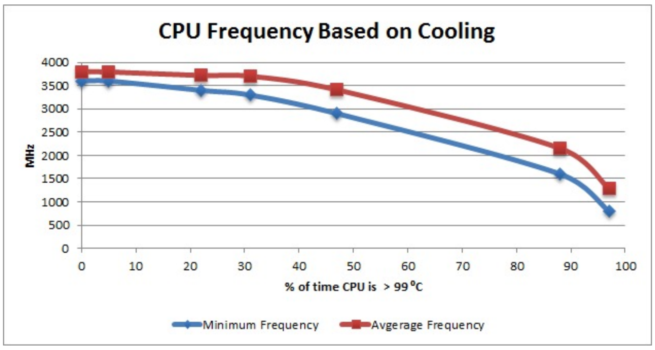


Figure 3: Burned chip

Figure 4: Throttling

Why do we need different technologies?

The evolution of CPUs (Central Processing Unit), GPUs (Graphics Processing Unit) etc. is probably the fastest progress humans have seen so far. In figure 2 the heat produced by the chips is indicated. Newer chips have a higher heat output or TDP (Thermal Design Power) than older ones due to the increased amount of transistors. In fact not only the total amount of produced heat has increased but also the heat density. Figure 5 displays that those numbers are quite high and that processors may produce more heat per cm^2than hot plates. Some approaches to cool the processors are not capable of transporting such a heat load. This is why we need different technologies and why there are still efforts to create better approaches.

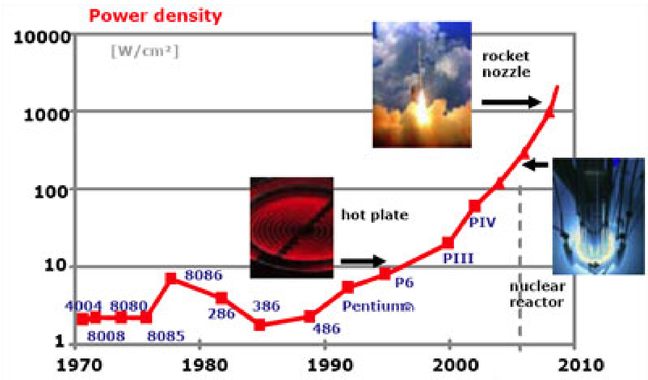


Figure 5: Power density history of Intel CPUs

How much heat does a processor produce?

This question can't be answered in general. There is a huge amount of different chips for different purposes which have different TDPs. Here is an overview of the most relevant chips (CPUs) from different everyday-devices to supercomputers:

Table 1: TDP overview

Device	TDP	Size	Heat density[1]
Smartphone	<5 W [2]	$\approx 10 \times 10$ mm [3]	<5W/cm^2
Notebook	35W	a bit bigger	$\approx$ 25W/cm^2
Desktop CPU Intel i3	50W	$\approx 20 \times 20$ mm	15W/cm^2
Desktop CPU Intel i7/AMD fx 9590	145W/220W	$\approx 20 \times 20/25 \times 25$ mm	40W/cm^2
Supercomputer	6.000.000 W [4]	$\approx 20 \times 20/25 \times 25$ mm	40W/cm^2
Server farms	12.000.000W [4]	$\approx 20 \times 20/25 \times 25$ mm	40W/cm^2

[1] Not of the system but of the chip
[2] not the TDP but max. power consumption. TDP is lower
[3] Apple A9
[4] not one CPU but the total TDP of all chips

3. Different methods of cooling

In general all cooling methods have the same structure. The heat is being produced by the chip and then spread by the heatspreader (see figure 6).

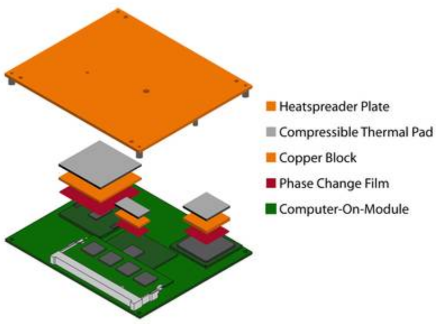


Figure 6: Composition of a CPU

Then the heat has to be transferred from there to the coolant which can be air, water or another liquid. After that the heated coolant is being transported to the chiller where the heat is being exchanged. Those are the main steps. For each step there are different technologies available on the market. In the following the most important ones will be discussed.

3.1. Heat transfer to the coolant

In the first step the heat has to be transferred to the coolant.

3.1.1. Convection and conduction

The easiest approach is natural convection and conduction. Here no additional equipment is required. The heat is transferred to the surrounding air via conduction which then will rise and produce an airstream (convection) that transports the heat away. This technique is the easiest one to implement but is strongly limited in terms of heat load. The maximum heat transfer is aprrox. 1W/cm^2 which is very low. This approach is usually used for all the peripherals which means everything but complex chips.

3.1.2. Heatsink

Heat sinks are based on the same principles as the method presented before. They transport the heat away via conduction and convection. The difference is that the surface is bigger by an order of magnitude so that more heat can be dissipated. Conduction spreads the heat all over the heatsink. The fin design (see figure 7 and 8) may vary and each has its advantages and disadvantages which depend heavily on the usecase.

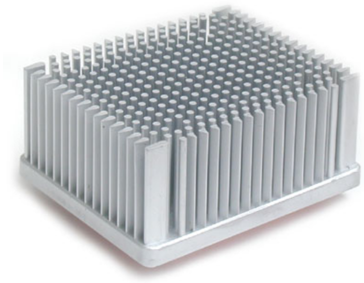


Figure 7: Fin design 1

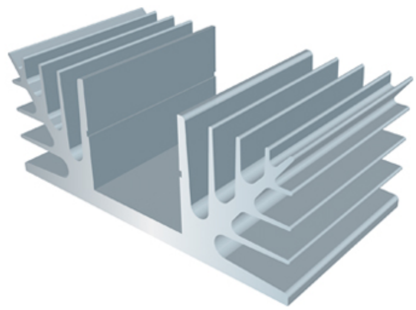


Figure 8: Fin design 2

From the heatsink the heat is transported away by air. The fin design supports the natural convection which leads to a more efficient airstream (see figure 9). The cooling capacity depends on the total surface, the design and also the material (thermal conductivity). With this method heat densities up to 50W/cm^2 may be handled but this number should be treated with care. It is the maximum that may be handled but is not a recommendation.

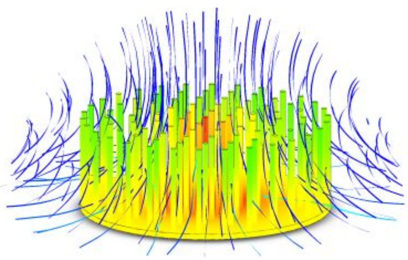


Figure 9: Supported convection

3.1.3. Heatpipe

A heatpipe is a sealed pipe made of copper (high thermal conductivity) which contains a working fluid and a wick (see figure 10 and figure 30 in the appendix). In step 1 the working fluid is being heated up. This leads to the evaporation of the fluid and thus to a higher pressure. Because of the pressure gradient the vapor migrates (step 2) to the lower temperature end where it condenses and spreads the absorbed heat (step 3). Finally the condensed fluid flows back through the wick structure due to capillary action.

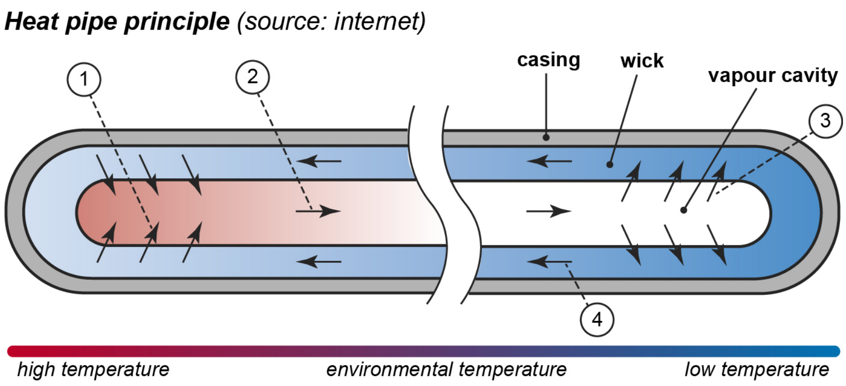


Figure 10: Heatpipe

Heatpipes have a higher thermal conductivity than solid materials. Increasing the diameter leads to an increase of the conductivity and therefore also increases the efficiency. Usually heatpipes are used complementary to just transport the heat away (see figure 29 in the appendix) and spread it via a bigger heatsink that does not suit directly on the chip (e.g. in laptops). This leads to a higher maximum cooling capacity (see figure 11) because the heatsink may be a ot bigger. Experiments showed that up to 100W/cm^2 may be transported with heatpipes. Again this is a maximum number and should not be taken as a recommendation.

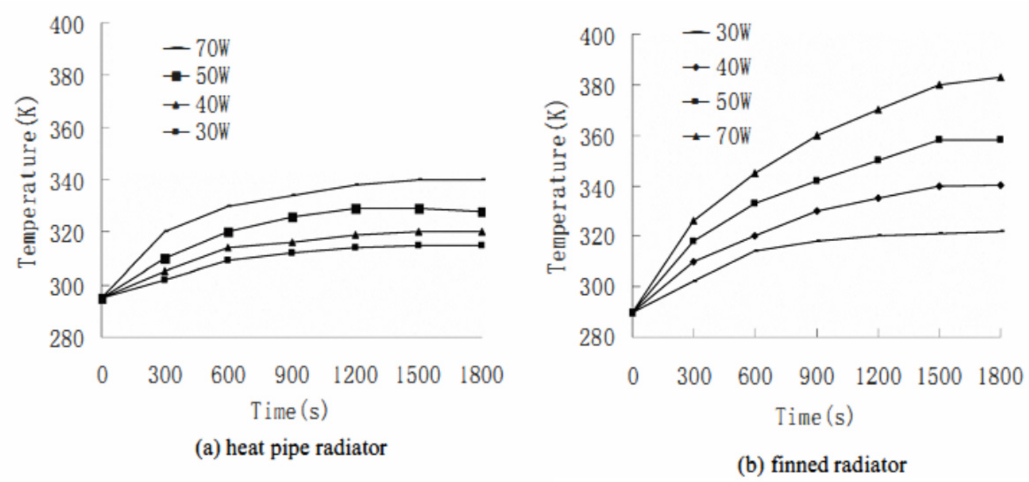


Figure 11: Comparison with/without heatpipe

3.1.4. Cooling blocks

This method is used when the coolant is water instead of air which has many advantages that will be discussed later. Cooling blocks have built in heatsinks to dissipate the heat more effectively to the coolant. For every component there are different blocks (see figure 12 and 13) which are designed to suit the hardware. The heat is transported away from the chip via conduction through solid material (usually copper) and then dissipated to the coolant in channels that enlarge the total cooling area.

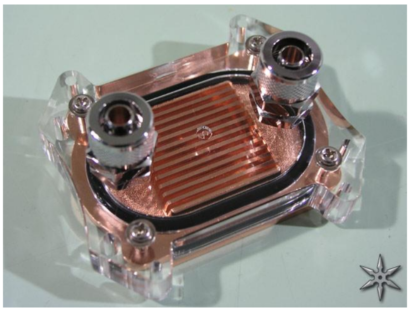


Figure 12: CPU Block

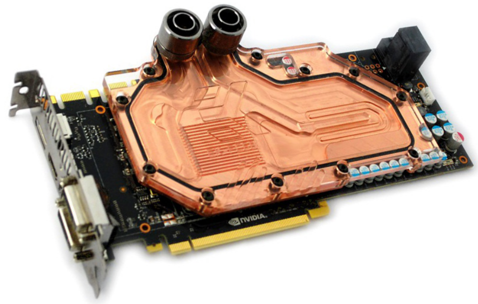


Figure 13: GPU Block

As long as the flowrate is small the current is laminar which means that the following equation applies:

$$\text{channel width} \propto \frac{1}{\text{heat transfer coefficient}} \tag{1}$$

This implies that the channels should be as small as possible to maximize the heat transfer. This is not always the best solution because the smaller the channel is, the bigger the resulting pressure drop:

$$\text{pressure drop} \propto \frac{1}{(\text{channel width})^2} \tag{2}$$

Without pressure there is no current that could transport the heat away. This means that there is a optimum between equation (1) and (2) which limits miniaturazitaion to usually a few milli- to several hundred micrometers.

3.2. Heat transport

After the heat is transferred to the coolant, it needs to be transported away. There are some different approaches which will be presented in this chapter.

3.2.1. Room-oriented cooling

This is the traditional and simplest technology. Cold air enters the room, cools down the components, gets warmed up and leaves the room. Apart from fans which push and pull the air no additional equipment is needed. To optimize the airflow and efficiency of the cooling system the cold air intake is under the floor (see figure 14). In this case natural convection supports the airstream and prevents mixing of hot and cold air.

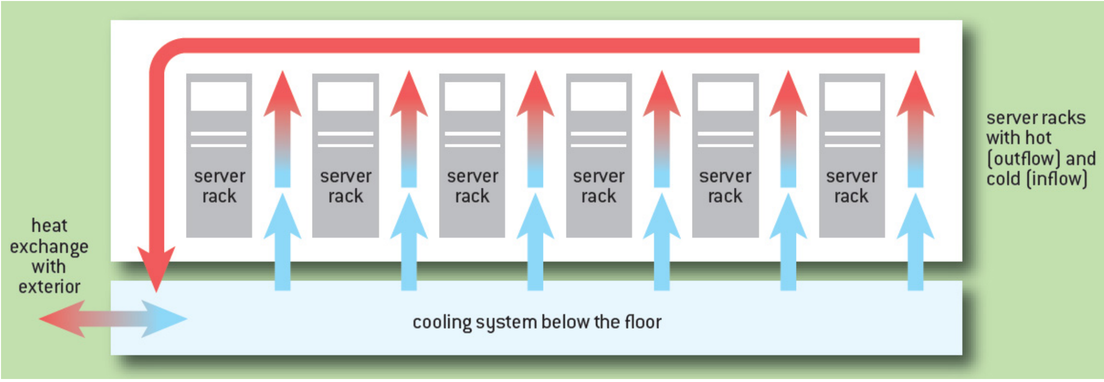


Figure 14: Room-oriented cooling

Such a system comes with a very high flexibility. No big changes have to be made if the racks are rearranged, hardware is upgraded or new racks are installed. In addition it is the cheapest solution in terms of acquisition. Also the installation is quite easy as it isn't very complex. But there are also some disadvantages. The efficiency of such a system is low because hot and cold air get mixed which leads to a lower cooling performance (see figure 15). Another problem is that different components have a different heat output which leads to inhomogeneous heat distribution in the server room.

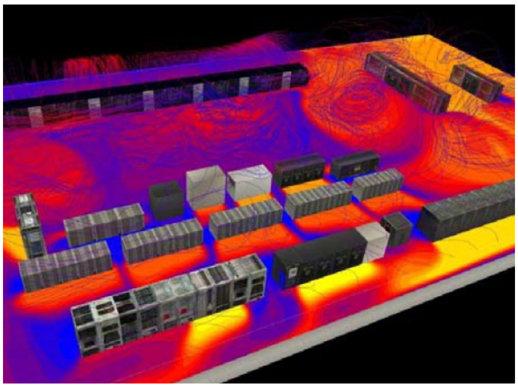


Figure 15: Mixing of hot and cold air

Another problem are hotspots. If the airflow does not reach a region (which is quite difficult to calculate in advance) then the heat will not be dissipated fast enough which can lead to hardware damage and an emergency shutdown of the server. To prevent that a huge airflow is required. Furthermore the maximum cooling capacity is limited to about 10kW per rack. But to handle this heat 1-2 m^3 per m^2 serverroom are required. For a 4000 m^2 serverroom this means 4000-8000 m^3 air which is a lot.

3.2.2. Row-oriented cooling

Row-oriented cooling is basically airflow-improved "Room-oriented cooling". The air of the different racks is separated to avoid mixing and there are chimneys or dropped ceilings which pull the hot air out of the room (see figure 16). This way the efficiency is improved by up to 30% compared to room-oriented solutions.

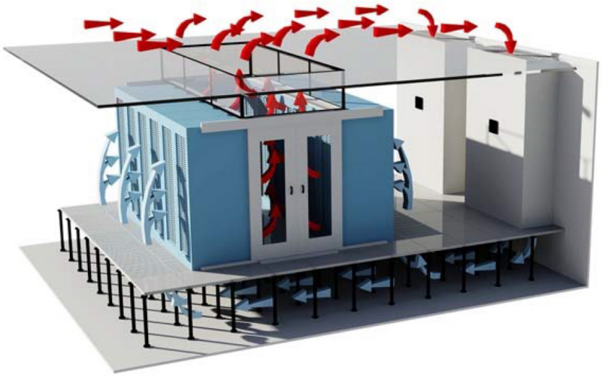


Figure 16: Separation of the air

This technology is less flexible than the one presented before. Chimneys or dropped ceilings are needed, which cost money, make the installation more complex and prevent easy rearrangement of the racks because the chimneys would have to be moved too. Even though it is easier, the calculation of the fan power to prevent hotspots is still hard. Furthermore the integration of new racks is more difficult but not impossible. Upgrading the hardware is no problem because this cooling solution is not hardware dependent. Heat loads up to 40kW/rack can be cooled.

3.2.3. Rack-oriented cooling

Here the separation is even stricter. To avoid hotspots and mixing of the air there is one chimney per rack (see figure 17). Therefore the efficiency is increased even further at the cost of a higher complexity, more difficult installation and higher acquisition costs. On the other hand the whole server room is cooler because no hot air leaves the rack.

Figure 17: Rack-oriented cooling

To enhance the cooling power it is possible to water cool the back doors of the racks so that the raising air is not too hot when reaching the components at the top. For this technology way more components are needed which also leads to a higher probability of failure. As the whole air of the room is not used in the cooling circuit less air is used for cooling. This means that if something fails, the coolant will be heated up more quickly. In the worst case this will lead to a emergency shutdown.

3.2.4. Liquid cooling

Air in fact is a bad thermal conductor. To transport the same amount of heat 3526 times more air (by volume; at 25 °C) than water is needed. This is due to the lower thermal capacity of air and the low weight per volume ratio. Therefore air is often replaced by water or any other liquid if high cooling capabilities are required. Not only a higher heat load might be a reason to consider water cooling but also low temperatures might be required or desired which can be obtained with water cooling (see figure 18). Hybrid cooling is also possible. This means that the components that produce a lot of heat are cooled by water and the rest of the components which are less critical are cooled by air.

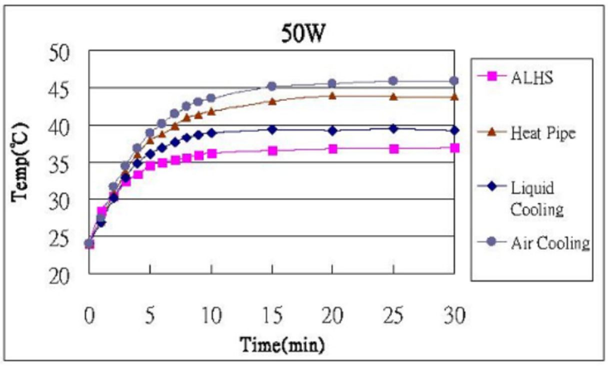


Figure 18: water- vs aircooling

The efficiency of water based solutions is increased by 15% over rack oriented cooling. This is because there is no mixing of hot and cold water and the probability of hotspots is really low. This leads to a cooling capacities up to 100kW/rack. Efficiency can be increased even further by increasing the inlet temperature of the coolant to about 40°C. This makes heat reuse possible and for heat dissipation way less energy is needed. The problem with water cooling is that a very complex infrastructure of pipes, connectors, pumps and cooling blocks is required. This means that the cost of acquisition is high and the probability of a failure and thus a dropout is higher because of the increased number of components. Also possible leakage is a problem which can lead to short circuits and hardware damage. Upgrading hardware or the installation of new racks is difficult because new hardware specific cooling blocks and new pipes/connectors are needed. Silent operation -which is possible with water cooling - might also be interesting for some usecases.

3.2.5. Oil-immersed cooling

Because oil is non-conducting it is possible to immerse whole racks or parts of the rack in oil instead of air. Oil has almost the same thermal advantages as water and in comparison to "ordinary" liquid cooling much more coolant is involved. This means that if a pump fails the system will need a lot more time to reach critical temperatures which gives the service team more time to react. Also hardware damage will be prevented. Silent operation is possible because no fans are needed. A problem is the exchange of hardware, which is not impossible but more difficult. Even though oil is non conducting for many products the immersion will void warranty which might be problematic. Hard drives have moving parts that would be slowed down due to friction and the low viscosity of oil need silicon cases which adds even more effort for installing such a system. Another problem is that the effort for maintenance is quite high.

3.2.6. Thermoelectric cooling

Another approach is thermoelectric cooling. Here semiconductors are used to absorb the heat. Depending on the current the electrons are forced to migrate from the n-doped area to the p-doped area or vice versa. If electrons area forced to move from the n- to the p-doped are they will have higher energy levels afterwards. This energy is taken from the thermal energy of the material so that this side will be cooled. If the elements are arranged right (see figure 19) one side will be cooled and the other side will be heated up.

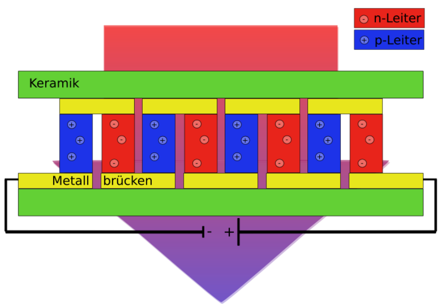


Figure 19: Priciple of a thermoelectric cooling

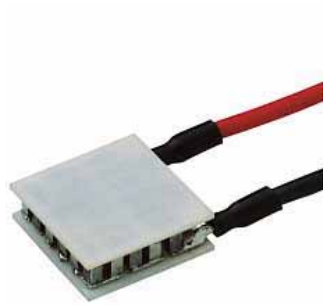


Figure 20: Peltier element

For this technology no cooling medium is need and there are no moving parts which leads to a lower probability of failure due to wear and tear. Also no other solution is so compact and accurate to regulate (voltage regulation). Another advantage is that temperatures sub zero are possible. One problem is that the component is cooled but the heat (produced by the other side of the element) is not transferred away but still stays in the rack. This means that additional air cooling is needed. Another problem is that for thermocouples materials are needed which have a high electrical conductivity and a low thermal conductivity but both are related to each other because they base on electron surges. But if the thermal conductivity of the material is high this means that some of the energy won't be used to cool the components but to maintain the temperature difference between the hot and the cool side because the material strives to reach an equilibrium regarding the temperature. This leads to a very low energy efficiency of only 10% of the carnot-cycle (will be explained in the next section).

3.3. Heat dissipation

After the transfer of the heat to the coolant and the transport of the coolant the heat has to be dissipated in some way so that more heat can be absorbed. There are again some different approaches which will be explained in the following chapter.

3.3.1. Gas based cooling

Gas in this case does not mean the air circulating through the serverroom but the working gas of a refrigeration machine. In such a machine gas is somehow compressed so that it gets heated up. This heat is then spread to the ambient/outside air via indirect cooling (no mixing of working gas and outside air). Then the cooled gas is decompressed again so that the temperature is lowered. The whole cycle is visualized in figure 19. Almost every fridge is based on this process.

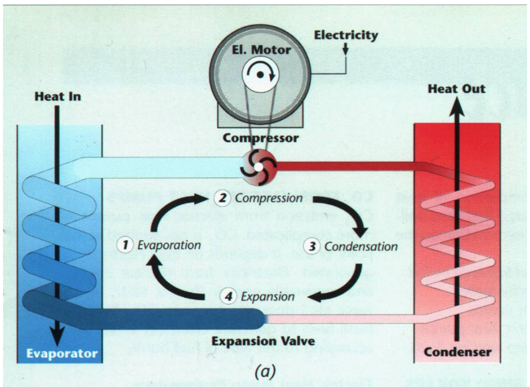


Figure 21: Principle of the thermodynamic cycle

This is the most common method as it is cheap to buy, it works in any climate (better or worse but it works) and it is easy to install. Furthermore it can handle low grade (low temperature difference) heat and the technology is mature. On the other hand it isn't the most efficient technology (the higher the outside temperature the worse the efficiency). The refrigeration machine alone consumes energy equivalent to 25% of the total cooling load.

3.3.2. Indirect free cooling

Indirect free cooling (IFC) is a way easier technology. It spreads the heat to the outside air indirectly (separated by a metal sheet). Therefore no energy is needed for cooling. The total energy consumption of such a cooling system is equivalent to 10-20% of the cooling load (due to fans, friction). This leads to very low operational costs.

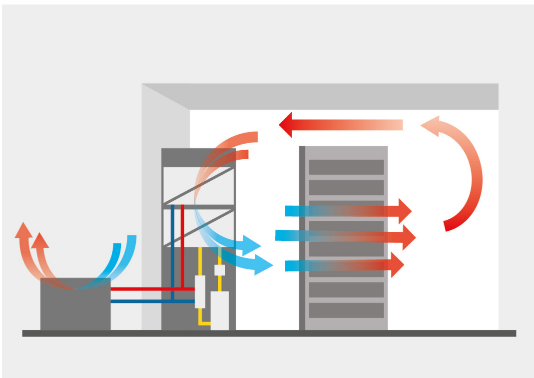


Figure 22: Indirect free cooling

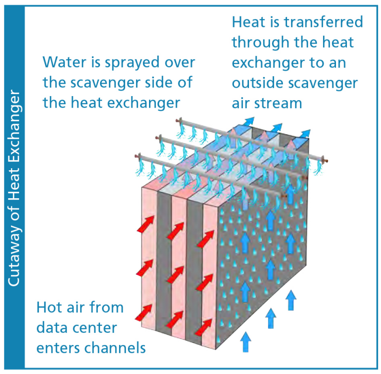


Figure 23: Evaporative assist

The problem is that this only works with outside temperatures below 10-15°C (depending on the heat load). Only then it is capable to dissipate enough heat because heat flow is proportional to the temperature difference between the outside and inside air. This is why IFC is often used complementary to a refrigeration machine to improve the efficiency but not as a stand alone solution. If the power of IFC needs to be increased it may be equipped with evaporative assist (see figure 23). This means that water is sprayed on the heat exchanger. The slow evaporation escapes heat from the ambient air which leads to a bigger temperature difference and thus to a higher heat flow. Another possibility is to integrate the cooling loop into open water (see figure 25). There the temperature fluctuation is not as high as the temperature fluctuation of the ambient air.

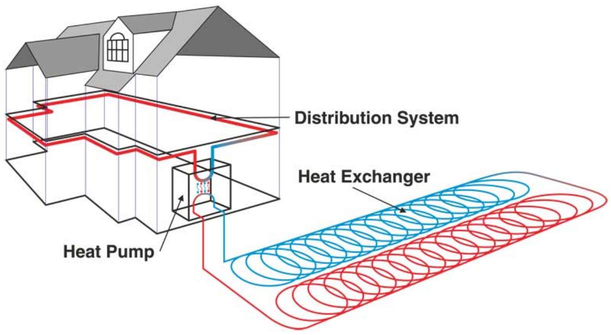


Figure 24: Geothermal exchange

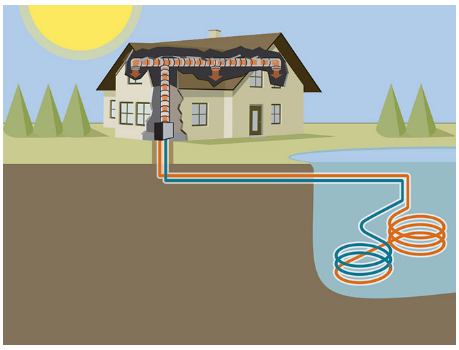


Figure 25: Open water

If there is no open water close to the server an alternative might be geothermal exchange (see figure 24). The advantage is again that there are only very low calculable temperature fluctuations. The temperature of the earth 2 meters below the ground is around 10-20°C. The problem is that the installation is quite labor intensive and about 35-50m of loop (see figure 31 in the appendix) are needed to dissipate only 1kW of heat. Geothermal exchange and indirect open water cooling may also be combined (see figure 32 in the appendix).

3.3.3. Direct free cooling

Direct free cooling (DFC) is almost the same approach as IFC. The only difference is that there is no separation between inside and outside air. DFC has a direct air intake (see figure (26)). This leads to a higher efficiency as the inside air does not have to be cooled which always leads to higher inside temperatures compared to DFC because for a certain heat flow the temperature difference has to reach a certain value.

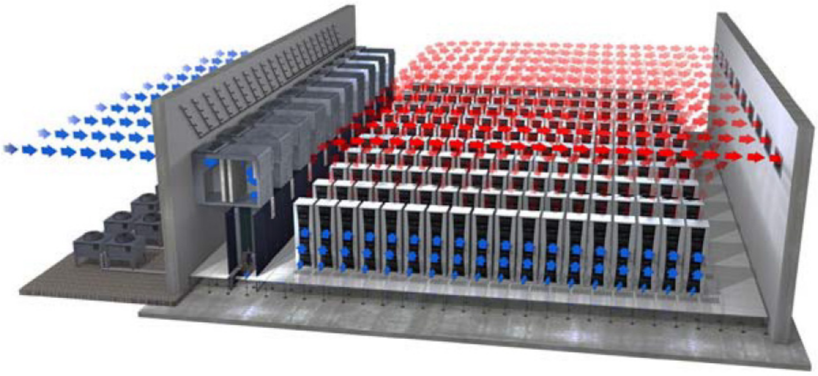


Figure 26: Direct free cooling

This is why DFC is capable to cool a server if the outside temperature is below 15-20°C. Also evaporative assist is possible but depends on how much humidity the hardware can tolerate. Air pollution also limits the field of application of this technology. For some usecases filters might be a solution but this is not always the better approach compared to IFC. DFC is about 40% more energy efficient than a refrigeration machine based cooling system (the fans still have to be powered) but needs about 50% more space because of the air intakes/evaporative assist/filters etc. An example for a completely DFC cooled server is the facebook server in Sweden (see figure 27).

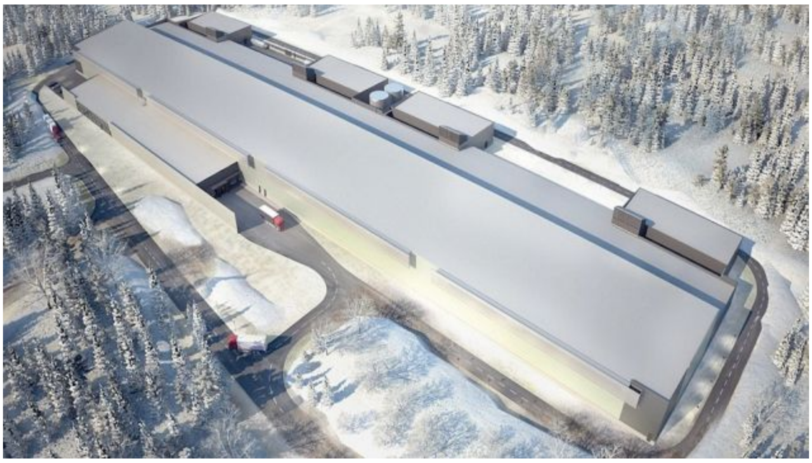
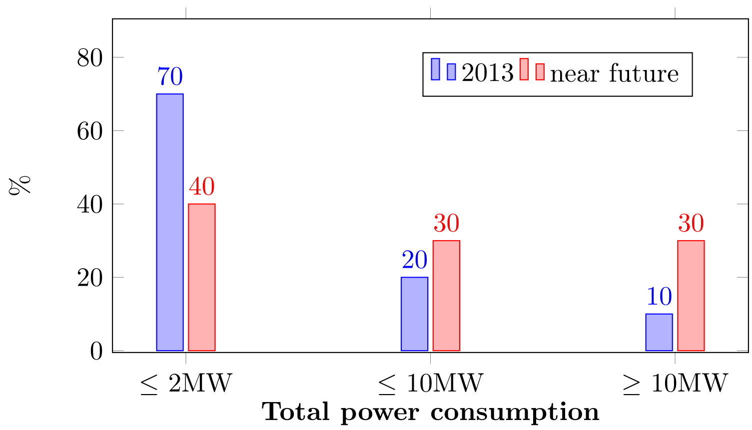


Figure 27: Facebook server in Sweden

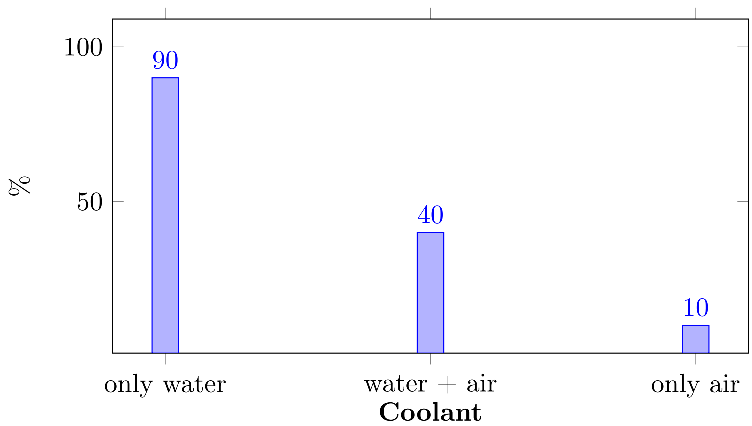
4. Interesting facts

This is a collection of facts found in papers that might be interesting to the reader.

1. The average heat density of a rack in servers is 10kW/rack but up to 30kW/rack are still usual numbers. Future plans indicate that some will reach 45kW/rack where cooling gets more and more difficult.
2. In general approved solutions are preferred. This means that cooling methods that are mature are preferred over newer and more efficient technologies. This shows that the goal of companies (of course not true for all of them, but especially the smaller ones) who build servers is not to make them as energy efficient as possible but to have a reliable server. This is why a lot of energy is wasted and many servers don't have very efficient cooling systems. This means there is a lot that may be improved in the future.
3. The total power consumption of servers (for clouds, internet etc) will rise as well as the number of "big" serverfarms that consume more than 10MW. This shows that efficient cooling technologies can make a big difference for a greener IT in the future.



4. Most servers use water as coolant because ot the limits of aircooling.



5. The heat is dissipated mostly via ambient air because this is by far the easiest solution.
6. Heat reuse is not too common because the heat is mostly low grade (low temperature difference). This is also something that should be focused on because the heat which is taken away from the server can be used to heat buildings or houses so that this heat is not wasted and the server is much more efficient.
7. Even though new technologies aren't used too often there are still some experiments with new approaches. E.g. Microsoft tested 300 computers to operate on the ground of the sea and looked for impacts on the environment.

Figure 28: "Microsoft puts the cloud in the ocean"

A. Images

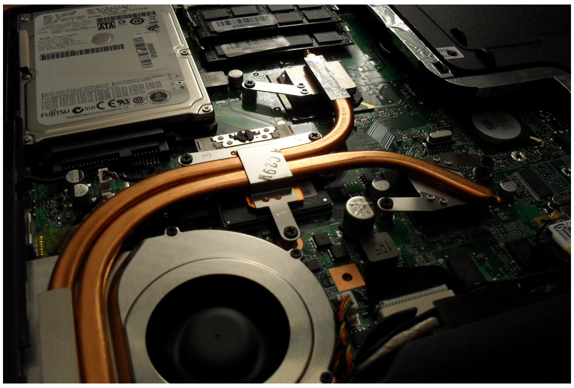


Figure 29: heatpipe in a laptop

Figure 30: cross section of a heatpipe

Figure 31: Geoloops

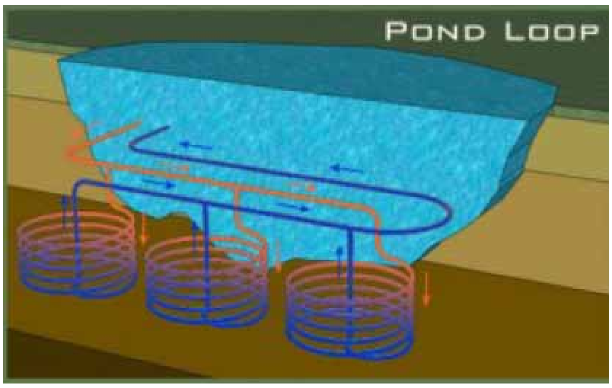


Figure 32: Geothermal and indirect open water cooling combined

B. Sources

These are the sources corresponding to the presentation about this topic. Some of the images used in the presentation might not have been used in this document.

http://large.stanford.edu/courses/2012/ph240/lee1/

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