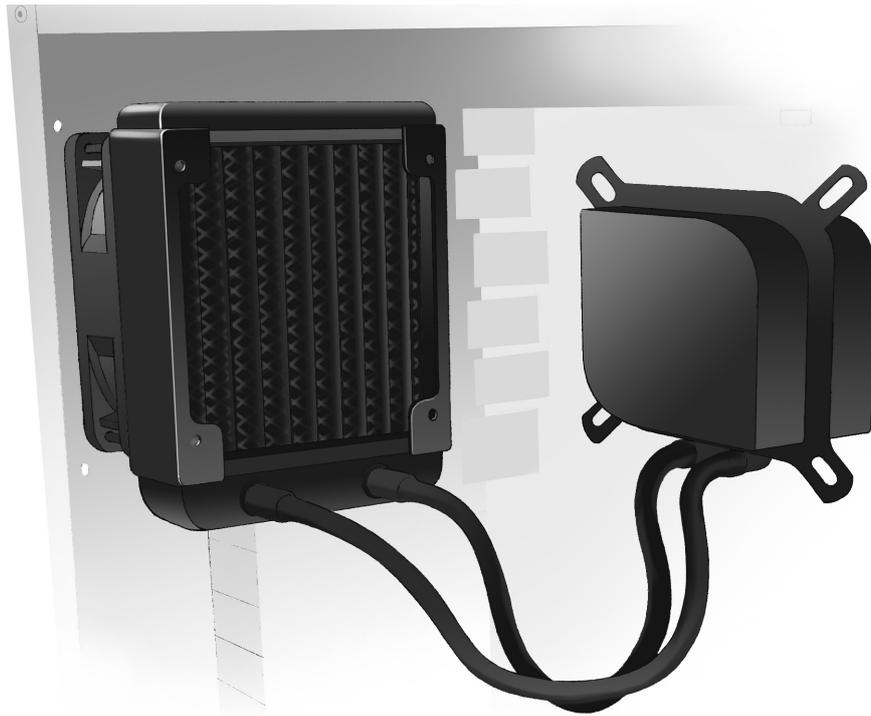


CHALMERS



Development of Liquid Cooling for PCs

Component Analysis for Factory Sealed Systems

Degree Thesis

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Department of Applied Mechanics
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DEVELOPMENT OF LIQUID COOLING FOR PCs
COMPONENT ANALYSIS FOR FACTORY SEALED SYSTEMS

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Cover:
Concept sketch showing a factory sealed water cooling in a computer case.

Department of Applied Mechanics
Göteborg, Sweden 2011

FÖRORD

Denna rapport är ett examensarbete för två studenter på Designingenjörsprogrammet vid Chalmers Tekniska Högskola, utfört i samarbete med FD Sweden AB (Fractal Design). Arbetets omfattning är 15 högskolepoäng, vilket motsvarar en halv termins heltidsstudier, och utfördes under våren 2011.

Vi vill tacka våra handledare, Karin Munch (Chalmers) och Hannes Wallin (Fractal Design), för de råd och det stöd de gett oss under projektets gång, samt Fractal Design för att de tillhandahållit lokaler och de produkter som använts vid testningarna.

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ABSTRACT

In recent years, existing solutions for cooling personal computer CPUs have been supplemented by a new product category, factory sealed water cooling loops. These systems, consisting of a water block with an integrated pump, a fan and a radiator, perform well compared to the air cooling solutions but are less effective than larger, custom-built water cooling systems.

This project aims to explore the most important aspects of a factory sealed system and to identify possible cost-effective enhancements of the performance.

The most significant differences between the different groups of water cooling loops are the block design and the pumping power. The performance of both categories is also largely dependent on the fan power, but increasing fan power has a large negative impact on the noise level.

Both radiator size and fan model choice appear, in tests, to be relatively unimportant, presuming that the noise level is kept constant. The position and direction of the fan, however, has significant impact on both the temperature and the sound level.

Water blocks can be designed in several different ways, both regarding the heatsink design and the flow direction. In simulation, flow with the inlet centered above the heatsink result in considerably lower pressure drop and slightly higher temperatures than flow through the block, for heatsinks with fin arrays.

Creating a competitive product in this product segment certainly seems possible, as there are performance-increasing changes to be made that seemingly has little impact on the production cost. Computer simulations are deemed to be suitable for the development of the block.

Keywords: Water, Liquid, Cooling, Electronics, Personal Computer, Heatsink

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SAMMANFATTNING

Produktkategorin kylare för persondatorers processorer har under de senaste åren utökats med en ny undergrupp, fabriksförslutna vattenkylningssystem. Dessa system, bestående av fläkt, radiator samt ett vattenblock med integrerad pump, presterar väl jämfört med luftkylningalternativen, men har lägre kylförmåga än mer omfattande, användarbyggda vattenkylningssystem.

Detta projekt syftar till att utforska vilka produktaspekter som begränsar prestandan av ett fabriksförslutet system, samt diskutera möjliga kostnadseffektiva förbättringar.

De mest signifikanta skillnaderna mellan de olika kategorierna av vattenkylningssystem är dels utformningen av blocken och dels pumpstyrkan. Prestandan kan i båda fallen ökas avsevärt genom starkare fläktar, men då på bekostnad av ljudnivån.

Både radiatorstorlek och valet av fläkt har, i tester, visat sig ha relativt liten inverkan på prestandan, givet konstant ljudnivå. Fläktens placering och riktning i relation till radiatoren har dock betydande inverkan på både temperatur och ljudnivå.

Vattenblock kan utformas enligt flera olika principer, både när det gäller kylflänsens utformning och flödets riktning. För kylflänsar med flänskorridorer ger flöde med centrerat inlopp ovanför kylflänsen avsevärt lägre tryckfall men enbart något högre temperatur än flöde rakt igenom kylflänsen.

Det bedöms finnas goda möjligheter att utveckla konkurrenskraftiga produkter inom denna produktkategori, då signifikanta förbättringar av prestandan troligtvis kan genomföras utan stora ökningar av produktionskostnaden. Datorsimulering bedöms vara mycket lämpligt vid utveckling av vattenblocket.

Rapporten är skriven på engelska.

Nyckelord: Vattenkylning, kylning, elektronik, persondator, kylfläns

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TERMINOLOGY

ACRONYMS

CFD – Computer Fluid Dynamics

CFM – Cubic Feet per Minute, 1 CFM equals 1700 liters per hour

CPU – Central Processing Unit, the main heat source in the computer. The CPU die is the CPU integrated circuit, which is mounted on a much larger circuit board and covered by an IHS, then installed on the motherboard

DIY – Do It Yourself, custom built system assembled by the customer

ID – Inner Diameter (used for tubing)

IHS – Integrated Heat Spreader, the aluminum casing of the CPU die

PWM – Pulse-Width Modulation, a standard for controlling the power usage of electrical devices

RPM – Rotations Per Minute (used for fans and pumps)

SPL – Sound Pressure Level, here measured in dB(A)

NOMENCLATURE

ΔP / Pressure drop / Head loss – the pressure lost when forcing a fluid through a system.

To have the same flow rate, a stronger pump is needed if the pressure drop is higher

ΔT / Temperature delta – the difference in temperature

k – Thermal conductivity of a fluid or solid

\dot{Q} – Heat flux, the amount of heat dissipated through the system per time unit

TERMS

Coolant – The fluid used in the system

Fin / Microfin – Pin / micropin with considerably larger length than width, typically the fin length covers the entire heatsink

Heatsink – Metal component used for transferring heat to a fluid. High-performance water heatsinks are typically designed with microfins or micropins

Pin / Micropin – Protruding piece of the heatsink base, primarily increasing the fluid-solid contact area. Pins with width less than one millimeter are often called micropins

Socket / Processor Socket / CPU Socket – Refers to the interface between the CPU and the motherboard. Typically, many other motherboard specifications are kept unchanged for all motherboards with the same socket

Thermal Compound/Paste/Grease / TIM (Thermal Interface Material) – Compound, typically ceramic-based, used to fill microscopic gaps between two metal surfaces

I. INTRODUCTION

Today, the most common method for thermal management of computer chips is air cooling, where the heat gets transported from the chip to a directly adjacent metal block, then transported either through solid metal or through heat pipes to a heatsink, from where the heat is transferred to the surrounding air. Heat pipes are sealed metal pipes, usually made of copper, containing only a small amount of liquid and vacuum. With water cooling, water in tubes transfer the heat from the block to the fins. Thus, the water in water cooling replaces copper rather than air.

The main advantages of water cooling, compared to conventional air cooling, are that the distance between the heat source and the heatsink can be longer and that the heatsink may be larger than what is possible in a usually restricted space around the heat source.

Traditionally, water cooling has only been used by a small group of computer users with considerable technical knowledge and interest. Now, however, factory sealed water cooling products are getting introduced to the market, which eliminates much of the hassle and the risk of traditional solutions. These products give the user roughly the same performance as the top-of-the-line air coolers, at roughly the same price point, rather than being fully comparable to the more expensive and more powerful user-built water cooling systems.

These factory sealed systems are constructed from several components: a fan, a radiator, tubing and finally a block assembly, which consists of a water block and a pump. A sketch of such a system is shown in Fig. 1-1.

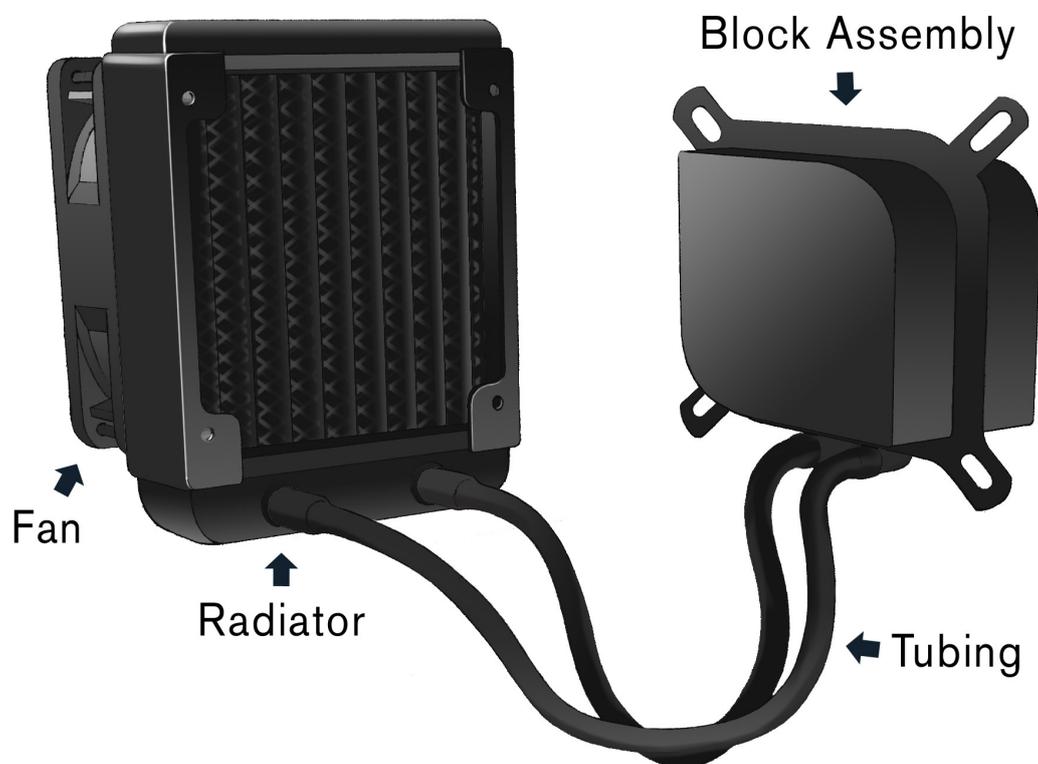


Fig. 1-1: Overview of a factory sealed water cooling system

I.1. PURPOSE OF THE STUDY

The present project aims to examine the components of a factory sealed water cooling system, both by physical testing and by theoretical analysis. For each component, the impact of different subcomponent design options on the total system performance will be evaluated.

I.2. RESEARCH QUESTIONS

- Is it possible to develop a liquid cooling product which can offer performance improvements compared to the best factory sealed solutions on the market, without making changes that substantially affect the product price?
- Which components have the largest impact on the performance of the system and which aspects of these components determine the performance?

I.3. DELIMITATIONS

- For the construction of the pump and the fans, only the requirements on the component from a system perspective will be considered rather than the function and design of the sub-components.
- While the performance impact will be examined, thermal compound composition will not be considered.
- As the radiator is presumed to be purchased from a third party, no actual optimization of the radiator will be performed. Instead, different aspects of radiator design will be considered only as part of the radiator choice guidelines.
- Liquid composition will only be touched upon briefly in testing and theory.
- User opinions will only be studied through online data, such as forums and review sites. For this product category, very well-described opinions are widely available online
- While manufacturing will be considered for all parts, no calculations or tests on manufacturing possibilities will be made.
- The cost aspect is to be evaluated only through estimations by the authors and by the developing staff at Fractal Design.

2. THEORY AND LITERATURE REVIEW

2.1. HEAT TRANSFER THEORY

The rate of heat transfer between a solid and a fluid, or vice versa, depends on several variables: contact area, temperature difference, average fluid velocity, thermal conductivity of the fluid as well as the relation between thermal and velocity boundary layers in the fluid, known as the Prandtl number (Çengel and Turner, 2005).

For turbulent flow in tubes, considered in the present project a sufficient approximation for the theoretical understanding, the total heat conductance can be described by Newton's second law of cooling, the definition of the Nusselt number and the Colburn equation (2-1).

$$\dot{Q} = \frac{A \cdot \Delta T \cdot 0.023 \cdot Re^{0.8} \cdot Pr^{1/3} \cdot k}{D} \quad (2-1)$$

Here, A is the contact surface area, ΔT is the temperature difference, Re is the Reynolds number, Pr is the Prandtl number, k is the thermal conductivity of the fluid and D is the characteristic length of the geometry. The Reynolds number is defined as $Re = V \cdot D / \nu$, where V is the average velocity and ν is the kinematic viscosity of the fluid.

Hence, apart from the variables that are dependant of the fluid composition (k , Pr and ν), \dot{Q} is proportional to A , ΔT , $V^{0.8}$ and $D^{-0.2}$. Thus, for example, doubling the area will cut the temperature difference in half, given no other changes. Changing the velocity will have affect the temperature almost as much, while altering the characteristic length has considerably less (and reversed) theoretical impact.

The thermal properties of the solid is only relevant for the solid-fluid transmission through the temperature difference, as it is the surface temperature of the solid that counts. Heat conduction through a solid is determined by Fourier's law of heat conduction (2-2), where k is the thermal conductivity of the material, A is the area, ΔT is the temperature difference and L is the thickness of the material.

$$-\dot{Q} = \frac{k \cdot A \cdot \Delta T}{L} \quad (2-2)$$

There are two materials with much better thermal conductivity to cost ratio than all others, these being copper and aluminum. Typical thermal conductivity values for these metals in their pure form are shown in table 2-1, but it should be noted that aluminum alloys with lower conductivity are often used in practice.

Table 2-1: Thermal Conductivity of Copper and Aluminum

Material	k [$W \cdot m^{-1} \cdot ^\circ C^{-1}$]
Copper	401
Aluminum	237

2.2. FLUID FLOW THEORY

With water as liquid, the flow regime is likely to be turbulent in all parts, at all relevant flow rates. In a pipe, the pressure drop through the pipe length is dependent on the pipe length L and characteristic length D , the velocity v , the density ρ and the Darcy friction factor f (2-3). The friction factor depends on the relative roughness of the pipe and the Reynolds number, which, in turn, depends on the velocity, the characteristic length and the viscosity of the fluid.

$$\Delta P = \frac{f \cdot L \cdot \rho \cdot V^2}{2 \cdot D} \quad (2-3)$$

Since f is determined by the implicit Colebrook equation, the effect of changes cannot be explicitly written. For example, decreasing the characteristic length will increase ΔP both directly and indirectly by increasing f through decreasing Re ; increasing V will increase ΔP quadratically directly but also indirectly decrease the pressure drop through decreasing f . In general, the pressure drop is high if the velocity is high and the characteristic length is low.

As for pumping power, the total flow energy is proportional both to the pressure and to the velocity squared, severely limiting the maximum possible velocity attainable without massive energy consumption.

2.3. LITERATURE ON HEATSINK DESIGN

While early liquid cooling systems, such as the prototype developed by Lee et al. (1992), used curved multi-pass channels in their block designs, modern water blocks, both commercial and experimental, typically use copper pins or fins that protrude from the main block core.

As early as 1981, Tuckerman and Pease proposed using water-cooled micro-channel heatsinks for thermal management of computer circuits. Since then, several research projects have attempted to determine the optimal shape for the heatsink, but as the results are highly dependent on both the chamber geometries and the flow rate, results may not be applicable for other conditions than tested.

Xie et al. (2008) examine the thermal resistance versus the pressure drop for different channel heights and different fin spacings. They find the optimal fin thickness and bottom thicknesses to be 0.3 mm and 0.2 mm, respectively, for a 20 mm * 20 mm fin-type heatsink with 6 mm high fins and 0.5 mm fin spacing.

In an extensive study of fin thickness and density, Li and Peterson (2006) show both that a ratio of 0.7 between fin width and pitch is optimal for both fin height 0.36 mm and 0.18 mm and that a fin density of around 120 fins per 10 mm base area is optimal on both heights. However, the tests were made with extremely weak (but constant) pumping power (0.02W), which likely means that the fin density is far too high for the present application.

Jasperson et al. (2010) compare pins and fins, but are using extremely small dimensions (0.2 mm fin width and spacing, 0.67 mm fin height). Therefore, both the fin and the pin variants are extremely restrictive, with pressure drops between 2 and 5 kPa at 3.6 liters per hour flow rate. Also, they do not compare the thermal resistance for a given combination of flow rate and pressure drop, but rather a combination of flow rate and pin dimensions. In another comparison between pins and fins, Salem et al. (2005) show that very thin and densely placed micro-fins (0.14 mm fin spacing) perform significantly better than a sparse array of very large pins intended for air cooling (2.4 mm pin diameter, 19 mm pin height). Salem et al. also show that the performance of the air heatsink could be significantly improved by reducing the pin height from 19 to 10 mm.

In a comparison between different pin shapes by Bauman et al. (2001), diamond-shaped pins outperformed a number of other forms. However, that test is made with much larger pins than found on modern top performance water blocks. John et al. (2010) compare temperature to pressure drop not only between square and circular pins, but also with different axial and transversal pitches. They conclude that the optimal choice depend on the Reynolds number, but their tests occur at far lower Reynolds numbers than likely found in actual products. Even though they perform their tests with water, the highest tested Reynolds number is 500, corresponding to very low velocities.

Jasperson et al. (2010) also discuss the plausibility of different manufacturing techniques for microchannel and micropin production. They consider casting, extrusion and sintering the viable options for mass production. Out of these, extrusion is only available for microfins, while casting and sintering can be used to produce heatsinks of either type.

In an investigation into the optimal heatsink shape for a automotive DC/DC current converter, Pickert et al. (2010) show that elliptical pins gives the system better thermal conductivity than other pin shapes, while actually resulting in slightly less pressure drop than plain fins.

In one of a very limited number of studies where the water flow through the heatsink is not parallel to the heated surface, Tsunekane and Taira (2007) determine that there is a large advantage in using microfins for cooling a high-powered laser. Out of the two tested fin widths, 0.14 mm and 0.3 mm, 0.14 mm proves to be the best choice. However, it should be noted that this test is performed with pump pressure more than one order of magnitude larger (0.2 MPa) than the pump pressures used in computer water cooling.

Older research papers mostly depend on experimental measurements, while recent projects often include CFD (Computational Fluid Dynamics) simulations, a branch of finite element analysis. Since correctly simulating the flow becomes significantly more extensive computationally with an increase in pin number, some researchers propose simplified models, such as the porous medium model used by Yu and Joshi (2002).

To summarize, while there has been numerous studies on heat sink optimization, the conclusion has to be drawn that the preferred design type is application-dependent. The results from the various studies can likely serve as excellent guidelines for choosing a decent starting point, and the methods used, especially the CFD analysis, could be used for developing and optimizing a water block for a factory sealed system.

2.4. LITERATURE ON OTHER ASPECTS OF THE PRODUCT

Stern et al. (2009), a group affiliated with Sun Microsystems, attempt to outline a comprehensive set of testing methods for closed-loop liquid cooling systems for computers, primarily regarding time degradation and external handling. The issues these tests attempt to reduce should be taken into consideration during the product development.

Nanofluids, a base liquid with metallic or non-metallic nanometer particles, have been shown to increase the thermal conductivity significantly (Choi and Eastman, 1995). In a test with a microchannel heatsink by Ho et al. (2009), the largest advantage was found to be about 70% at the largest flow rate tested, a flow rate that required relatively little pumping power (less than 1W). While cost restrictions may decrease the importance of these findings for the present project type, evaluating the cost could be worthwhile.

3. METHOD

A major part of the project focused on evaluating existing products in experimental studies. The experimental analysis of the sub-components was then supplemented by a theoretical analysis, focusing on the parts estimated to be the most important for the performance of the product.

3.1. EXPERIMENTAL TESTING

The competitor product evaluation was done through experimental testing in a controlled environment. The testing was designed to be as close as possible to standard procedure for reviews on products in this segment, partly since its prevalence is due to a common acceptance of its relevance and partly because the sales of the product are presumed to depend heavily on such tests performed by reviewers.

To acquire as relevant results as possible, the testing equipment, such as the other computer parts, was chosen to mirror a standard setup for a typical user. The tests were thus performed using standard components installed in a standard computer case, and with normal external conditions. Details of the testing procedure, as well as a list of the components in the testing system, can be found in Appendix A.

3.1.1. REFERENCE PRODUCTS

A total of eleven cooling products were chosen for testing. Four of these were air coolers, Intel Stock, Scythe Shuriken, Gelid Tranquillo and Noctua NH-U12P SE. Various factory sealed water cooling products made up for five of the remaining products, Antec Kühler H2O 620, Corsair H50, Corsair H70, CoolIT Vantage ECO and AVC Hercules Pro, and finally, two DIY systems were chosen, XSPC Rasa 750 RX240 kit and Swiftech X2O 320 kit.

3.1.2. COMPONENT TESTING

Further component tests were done, both using parts of the water cooling products and using other DIY components in different, for the project relevant, combinations. These include tests of CPU water blocks, radiators, fans, tubing, liquid, thermal compound and fan configurations.

3.2. COMPUTER FLUID DYNAMICS SIMULATION

Computer simulations of both fluid flow and heat transfer was done in ANSYS, a commercial software package that was used in several of the studies mentioned in chapter 2.3. Simulating this type of fluid flow problems is an iterative process, where changes of a large number of parameters in the design can be made indefinitely to change the performance of the water block.

4. TESTING RESULTS

4.1. SYSTEM TESTS OF COOLING SOLUTIONS

The results over time of the main product tests can be seen in Fig. 4-1. As the reporting interval of the CPU is 1°C, a bar graph may be misleading. Therefore, in addition to the bar charts shown in this chapter, the temperature over time is also available for most tests as line graphs in Appendix B.

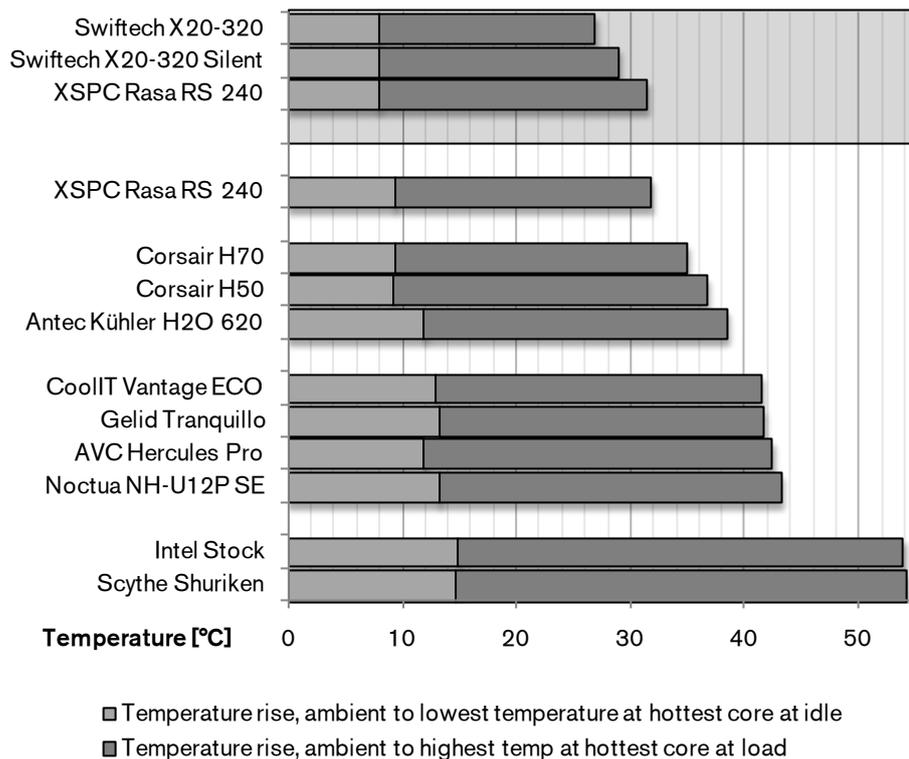


Fig. 4-1: CPU temperature with various cooling solutions. Tests with grey background were conducted outside the computer case (see next page).

It can be noted that the products have gathered in four different groups based on their performance. The first group consists of the Intel Stock and Scythe Shuriken coolers, which are both air coolers in the low price range. Both performed poorly, as the tests had to be aborted since the maximum CPU temperature (set in OCCT) of 75°C was reached in both instances. Hence the corresponding lines in the graphs reaches comparatively high temperatures and ends prematurely.

Larger air coolers from Gelid and Noctua plus two of the factory sealed water cooling products from AVC and CoolIT make up the second group. The air coolers peak at about 42°C, where the Gelid has a slight edge over its Noctua counterpart, with the AVC and CoolIT units performing in approximately the same range. It can be argued that the CoolIT Vantage ECO may perform better compared to the others at higher temperatures, since its integrated pump is controlled by a sensor close to the liquid coolant in the system. During the tests the pump was working at a relatively low speed, which could mean that the coolant was not hot enough for the pump to increase its rotation speed.

Higher temperature from the CPU would lead to higher coolant temperature, and could possibly mean that the product would close in on the next group.

The remaining factory sealed water cooling products, from Corsair and Antec, seem to have a considerably higher cooling capacity, and form a group of their own. Considering that all three products are developed by Asetek and have a very similar design, the results correspond well with each other. It should be noted that the Antec Kühler would have performed closer to the Corsair products if the fan had been installed in an intake position, where the air would travel forwards, instead of in the exhaust setup that was depicted in the manual of the product (see chapter 4.3).

A single system, the XSPC Rasa 750 RX240 kit, can be found even further down, rising to about only 31°C for the duration of the test, and thus forming the fourth and last group of the test.

Further tests were done using one additional DIY water cooling system, the Swiftech X2O-320 Edge, in comparison to the already tested XSPC Rasa 750 RX240 kit. Three tests were completed in this session, and the results can be seen in the upper section of Fig. 4-1. All three tests were done with the cooling systems placed outside the case, as the Swiftech system was unable to fit into the chassis. In this test the XSPC system measured about one to two degrees lower compared to the previous test, which is natural as the air in the room is a few degrees colder than the case air.

Still, the XSPC kit was outperformed by its Swiftech counterpart by quite a margin. However, the Swiftech radiator measured 360 mm, and three powerful fans were attached to it, making the system reach very high noise levels. Therefore a second test of this system was conducted, now with the fans installed to a fan control and the pump connected to a PWM control, reducing the noise considerably. In this test the Swiftech kit performed slightly better than the XSPC system regarding temperature levels, but were significantly quieter.

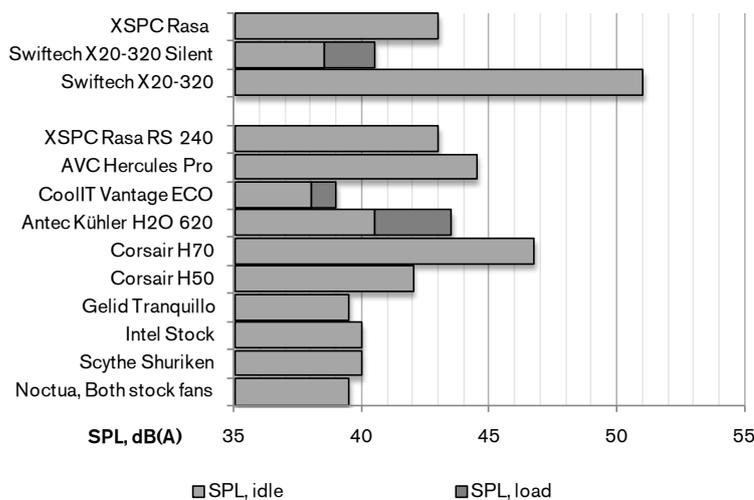


Fig. 4-2: Recorded sound pressure levels of the cooling solutions

The sound pressure levels reached by the different systems (Fig. 4-2) varied between 39 dB(A) and 51 dB(A). In this regard, the air cooling systems, the CoolIT and the second Swiftech configuration performed well, while the Corsair H70, the AVC Hercules and the XSPC kit performed significantly worse. Apart from the first, full power, test with the Swiftech, the H70 was loudest at around 47 dB(A).

Regarding the perception of the sounds, it can be noted that both the H70 and the Intel Stock fan was perceived to be louder than the chart conveys, while the H50 was perceived as rather quiet, considering the SPL.

4.2. COMPARISONS OF VARIOUS COMPONENTS

While all the components that are involved in the heat transfer have an impact on the system temperature (since the exit temperature of one subsystem is the entry temperature of the next), some are bound to have more impact on the total temperature difference through the system than others.

To assess the relative importance of the different components, several rounds of tests were performed with only one component changing between different test runs.

4.2.1. CPU WATER BLOCKS

In order to assess the importance of the CPU water block, five blocks from different systems were tested using the Swiftech pump and radiator. Since this pump is relatively powerful, this test is likely to favor high resistance blocks as the pump works near its maximum flow rate.

In the test, the Swiftech Apogee block performed extremely well, while the XSPC Rasa block barely out-performed the two Asetek blocks from the Corsair H50 and H70. With a temperature gap of more than five degrees to the H50, the block from the AVC Hercules did not perform very well under these circumstances (Fig. 4-3).

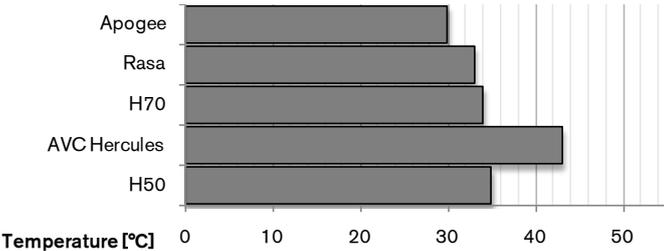


Fig. 4-3: CPU temperature with various water blocks

4.2.2. RADIATORS

The temperature difference span induced by the various radiators was, for the most part, very slim (Fig. 4-4). With the exception of the Magicool 280, all the radiators reached a maximum system temperature within a span of 2°C.

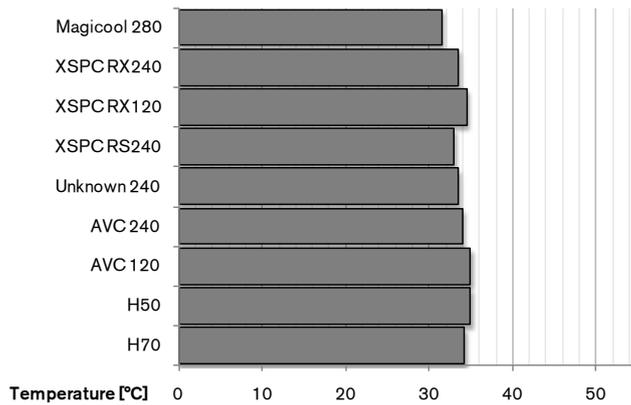


Fig. 4-4: CPU temperature with various radiators

4.2.3. FANS

As the fans is one of the active, noise producing, components in the cooling system, the main question to be answered by the fan tests were whether fans differed in the amount of air they could move through the radiator at a given noise level. Thus, the fan tests were performed at a constant sound pressure level, measured in dB(A).

All fans were tested with the total system SPL at 39 dB(A), then, if possible, at 41 dB(A). Several fans did not generate enough noise to bring the total value to 41 dB(A), even at full speed, and are therefore represented only at 39 dB(A) (Fig. 4-5). Apart from the AVC Hercules stock fans, all tested fans kept the system temperature within a two-degree span, both at 39 and at 41 dB(A).

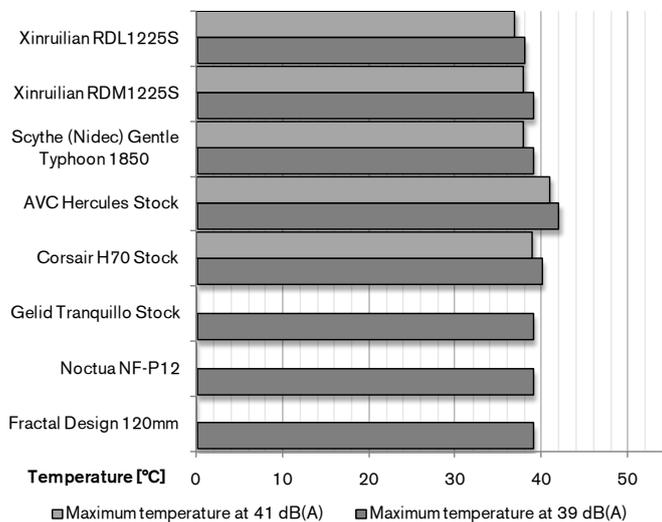


Fig. 4-5: Thermal comparison of fans, both at 39 and at 41 dB(A)

4.2.4. BRIEF EXAMINATION OF THE IMPACT OF TUBING AND LIQUID

Both tubing diameter and liquid choice were briefly examined using the same setup as in the block test. In these circumstances, using a relatively strong pump, neither the change to a considerably smaller tubing diameter nor using distilled water instead of the PrimoChill PC Ice coolant gave any significant impact on the resulting cooling performance (Fig. 4-6).

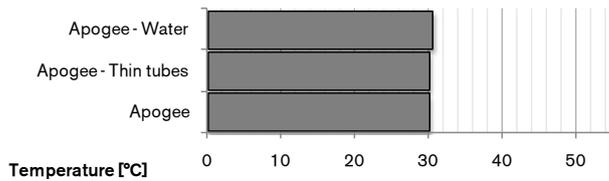


Fig. 4-6: Performance impact of using a different liquid and different tubing diameter

4.2.5. THERMAL COMPOUND

A thermal paste comparison test was executed to examine if any notable changes in CPU temperature could be detected when using different thermal compounds.

The thermal pastes included in the test (Fig. 4-7) were Arctic Cooling MX-2, Arctic Silver 5, Noctua NT-H1 and the Scythe-branded compound included in the Scythe Shuriken heatsink package. Out of these, it can be noted that the Arctic Silver has a recommended curing time of 200 hours, with a manufacturer specified temperature drop of 2-3° with fully cured compound compared to the temperature shortly after the application (Arctic Silver, n.d.). The Noctua and Arctic Cooling compounds are both specified as non-curing, while the compound from the Scythe Shuriken package had no specification.

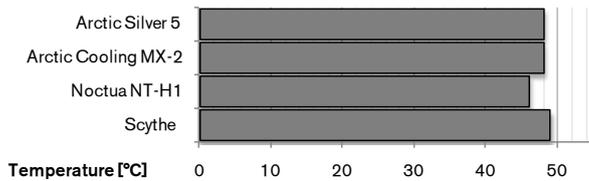


Fig. 4-7: CPU temperature with different thermal compounds

4.3. TESTING OF DIFFERENT FAN CONFIGURATIONS

The fan, or fans, can be arranged in a number of ways in relation to both the case wall and the radiator. In this report, the fan configurations are referred to according to Fig. 4-8. For example, if the fan is between the radiator and the wall, and pulls air from outside the case through the wall and then pushes the air through the radiator, this is called a push intake setup.

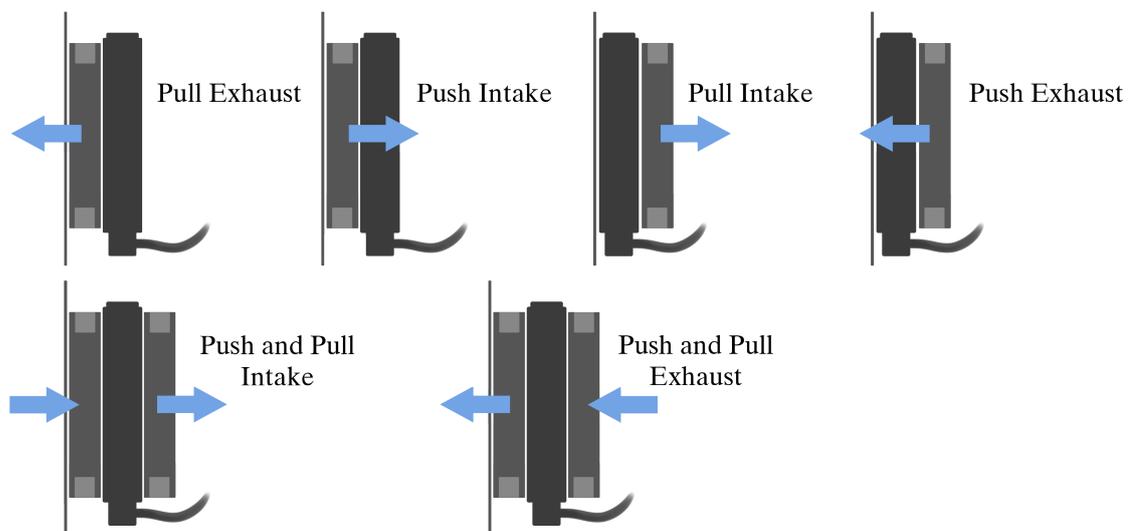


Fig. 4-8: Naming convention for fan configurations.

In order to assess whether the fan configuration matters for system performance and, if so, determine which configuration to recommend, all possible configurations were tested.

In the first test, the Xinruilian RDL1225S fans were used in both all the four single-fan configurations and both dual-fan configurations that keep the airflow from both fans in the same direction (Fig. 4-9). For each fan configuration, the voltage was set to keep the total system noise to 39 dB(A). At this sound level, two configurations stood out: Push and Pull Intake was slightly better, while Pull Exhaust performed significantly (around 4°C) worse.

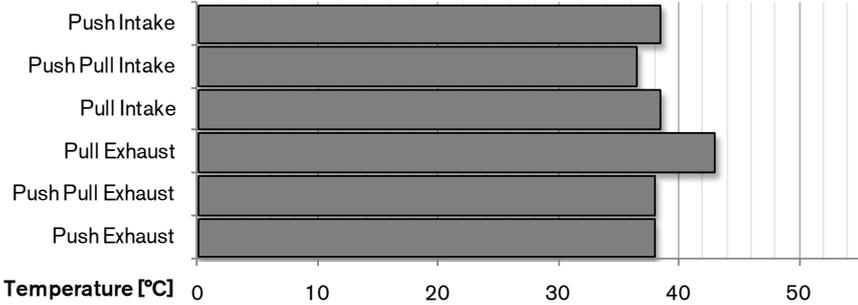


Fig. 4-9: The effect of fan orientation on temperature, with fan speed limited by SPL at 39 dB(A)

Since Pull Exhaust is the recommended configuration for the Antec product, the test was repeated with the Antec stock fan. This time, the tests were done at both 40 dB(A) and with the fan at full voltage. Using the Antec fan, pull exhaust was closer in performance to the other configurations in both the 40 dB(A) test (Fig. 4-10) and the full speed test (Fig. 4-11). However, just as in the test with the Xinruilian fan, it was the worst choice.

In both these tests, the two Intake variants (both Push and Pull) were better than the exhaust configurations and well within the error margin of each other.

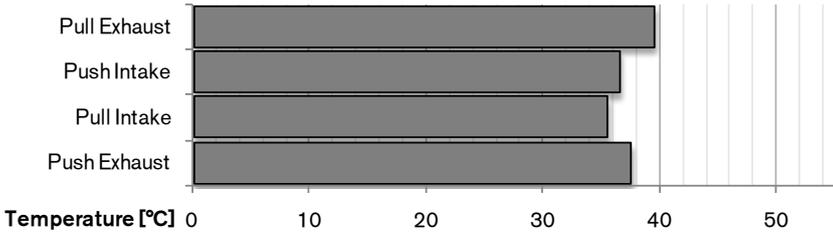


Fig. 4-10: Comparison between different fan configurations, Antec fan limited to 40 dB(A)

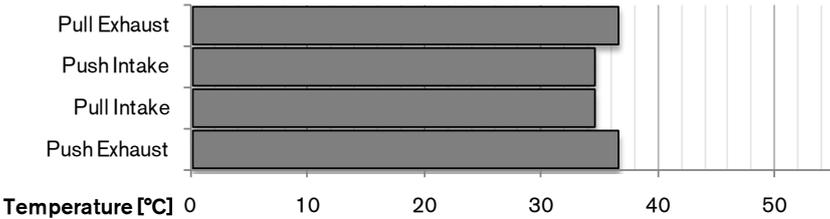


Fig. 4-11: Comparison between different fan configurations, Antec fan at full speed

However, in the full speed test, the sound pressure level differed quite audibly between the intake variants (Fig. 4-12): Push Intake generated a total system noise of 45 dB(A) while the equally well performing Pull Intake configuration only generated 42 dB(A).

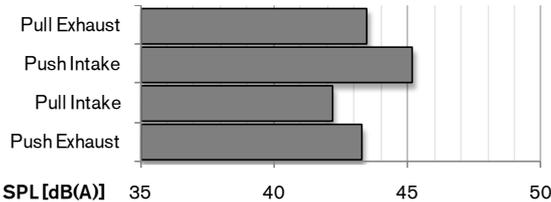


Fig. 4-12: Sound pressure level with the Antec fan at full speed in different configurations

Finally, tests were performed with and without a fan shroud, basically an empty frame that is placed between the fan and the radiator, which supposedly gives a more evenly distributed airflow. No significant differences were recorded in these tests.

4.4. SIMULATION TESTING ON HEATSINK FLOW DIRECTION

To help determining which flow direction to use in the block construction, top inlet, side outlets or side inlet, side outlet, simulation testing was performed using a simplified block model and the ANSYS software.

The tests were all performed using microfins, with the fin-channel width ratio at 0.7 and 3 mm fin height. The size of the simulated block was 20*20 mm, less wide than a CPU block, therefore the flow rate was set to 67 liters per hour, which would equal 100 liters per hour at a 3 cm wide block. The bottom of the block is 3 mm thick, and the bottom surface was subjected to 50W of heat. The thickness of the bottom block is likely much larger than optimal, as the temperature difference between lower and upper surfaces of the copper bottom is roughly half the total heat source to inlet temperature drop.

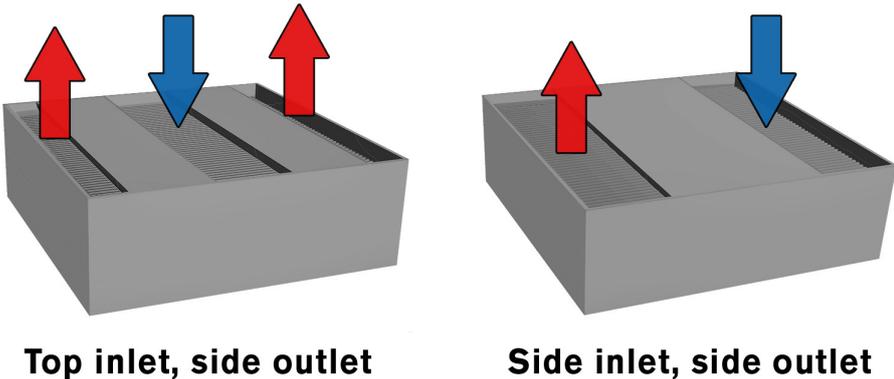


Fig. 4-13: Images of the simulation setups.

Inlet width was 4.8 mm in both test setups. The outlet in the side inlet setup was also 4.8 mm, while the two outlets in the top inlet setup were both 2.4 mm. Both setups are depicted in fig 4-13. All inner inlet and outlet edges were rounded with a 1 mm radius.

The pressure drop between inlet and outlet(s) compared to the difference between the area-weighted average temperature on the heat source surface and the inlet water temperature is shown in Fig. 4-14. Tests were conducted with 30 and 50 fins for both side and top inlets. In both tests, side inlet results in slightly better temperatures and considerably more pressure drop.

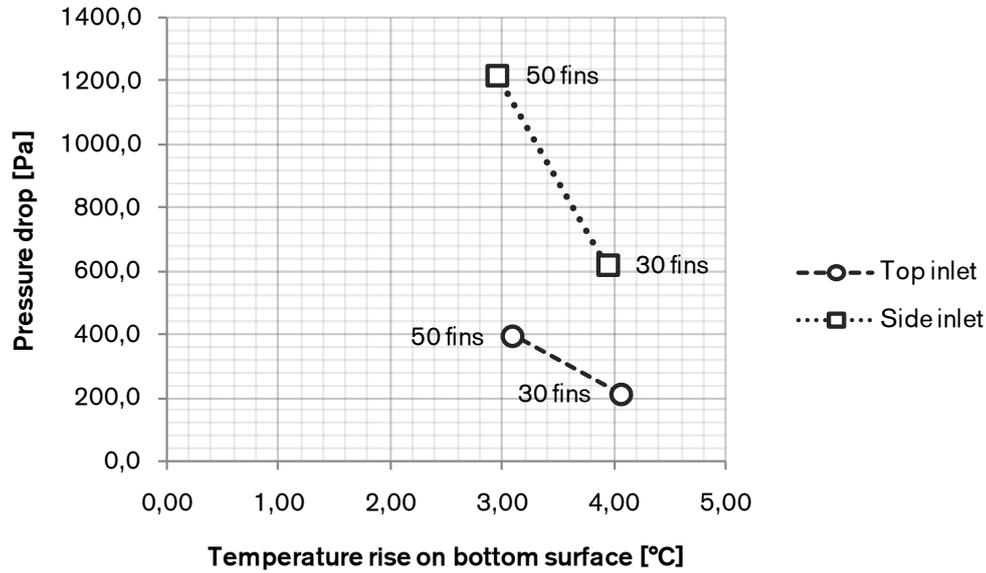


Fig. 4-14: Temperature difference versus pressure drop for the different inlet positions.

Several factors could be of importance to the results presented, including fin height, gap between fin ends and chamber wall, radius of rounded corners and inlet and outlet sizes, out of which the latter is deemed to be the most likely to have a large impact on the results.

In the simulations above, the inlet and total outlet areas remained constant, 4.8 mm wide. As the height of the fins is 3 mm, the outlet area, half the inlet area and the cross-section area for the heatsink are all very close in the top center simulation. In contrast, in the side entry block, the cross-section area of the heatsink is only roughly half of the inlet and outlet areas, leading to sudden contraction and expansion in the inlet and outlet areas, respectively.

As this leads to pressure loss, an additional simulation run was performed with a modified 50 fin side inlet model, which had 2.4 mm wide inlet and outlets. The inlet velocity was doubled to 0.4 m/s in order to keep the flow rate constant. This simulation did, however, result in a much higher pressure drop (1716 Pa) than either of those shown in Fig. 4-14 and a slightly lower temperature (2.86°C). This may, in turn, be due to the increased distance through the fins from inlet edge to outlet edge. Shortening the block 4.8 mm instead of increasing the length of the upper wall 4.8 mm may possibly yield a different result.

5. PERFORMANCE CONSIDERATIONS

In this chapter, the relevant aspects of each component will be discussed, based on testing and theory. For each aspect, pros and cons of different options are weighed against each other in order to make informed component choices.

5.1. RADIATOR

The radiator is mounted at the case wall, together with the fan (Fig. 5-1).

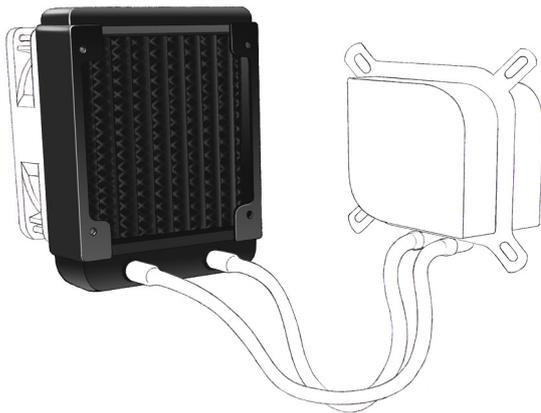


Fig. 5-1: System overview with radiator highlighted

In order to keep the difference between room temperature and water temperature low, the radiator has to be constructed from materials with good thermal properties and provide large surface areas for both water and air contact. It must also provide low resistance to both air and water flows. In Fig. 5-2, a sketch with the names used for various parts of the radiator construction is shown.

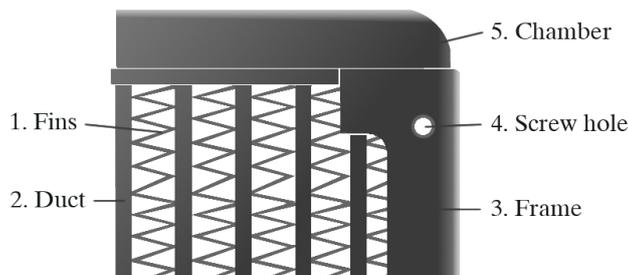


Fig. 5-2: Naming convention for radiator parts

5.1.1. RADIATOR SIZE

Since the radiator is to be mounted in a fan/radiator slot in the computer case, the size must conform to a standard fan slot size. Fan slots in computer cases are usually square and either 80 mm, 92 mm, 120 mm, 140 mm or 180 mm large. In modern computers, the fan slots near the top rear edge (closest to the processor) are usually 120 or 140 mm, with a single 120 or 140 mm at the rear panel and often a double 120 or 140 mm at the top panel. Thus, possible sizes for radiators in a CPU water-cooling loop include 120*120, 140*140, 120*240 and 140*280 mm.

A larger radiator gives the system a larger area to dissipate heat, which decreases the temperature deltas between both air and radiator and radiator and water. Out of these, the air-radiator delta is much larger, thus more important to optimize. A double radiator will, however, require two fans, which means that each fan will have to spin at a lower speed to keep the system noise level constant. Thus, the air velocity will decrease, which increases the air-radiator temperature difference. In the testing, see chapter 4.2.2, the temperature gain from a double radiator seemed to be around 1°C at the testing load and with constant sound level, a performance gain that can at most be considered moderate.

The choice between 120 mm and 140 mm wide radiators, single or double, mostly comes down to fan performance. In general, 140 mm fans will move more air at the same noise level than their 120 mm counterparts. 140 mm wide radiators do, of course, also give the system 36% ($140^2 * 120^{-2}$) more radiator area.

Taken together, a system with a 280*140 mm radiator will likely outperform a system with a 120*120 mm radiator with around 3°C at a load of 100W. However, such a system will not be possible to install in as many cases as the 120*120 mm one. Thus, offering the customers a few products with different radiator sizes may be the best option.

Radiators are also offered in a variety of thicknesses, mostly ranging from 25 to 60 mm. Thicker radiators often have much wider fin spacing in order to keep the air pressure drop at a reasonable level. Therefore, the thicker radiators outperform the more tightly spaced thinner ones at very low fan speeds, since the fans generate much less static air pressure at low speeds (less than 1000 rpm). However, at medium or high fan speeds, the wider spaced radiators typically perform worse than the denser ones.

Since good performance is most important under full load, when fan speeds below 1000 rpm are not sufficient to dissipate the heat with a reasonable temperature delta, a radiator with close fin spacing most likely gives the system the best overall performance.

5.1.2. FLOW VELOCITY AND DIRECTION

The heat dissipated from the water to the radiator itself has, as described in chapter 2.1, an almost linear relationship to the flow velocity. Thus, if the flow speed doubles, the temperature delta between the water and the radiator is cut in half. Therefore, once the temperature delta is small enough, the performance gain from increased flow becomes negligible.

For most radiators, this appears to occur around 100-150 liters per hour in both data released by radiator manufacturers and in tests by independent reviewers.

Thus, it is reasonable to either design the system around this flow rate, or to have a radiator with a much smaller water cross-section area, to reach the same velocity with a lower flow rate. Reaching the same velocity in a smaller cross-section at a lower flow rate will, however, increase the pressure drop, thus at least partly negating the pumping power gains from the flow rate decrease.

At 100 liters per hour, the temperature difference between inlet and outlet will be 0.86°C in order to transfer 100W in pure water (determined by using 5-1). Having a small

temperature difference between inlet and outlet is to be preferred, as this gives cooler water in the outer regions of the CPU block.

$$\Delta T = \frac{\dot{Q}}{c_p \cdot \dot{m} \cdot 1000} \quad (5-1)$$

Most radiators are double-pass constructions (Fig. 5-3), where the water can pass through half the ducts in one direction up to the top chamber, then through the other half down towards the outlet. Some radiators are, instead, multi-pass constructions, where the water will go up and down the radiator height more than once. Given the same cross section area for a single duct, this gives a much smaller total cross-sectional area, and thus much higher velocities. The high velocity, in addition to the much longer water path, increases total water resistance significantly.

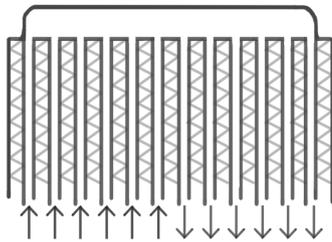


Fig. 5-3: Flow in ducts and upper chamber of a double-pass radiator

In addition, the number of ducts vary between different radiators, for example the AVC Hercules radiator have 18 ducts while the radiator from the Corsair H70 only has eight. More ducts give a larger pressure drop, presuming that the total cross-section area and thus the velocity is kept constant. However, more ducts decrease the width of the fins, increasing average temperature on the fins. It also increases the surface area of the radiator that is exposed to the fan slightly, thus increasing the air pressure drop, the air velocity and the sound level.

5.1.3. RADIATOR MATERIAL

The radiator consists, in essence, of three parts: the fins, the ducts, and the mounting frame. The material choice in the first two have different impacts on the heat transmissions, while the latter has no impact on the performance of the radiator.

Many radiator manufacturers use copper for the fins, which leads to better heat conductance through the fins for a given thickness, resulting in either a lower temperature drop between the ducts and the air contact surface or in thinner fins, which reduces the noise. However, the radiators supplied with all the pre-assembled systems tested in chapter 4.1 had aluminum fins, in all likelihood due to cost considerations.

The temperature gains to be had from using copper instead of aluminum is likely around 2°C (at 100W), while not having any detrimental effects on any other aspect of the product than the production cost. Thinner fins gives less flow resistance for the air and therefore decreases the amount of noise generated. However, the fins must be thick enough to transfer the heat from the ducts to the entire fin surface.

As for the ducts, most radiators, even those with copper fins, are equipped with ducts of aluminum. Most likely, this is because the difference in required thickness is not as relevant for the ducts, since the ducts will be fairly thick in either case due to their inner dimensions.

5.1.4. RESERVOIR

While DIY water cooling systems typically have specific reservoirs, the integrated water cooling solutions do not. Instead, these systems are built with as low permeability as possible in mind, especially regarding tubing choice (see chapter 5.6.2). However, no tubing is completely impermeable, thus some margin for water loss must be had. The part of the product where lack of fluid has the least adverse effects is the top of the radiator, in the chamber between the inlet and the outlet ducts. Therefore, in order to make choosing thin tubing walls possible, this chamber should not be too small.

5.2. WATER BLOCK

The block is mounted on the motherboard, with firm contact to the CPU (Fig. 5-4), and is one of the most critical components in a water cooling loop.

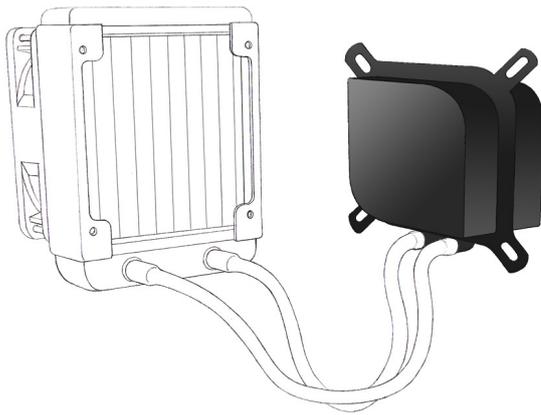


Fig. 5-4: System overview with block highlighted

5.2.1. MAIN BLOCK MATERIAL AND SIZE

In a three-dimensional heat transmission such as through the processor block, a large base thickness will result in a higher temperature delta between the top and bottom surfaces, while also resulting in a larger cross-section area and thus lower temperature deltas across the surface. This will result in an optimal thickness (for a given heat source and heatsink), through which there will be a temperature delta with the thermal conductance as the only variable.

As noted in 2.1, the two metals with the most relevant performance per cost properties are copper and aluminum. As the thermal conductance (k) for copper is nearly twice as high as for aluminum, the temperature difference between the CPU mating surface and the water contact area will be twice as high for aluminum compared to copper. As the temperature difference through the block is estimated to be in the order of a few degrees, this is a significant difference.

A combination of two different metals, such as the copper-plated aluminum on the AVC Hercules, serves no practical purpose, as the surface area material has no significant impact on the heat transfer to and from the block. Instead, this choice can, presumably, be attributed to the marketing value of a copper finish.

The optimal base thickness is bound to differ between different heatsink designs, but is relatively easy to determine by simulation. If it turns out that the ideal thickness is so thin as to possibly interfere with the strength of the material, calculations will be necessary to ensure that the block will be able to withstand the applied forces without significant deformation. In similar simulations, near-optimal fin height and fin length should be determined for the specific block design used.

There exists no industry standard for the size of the CPU block, and different manufacturers use differing sizes and shapes in their designs. What can be noted is that larger block areas will not necessarily improve performance, and may instead only serve to make the product more expensive, as copper has a relatively high price. A large bottom area of the block assembly, either from a wide copper base or from the upper block part may also interfere with tall capacitors on some motherboards and is therefore to be avoided. The block should, ideally, have at least the same area as the CPU IHS, to make sure the latter is fully covered and thus maximizing the mating area.

Depending on the material used in the mounting of the product to the motherboard, and the amount of force used to fasten the block to the CPU, it might be necessary to manufacture the block into having a slightly convex surface facing the CPU (known as a bow). This is both due to the slight bending of the block base when force is applied to the edges from above and on the middle from below, and due to the fact that the CPU IHS is not completely flat and commonly slightly concave. This could possibly make the block have slightly less contact with the CPU in the very middle of the IHS, directly above the CPU die where contact is most desired, impairing the over-all performance of the product.

Having the surface designed to be convex from the beginning prevents this scenario, but requires careful calculations and manufacturing. Possibly, the bow could result from the block assembly, if the center of the upper part is slightly below its edges.

5.2.2. FLOW THROUGH THE HEATSINK

There are two main variants in block design regarding heatsink water inlet position: flow-through, where the water enter on one side of the heatsink; and top centered, where the water enters from directly above the center of the heatsink and spreads toward the sides.

Out of these, the top centered variant has a small advantage in that the coolest water enters at the most critical point - directly above the processor. However, as the temperature increase in the water between inlet and outlet is very small compared to the difference between water temperature and copper temperature (a ratio of roughly 1:10), this is not of great importance.

For a given fin height and a given heatsink cross-section area, the velocity in a side inlet block will be twice as high on average, since only half the water needs to go through each half of the heatsink. This has a significant impact on both the heat transmission rate and the pressure drop, but the impact on temperature is only linear while the effect on pressure drop is squared (see chapter 2). Therefore, a block with top inlet will allow for a denser heat sink at a given pressure than the side inlet variant, which will have greater impact on the heat transmission through the increased surface area.

The simulation test conducted on inlet position, as shown in 4.4, appears to verify that the number of fins are more important for the heat transmission, while the pressure drop depends heavily on the inlet position. Therefore, a system with several outlets is to be recommended. It seems reasonable that having the flow pass only a quarter of the heatsink on each pass through the block would improve performance over pressure drop even more. However, the difficulty in accommodating the flow through such a block, as well as manufacturing limitations on the thickness of heatsink fins, makes the feasibility of this uncertain.

In the Asetek blocks, such as the Corsair H70, the flow follows another variant, which could be described as top flow-through. The flow comes from the top, but not at the center, with some of the water exiting the block against the main flow direction and then reentering it between the fins further from the center.

5.2.3. HEATSINK TYPE

For the heatsink, there are two main options: long thin fins or a matrix of pins (Fig. 5-5). For the pins, these can be of various shapes, see chapter 2.3. Since the flow through the heatsink is massively affected by many other parameters, such as the heatsink height, the position and shape of the inlet(s) and the outlet(s), a definitive answer to which kind of pin or fin shape which is optimal to use given certain circumstances is hard to achieve. Some basic simulation tests were performed as part of this project, but the results were at best inconclusive.

Neither principle (pin nor fin) seems clearly better than the other, which is reflected in the mix of solutions between the top-of-the-line water blocks available on the market. Given that the width of the pins is smaller than the space between them, which is usually the case, the area exposed to the water becomes larger with pins.

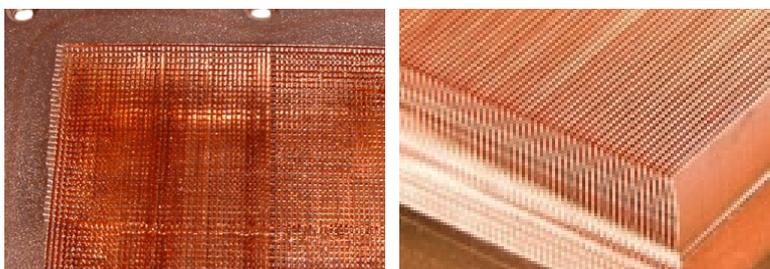


Fig. 5-5: Closeups of the Swifttech Apogee (a pin heatsink) and the Coolit Vantage (a fin heatsink)

When it comes to production, fins have a definite advantage. If machined, only half as many machining operations are needed, and fins can be created using other methods, such as skiving.

5.2.4. FLOW BETWEEN PUMP AND HEATSINK

To combine fins and a top centered inlet, the inlet must be very wide perpendicularly to the fins, otherwise the fins beyond the inlet will not have any flow. In order to get the flow from the pump into this wide inlet, without massive pressure loss, a chamber of some size must exist between the pump and the inlet. Such a solution, including the chamber in between block inlet and heatsink inlet, can be seen on the Koolance CPU-370 (Fig. 5-6). The main downside of this is that the overall height of the pump/block assembly increases.



Fig. 5-6: Injection chamber and injection plate of the Koolance CPU-370, seen from below
Image source: Skinnee Labs (<http://skinneelabs.com/cpu-370-review/2/>), cropped.

Since the chamber should be wider than both inlets, and since the pump impeller should be inserted from below but must have wider blades than the pump outlet, the upper part of the block cannot be manufactured as a single part.

5.2.5. HEATSINK SHAPE AND FLOW CONCENTRATION

While the IHS on most modern CPU:s is both square and large, the actual CPU die is much smaller and, on some architectures, the CPU die may not be square, such as on the popular Intel Core i7 series (Fig. 5-7). In order to provide the most effective cooling for i7 processors, several blocks, such as the Swiftech Apogee XTL, have rectangular inlets and a recommended mounting direction.

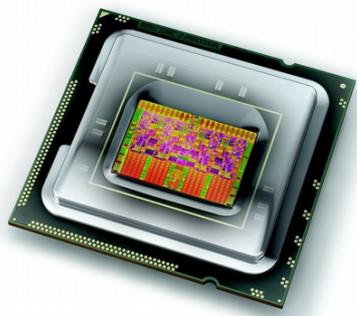


Fig. 5-7: The Core i7 CPU, with the die position superimposed on the IHS
Image source: http://www.xbitlabs.com/articles/cpu/display/intel-core-i7_2.html.

Thus, it is optimal to have the injection inlet in the same direction as the normal mounting orientation of the i7, which means that the inlet should be in the up-down direction inside the computer, thus perpendicular to any text on the outer shell of the product.

5.3. THERMAL COMPOUND

As mentioned in chapter 4.2.5, some thermal compounds require curing time for optimal performance. By adding the test data and the manufacturer temperature drop claims together, it seems plausible that the Arctic Silver compound will reach the same performance as the Noctua paste after curing. However, having that performance from the start must be seen as a significant advantage both for product reviews and for the user experience. It is very likely that the user checks the temperatures immediately after installing a new cooling solution, but much less likely that the user checks the temperatures again after 200 hours of computer use to form a new opinion.

Since the temperature gaps between the different compounds must be seen as significant, the thermal compound choice should be carefully made after a more thorough study than the time constraints of this project allowed. Apart from the thermal paste choice, the compound application also has a large impact on performance (Appendix A).

5.4. FANS

One of the components with most impact on the performance of the system is the fans. However, increasing fan power also significantly increases the noise level, as the fans are usually the main source of noise. The fan is mounted directly adjacent to the radiator, either with the radiator between fan and case or vice versa (Fig. 5-8).

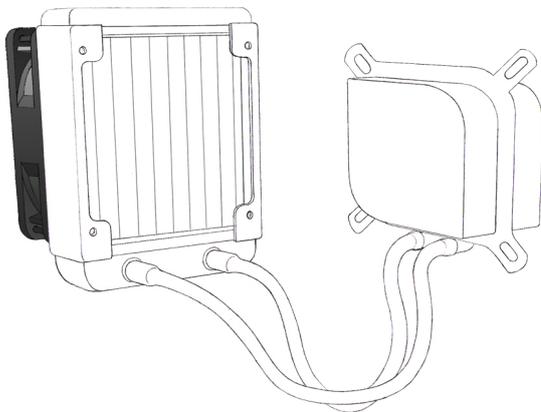


Fig. 5-8: System overview with fan highlighted

5.4.1. FAN MODELS

Computer fans are available with a wide range of specifications regarding static pressure, flow rate and sound pressure levels. Also, there are many fan manufacturers that claim significant performance or noise level gains from minor design changes, such as small notches on the fan blades.

According to the testing performed in 4.2.3, the difference between various fans when running at the same noise levels are, however, rather small, with the fans supplied with the AVC Hercules a notable exception.

Thus, the choice of fan brand and model seems remarkably unimportant.

5.4.2. NUMBER OF FANS

According to the tests in 4.3, there seems to be performance gains to be made by equipping the radiator with two fans in a push/pull configuration rather than just having a single fan, even when keeping the sound level constant and thus lowering the voltage of the individual fans. These gains are, however, rather small, and should be weighed against both the cost of an extra fan as well as the increased difficulty to fit and install the unit within the computer case.

It seems that most of the performance gain usually achieved with a push/pull configuration is due to the increased fan power and could instead be achieved with a single, more powerful, fan.

However, from the test in 4.3, there seems to be roughly a one degree performance gain to be had even with constant noise level, which may be interesting in a premium product variant where the maximum possible performance is desired.

5.4.3. REQUIRED AIR PRESSURE

The air velocity, when pushing 0.03 m³/s (65 CFM) through the radiator area (assuming 1/3 of the area is radiator water ducts) corresponding to the fan blade paths ($8.4 \cdot 10^{-3} \cdot \frac{2}{3}$ m²), averages at 5.5 m/s.

In theoretical calculation, at that speed and by modeling the radiator as 4 * 1 * 20 mm rectangular ducts, the pressure drop through the radiator is around 1.58 Pa (0.16 mm H₂O). As a reference, the Xinruilian RDL1225S, a fan with high pressure rating, is rated at 65.1 CFM and 2.6 mm H₂O, a considerably higher pressure (Xinruilian Science & Technology, n.d.). As with the pumps however, the fan will not deliver the maximum flow rate and pressure at the same time.

This supports a notable result from the fan testing, where there was no significant correspondence between rated static pressure and system performance, contrary to common expectations among customers.

5.4.4. FAN CONFIGURATION

When it comes to fan configuration, recommending the optimal configuration is important, as this increases the performance of the system remarkably without affecting cost or production methods at all. To make sure that the recommendations are sound, the results found in 4.3, where the pull intake configuration was clearly superior, should be confirmed by repeating the tests for a variety of different computer cases. Due to time constraints, this was deemed to lie beyond the scope of this project. However, the results are the same as those presented by Asetek (2011a), even though this is not the configuration recommended in all Asetek produced systems.

5.4.5. AUTOMATIC FAN SPEED

Since modern processor energy saving technology can vary the amount of energy consumed, and thus the amount of heat to be dissipated, by more than a factor of ten, having the maximum cooling performance at all times is not necessary. By decreasing pump and fan power while the computer is idle or under limited load, both the energy consumption of the cooling system as well as the noise level can be lowered.

This also enables better load performance as the noise level limit for full speed operation can be raised, while not changing the noise level for normal operation.

Several methods can be used to achieve this, including temperature sensors included in the cooling solution, PWM signals or voltage variation from the motherboard, computer software or physical user control (Appendix C).

5.5. PUMP

The pump is an important part of the product as well, as the pump strength determines the flow rate, and thus the velocity, in both the radiator and the water block. While doubling the flow rate roughly doubles the heat transmission rate (and thus cuts the temperature delta in half), doubling the flow rate requires eight times more pumping power. On integrated systems, the pump is usually part of the block assembly.

5.5.1. PUMP STRENGTH

As stated in the radiator section above (chapter 5.1.2), the benefit from increasing the pumping power is negligible once the temperature delta between the radiator and the fluid is small enough (roughly below two degrees). This, for most radiators, occurs around 100-150 liters per hour.

As the solid-fluid interface surface area in the block is so much smaller in the processor water block, it is unlikely that the temperature delta will be so small that the possible performance gain becomes negligible. However, as the block design supposedly is to be made specifically for this project, the block can be designed to have good heat transmission properties and a reasonable flow resistance at the expected flow rate.

The pumps used in all the tested liquid cooling systems were considerably weaker than those included in the DIY kits. While no specific pump testing was performed as part of this project, all other parts were tested at constant pump pressure, thus the remaining performance difference between the factory sealed and the DIY systems can likely be attributed to the pump, making it a significant contributor to the overall system performance.

The required pump pressure, at the specified flow rate, is equal to the total flow resistance of block, radiator and tubing. At 150 liters per hour, these are estimated to be around 4 kPa, 1 kPa and 1.5 kPa, respectively. Thus, to achieve a 150 liters per hour flow rate, the pump should be able to provide around 6.5 kPa at 150 liters per hour (the pump curve should pass through the 150 liter per hour / 6.5 kPa point).

Since none of the components are specified at this point, these values are estimated. The resistance in the pump and the block correspond roughly to published data on existing DIY components, while the tubing pressure drop is calculated with 8 mm ID tubing and two sharp 90° bends.

The numbers should, however, be sufficiently precise to serve as guidelines when choosing a pump from existing models. Then, once the pump, the radiator and the tubing

are chosen, the block can be designed in such a way that it has a flow resistance at the specified flow rate equal to the remaining pump head at that flow rate (having deducted the pressure drop from radiator and tubing).

Corresponding to the situation with fan speed control (Chapter 5.4.5), similar gains can be had from automatically changing the pump speed (Appendix C).

5.5.2. PUMP EFFICIENCY

Pump efficiency is a major factor for determining the total energy consumption of the cooling solution. Also, an efficient pump will generate less heat, which decreases the total heat that needs to be dissipated from the water block. The efficiency of a pump is not constant for all workloads, thus it is not only important that the pump will supply the required pressure at the specified flow rate, but also that the pump operates near its maximum efficiency at that flow rate.

While the pumps used in computer water cooling seldom generate as much noise as a few powerful fans, the pump could easily be the main source of noise in a system with slow or medium speed fans. Therefore, it is important to keep the sound pressure level ratings in mind when choosing pump.

5.6. TUBING

The tubes connecting the water block to the radiator (Fig. 5-9) has significant impact on the total flow resistance, and must also be bendable to facilitate easy installation.

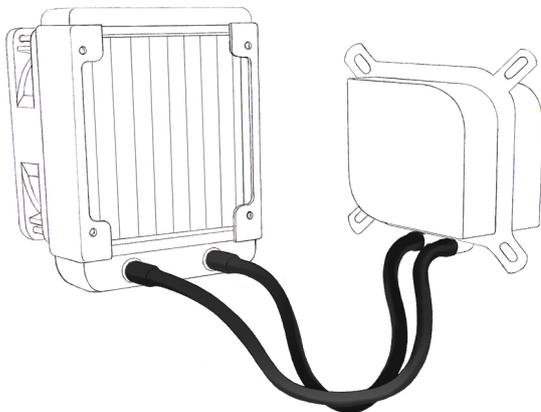


Fig. 5-9: System overview with the tubing highlighted

5.6.1. INNER DIAMETER

Due to the nature of flow resistance, a moderate increase in flow rate without changing the tubing diameter will result in a very large increase in the tube pressure drop. Therefore, in order to have a flow rate of 100-150 liters per hour, the inner diameter of the tubing must be larger than the 6 mm that the Asetek products use. In table 5-1, estimated total flow resistance for 50 cm of 6 mm, 8 mm and 10 mm ID tubing with 150 liters per hour flow rate is shown.

Table 5-1: Pressure drops through different tubing diameters with 150 liters per hour flow rate

TUBING ID	PRESSURE DROP
6 mm	3300 Pa
8 mm	850 Pa
10 mm	300 Pa

The AVC Hercules comes with 3/8" (roughly 9.5 mm) inner tubes, which decreases the pressure drop by about 550 Pa compared to 8 mm tubing (9% of the estimated total system pressure drop). However, this comes at a cost of more tubing material, more liquid, as well as possibly making the tubes harder to bend.

5.6.2. MATERIAL

For the tubing material there are two main design factors, the permeability and the stiffness. The requirements for low permeability are extremely high in this type of product, since the liquid loss over time must be really small. The requirements on the tubing are dependant on radiator design, as the top chamber where the ducts from the inlet and the ducts from the outlet meet is both the best and the most likely place for air to accumulate. This chamber is estimated to be roughly 13 ml (105 * 18 * 7 mm) on the radiator included on the Corsair H50, while the chamber on the AVC Hercules radiator is around 24 ml (108 * 22 * 10 mm).

A comparison of different plastic materials were made, the results of which can be seen in Table 5-2. From the table, it can be noted that while PVC is a popular material for DIY systems, not even the laboratory-grade Tygon R-3603 PVC compound is possible to use in this type of application as it would require centimeter-thick tubing walls.

Table 5-2: Required thickness of different materials in order not to lose more liquid than 10 ml over five years, using 50 cm tubing with an inner diameter of 8 mm. Sources: ¹ DuPont (2010), ² Saint Gobain (2011). The source data is water vapor transmission rate, measured according to ASTM E-96 test procedure.

COMPOUND	MATERIAL TYPE	REQUIRED THICKNESS (MM)
DuPont FEP	FEP	0.36 ¹
Tygon R-3603	PVC	11.02 ²
Tygon R-1000	PVC	19.46 ²
Tygon A-60-G	Norprene	0.74 ²
Tygon XL-60	Tygoprene	6.22 ²

Corrugated FEP tubing is used in many current sealed liquid cooling systems, including all products from both Corsair and CoolIT. These tubes, however, have a large drawback in their stiffness, which makes the cooling solution harder to install. In addition, they are corrugated on the inside, which results in a much higher pressure drop, in the order of three times as much as a smooth pipe with the same inner diameter. The thickness of the walls on these tubes is around 0.5-0.7 mm.

On both the Antec Kühler and the AVC Hercules, synthetic rubber is used. On the AVC, the specific material type is Norprene, which, as seen in Table 5-2, has roughly

twice the permeability of FEP. This is not a major problem, as a wall thickness of roughly 1 mm is still very thin. However, the tubing supplied with the Hercules has a 2 mm wall thickness, which must be seen as more than strictly necessary. The Norprene tubing has a tendency to fold when bent too sharply, which AVC counteracts by surrounding the tube with a metal spiral. On the Antec, a different, unspecified, compound is used, which is more flexible and less prone to folding (Asetek, 2011b). Overall, the Antec tubing material is deemed to be very suitable for the product category.

5.7. LIQUID

The coolant used in most factory sealed water cooling systems is a mixture of water and ethylene glycol, based on their thermal properties as well as being easy to attain and handle. Ethylene glycol is commonly used in fluid based heat transfer systems (MEGlobal, 2008), and although it is poisonous to humans if consumed, this will not be seen as an issue in this type of product. Ideally, the liquid would be non-conductive to prevent major damage to surrounding components if a leak were to occur. However, even if both distilled water and the ethylene glycol are essentially non-conductive, micro particles of copper or aluminum will spread throughout the liquid after being dislodged by the wear of the block and radiator.

The ethylene glycol is added to the water to prevent a build-up of algae and to prevent oxidation due to there being two different metals in the loop (copper and aluminum). As the system is closed, no exchange of water (which is a common method for avoiding these issues in a DIY system) is possible, which makes these measures crucial.

Several manufacturers sell specialized non-conductive fluids for use in water cooling, but these will, just as the pure water, become conductive due to the metal micro particles from block and radiator.

5.8. MOUNTING HARDWARE

Relatively high pressure between block and CPU is required for good thermal conductance, and high pressure also reduces the risk of an uneven installation, where the contact between block and IHS could, at worst, be at a single corner. However, too much pressure may damage the computer components.

Many manufacturers use different techniques for limiting the pressure, such as the limited threading on the Asetek screws. This needs to be done carefully, as the low mounting pressure is probably a significant reason for the mediocre performance of the tested AVC block, on which low pressure was evident based on the thermal compound spread.

A test was conducted with increased pressure on the Antec Kühler, simply by adding a second backplate that the screw threads entered after the first, basically causing the first backplate to act as a washer. This did not yield any significant performance increase, hence the mounting pressure of the Asetek solutions is deemed sufficient.

6. CONCLUDING REMARKS

As expected, while the performance of the system depends on all components involved in the heat transfer, a few components have a much larger impact than others. The most important components are the block, the pump and the combination of radiator size and fan speed.

Out of these, only the block design does not affect the sound level. There are several different types of heatsinks, but neither microfins nor micropins have a clear advantage over the other. The optimal dimensions of the heatsink elements seem to depend on several variables, most importantly the pump strength. For a fin array heatsink, a top inlet gives a much lower pressure drop while it has only a very small temperature disadvantage compared to a side inlet, flow-through, heatsink.

Radiator size mostly matters if the increased number of fans are all allowed to spin at the same speed rather than keeping the noise level constant. Otherwise, the decreased air velocity will partly neutralize the performance gains that were had from the increased surface area. Fan models and specifications seem remarkably unimportant when testing at constant sound level, but increasing the fan speed and thus also the system noise will decrease the temperature significantly. With automated fan control, this can be done automatically when necessary.

Another important factor to the system performance is the fan configuration. A good configuration can decrease both temperature and sound level significantly, compared to a less suitable one. However, recommending a configuration is difficult, as the optimal choice is bound to depend on the air flow through the computer case.

Further examination is necessary to determine the optimal heatsink geometry for use in different circumstances.

6.1. DEVELOPMENT POTENTIAL

Since several components can be changed for the better without apparent additional production costs, creating a competitive system on this market certainly seems possible.

To increase performance, such a system should, probably, use a top inlet position in the block. The flow rate should also be increased compared to the existing systems, partly by using a stronger pump than the ones used in the factory sealed water cooling systems available on the market today and partly by decreasing the flow resistance in both the tubing and the block.

For developing a competitive block assembly, CFD simulations is deemed to be a good approach.

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APPENDIX A. TESTING DETAILS

A.1. COMPUTER COMPONENTS

The components for the testing computer were selected mostly on basis of being reasonably quiet, in order to not interfere with the SPL measurements. A CPU with high power consumption was selected, as while the relationship between the temperatures of different products are expected to remain constant on different CPUs, the resolution of the reported temperatures is limited.

Table A1: Components in the test computer

COMPONENT TYPE	PRODUCT NAME
CPU	Intel Core i7-950 @ 3.07 GHz
Motherboard	Asus P6T Deluxe V2
Case	Fractal Design Arc Midi Tower (including Fractal Design fans, 3x140mm)
Graphics card	Radeon HD 5450
Power supply	Fractal Design Newton R2 800W
Hard disk drive	Western Digital 1600AVJS
RAM memory	Corsair 4x2 GB XMS3
Operating system	Windows 7 Professional 64 bit

To avoid differences in heat generation due to energy saving features, such as Intel Speedstep (Intel, 2004), those features were disabled before testing.

The coolant fluid used for both the DIY systems and for all component tests was PrimoChill PC ICE, apart from in the very limited fluid test.

A.2. SOFTWARE AND STATISTICS

To maximize the CPU temperature during a short time span, the software package LINPACK, originally used for solving linear equations, was used.

Temperature measurements were taken from the CPUs integrated sensors using Core-Temp (v. 0.99.8). These logs were then processed with Microsoft Excel, generating graphs and figures. OCCT (v. 3.1.0), a user interface for several testing algorithms including LINPACK, was used during the tests for a better overview and easier management. In OCCT the Test Type was set to Infinite and the Maximum CPU Temperature parameter was set to 75°C, of which the latter caused a few tests to abort due to insufficient cooler performance.

The load from OCCT decreased significantly for a short period roughly every five minutes, which leads to the temperature declines shown in the graphs.

A.3. SETTINGS

Since the processor generated enough heat to pass the 75°C limit with some heatsinks even at the stock frequency, and as the temperature deltas were reasonably large, no overclocking of the CPU was performed. The case fans were set to spin at reduced speed with a fan control, which was then kept unchanged throughout the tests.

All coolers were tested with their respective recommended settings and supplied components, such as fans and mounting hardware, with the exception of thermal compound (see A.5). In the main test, every product was tested twice, with re-installation and re-application of thermal paste in between, to make sure that reliable results were attained. The average measured temperatures of these two tests were then used for the comparison charts. During the product test, there were two tests (out of 24) where the test runs differed significantly, the cause was, however, visually identified in each case (wrong fan pin header for the pump and insufficient thermal paste). Therefore, after the full product test was completed, the part tests were conducted with only one test run each, but with careful visual inspection.

The tests were done with the products mounted inside the case and with all case sides closed, unless otherwise mentioned.

A.4. MEASUREMENT AND INSTRUMENTS

Between each test run, ambient sound pressure level (SPL) and room temperature were checked. SPL was measured both before, with the test computer off, and during each product test. The sound level measurements during the tests were taken with no audible sounds from sources other than the testing computer, apart from the ambient background noise, which measured 35 dB(A).

The instrument used was a Voltcraft SL-200, using the dB(A) setting. Both the SPL meter and the testing computer were placed in marked areas, 40 cm apart. The SPL meter was placed on a small tripod, 12 cm above the table surface. Measurements were taken with the meter at the “fast” setting.

Room temperature was measured before and after each test, using a standard electronic thermometer with two sensors, displaying both readings on a display. The sensors were placed close to each other and the computer air intake, then the room temperature was determined by using the average value. The temperature delta between the ambient room temperature and the temperature reported by the software was used in the product temperature comparisons rather than the reported temperature itself. All tests were conducted with a room temperature between 20° and 25°C.

A.5. THERMAL COMPOUND CHOICE AND APPLICATION

For the tests, the Arctic Silver 5 thermal compound was used. This compound has a recommended curing time of up to 200 hours, during which the thermal conductivity supposedly increases. To avoid having the curing time affect test results, all measurements were taken after the first start-up after the thermal compound was applied.

The compound was applied in an x-shaped pattern, with the thin lines covering approximately half the Integrated Heat Spreader (IHS) diagonally. Different methods of applying the compound were tested beforehand, and the x-shape method was deemed having a good spread with consistent results. With the compound in place the cooling product was attached to the CPU, the paste spreading automatically due to the pressure from the mounting. After each test, upon removal of the heatsink or block, the residual paste was examined to ensure that the spread was sufficient and that there was minimal extra compound between the heat source and the heatsink or block.

A.6. TESTING PROCEDURE

Before application of thermal paste, both the IHS and the heatsink block were cleaned with a cloth, dampened with a small amount of alcohol. After installation of the cooling system to be tested, the computer was booted and all diagnostic software was started. Other processes and background programs were kept to a minimum as to not interfere with the testing. Before LINPACK was started, the computer was left untouched for about three minutes, to make sure it was completely idle. During this time period the temperature logging via CoreTemp was initiated. After starting the test, CPU temperatures were regularly checked to ensure that no errors had been made during the mounting of the product. If the maximum temperature reached on the hottest CPU Core had remained the same for at least ten minutes, the test was considered to be finished. This resulted in different test session durations for different products.

When the tests were finished, LINPACK was shut down, and the computer was left idle to regain normal temperatures. The logs generated by CoreTemp were then transferred into Microsoft Excel, where different test sheets, depending on test type, had been prepared. This concluded the procedure, and the computer was shut down to allow installation of the next product.

A.7. NOTES ON COMPONENT TESTS

In the block tests, the block units taken from the factory sealed systems were connected to the other components by thin tubing, and their pump blade assemblies were left in place. Both these factors increase flow resistance, but the pump is presumed to be powerful enough to make these factors irrelevant. The pump electrics, including the electromagnets, were removed.

The radiator tests were done with a DIY system for easier installation and customization, which also reduced the time required to empty the system of liquid once a new radiator was to be mounted. The water block used in the tests was the XSPC Rasa previously used in the water block tests, and the pump/reservoir were the XSPC X2O 750. PVC tubing with ½ inch ID was used, except for the radiators from the factory closed systems, which required thinner tubing.

Both the radiators and the pump/reservoir were placed outside the case in marked areas, to make the installation and testing process more efficient. After installation of the system and the fans, and correct placement of all components was ensured, the SPL was measured to keep the different radiator setups at a constant level.

In the fan and fan configuration tests, fan speed, and thus noise generation, was controlled by setting the voltage using a standard PC fan control. For most fans, sound pressure level was strictly growing with increasing voltage. However, on the Scythe Gentle Typhoon, a higher voltage could result in a lower SPL. Thus, fan voltage was set to a high value and then decreased until the SPL was sufficiently low.

The TIM comparison was done with a Noctua heatsink (model NH-U12P SE2) and an attached Noctua fan (model NF-P12).

A.8. REGARDING RECORDED NOISE LEVELS

The contribution from different sound sources to the total measured noise can be seen in Fig. A-1, as measured with the Antec Kühler and the Xinruilian RDL1225S fan. Apart from the CPU cooling, no other component in the computer setup measures over 29 dB(A). For these measurements, the system was not under load, therefore the pump, which is temperature controlled, was very silent at roughly 27 dB(A). However, even with an increased pump speed, the pump is not likely to become a more significant noise source than the radiator fan.

With the fan at full speed, the total measured noise is 41 dB(A) including the background noise, out of which the fan contributes around 39 dB(A), making it the clearly most important contributing source. Measurements were also taken with the fan at a much lower speed, with the fan noise below 30 dB(A), in which case the total measured sound level was around 37 dB(A).

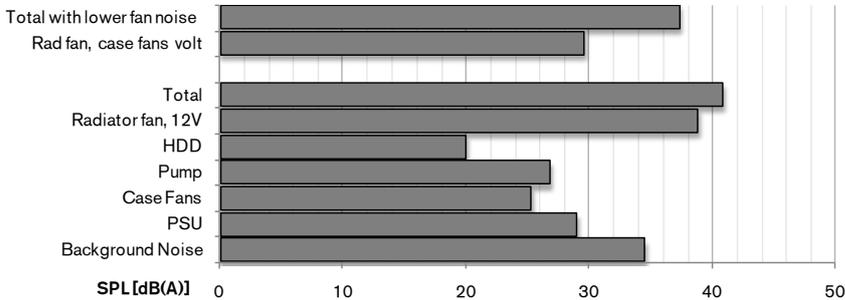


Fig. A-1: Estimated SPL of various sound sources

It could be noted that the noise level of many personal computers will not be as dependant on the CPU cooling method, as the other components used in the testing computer were chosen for their low sound pressure level ratings.

APPENDIX B. LINE GRAPHS OF TEMPERATURE

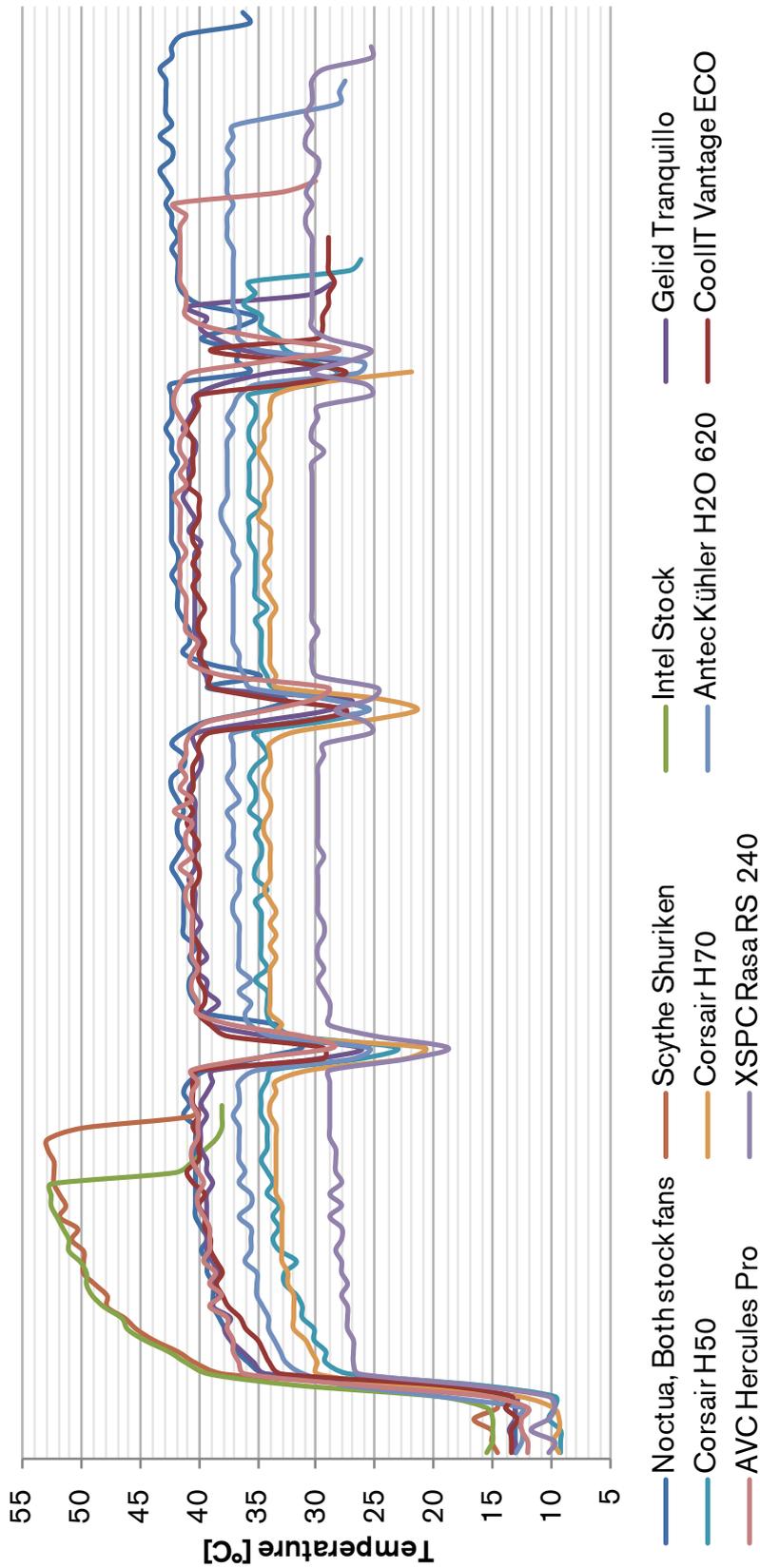


Fig. B-1: CPU temperature with different cooling solutions over time

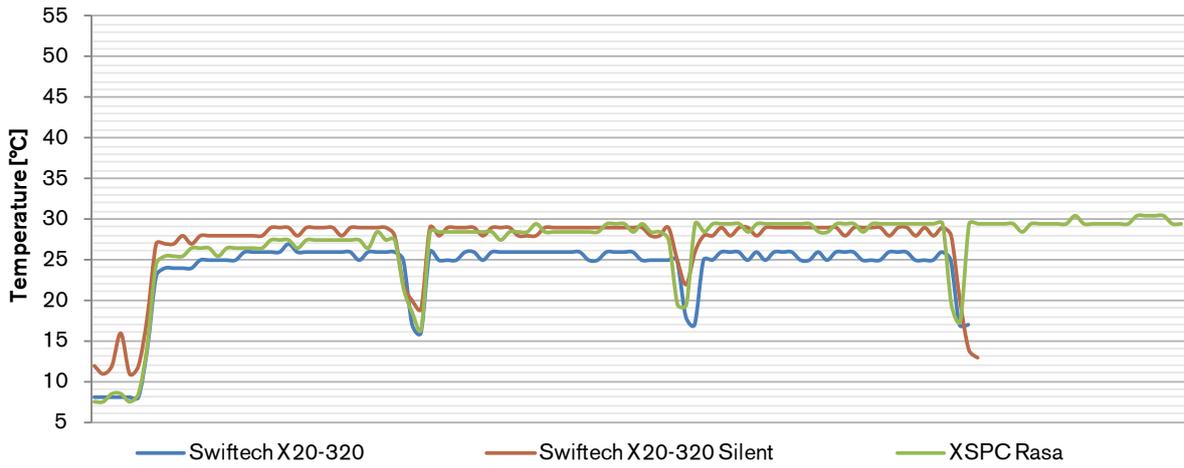


Fig. B-2: Temperature of the cooling systems tested outside of the case

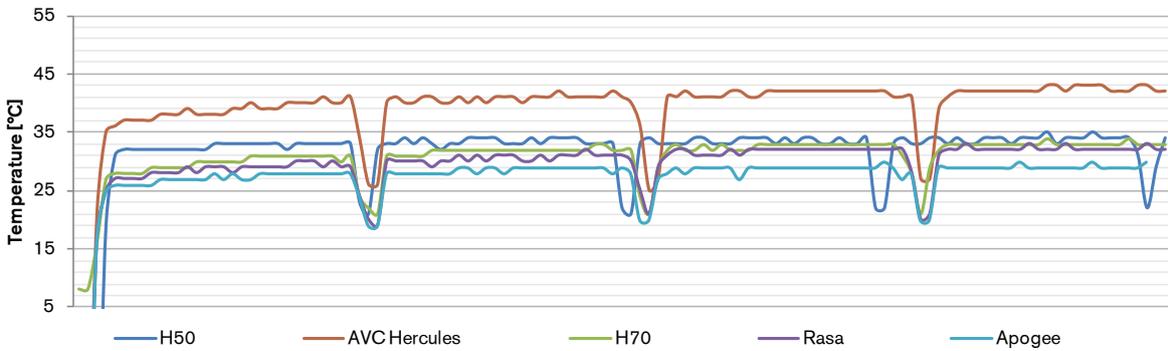


Fig. B-3: CPU temperature with various water blocks

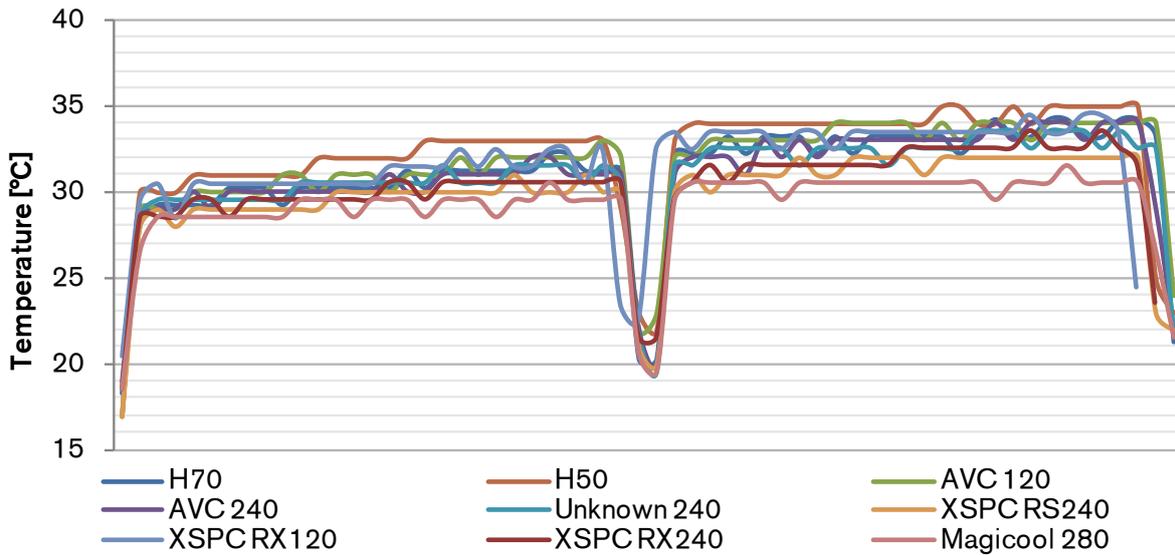


Fig. B-4: CPU temperature with various radiators

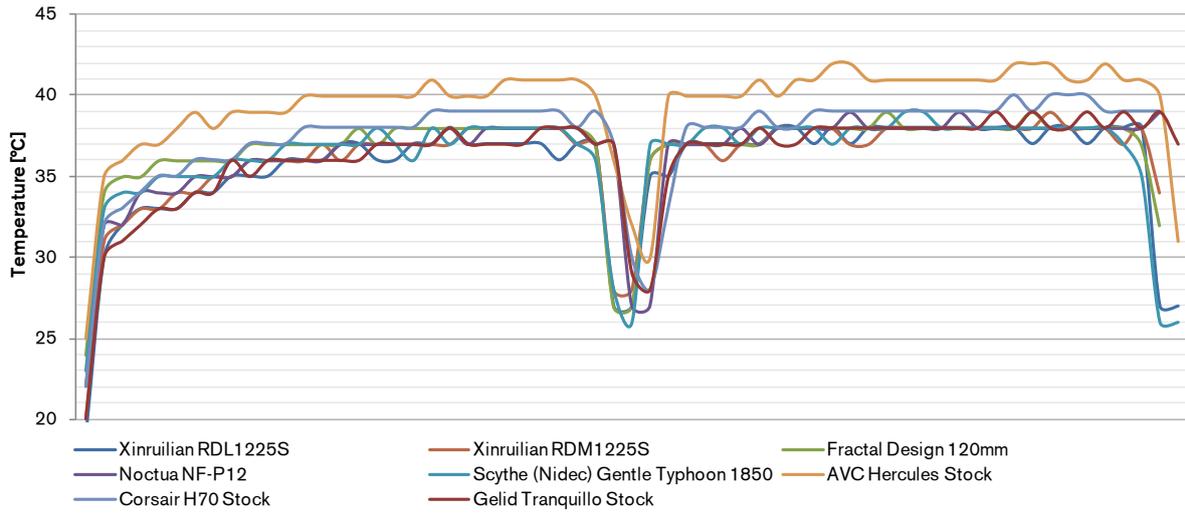


Fig. B-5: Fan comparison with 39 dB(A) constant SPL

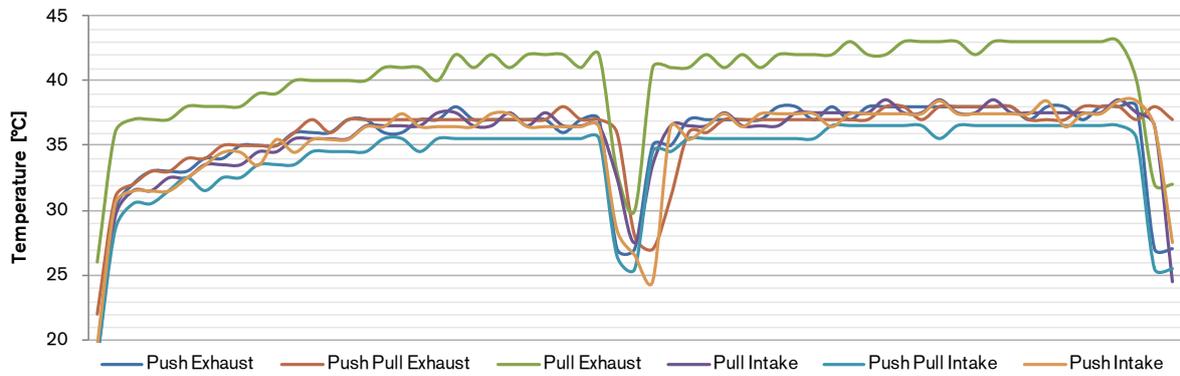


Fig. B-6: The effect of fan orientation on temperature, with fan speed limited by SPL at 39 dB(A)

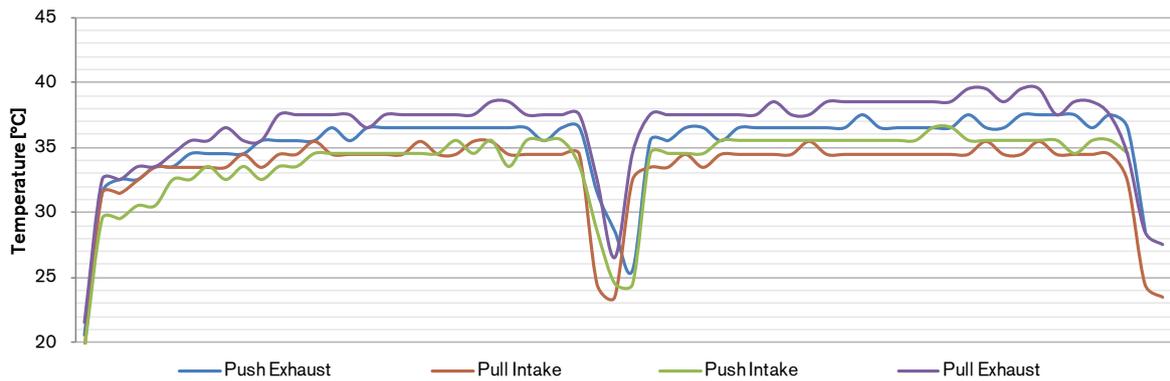


Fig. B-7: Comparison between different fan configurations, Antec fan limited to 40 dB(A)

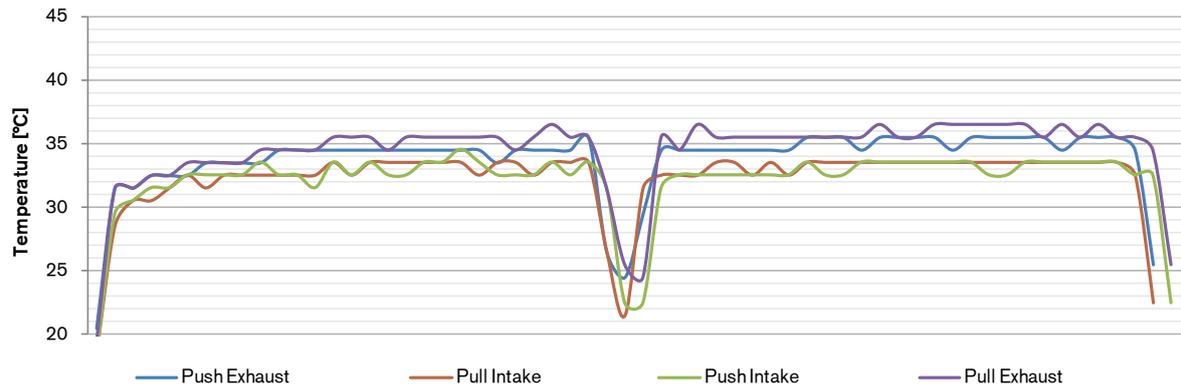


Fig. B-8: Comparison between different fan configurations, Antec fan at full speed

APPENDIX C. AUTOMATIC FAN & PUMP SPEED

C.1. BUILT-IN SENSORS

Including sensors in the product has one main advantage in that it comes with few requirements regarding the surrounding components, having only to supply the specified voltage. However, this does require extra components in the cooling solution (sensors, electronics), and the relationship between registered temperature and cooling power will have to be factory set. Such a solution could, however, include an adjustment knob or a switch between a limited number of different temperature-power relationship curves, allowing the user to adjust the temperature response according to his or her requirements.

The sensor can also be installed in different parts of the water block assembly. In the Coolit Vantage, one of the products tested in chapter 4.1, the sensor is placed near the water between the radiator and the pump, causing both a delay in the reading and large seasonal and/or regional variation. The real indicator of the amount of heat transmitted in the system are the temperature deltas, such as the difference between water and air temperature, rather than the specific temperatures. A temperature response curve created for 20°C ambient temperature will have the fans and the pump spinning at full speed when the temperature in the water reaches 30°C (10°C temperature delta), which means that in a 30°C ambient room the system will work at full power continuously, which is completely unnecessary. This variation, as well as the delay, will become less significant if the temperature is measured at the copper block surface instead, since the ambient variations become less significant compared to the much larger temperature delta between copper and air.

For a system with integrated sensors, the fan power cables must be connected to the pump assembly in order to control both pump and fan speed. This may be advantageous if executed well, but may be a disadvantage as well if connecting the fan cable directly to the motherboard is easier in the computer case. However, having some way that the fan cable can attach and run along the tubing and a fan header near the tube inlet/outlet would perhaps make the product better no matter what fan speed control variant is used.

In any case, using built-in sensors most likely requires the development of a custom circuit board for the pump.

C.2. MOTHERBOARD CONTROL

Modern computer motherboards have automatic fan control options that are based on the temperature readings from the processor itself. There are two kinds of fan headers in common use, the four pin PWM enabled header and the three-pin voltage variation header. On the three-pin header, the voltage of the positive pin varies depending on the temperature and the motherboard settings, usually between around 6V and 12V. There is, however, no established standard on the lower bound.

On the four-pin header, the positive pin always supplies 12V voltage, but there is a fourth pin (in addition to the fan speed reporting pin, the positive pin and the ground pin) that indicates the percentage of maximum speed that the fan (or pump) is expected

to run at. On most motherboards, the CPU fan header is four-pin while the case fan headers are three-pin. For a CPU cooling solution, using the CPU header is recommended as most motherboards have a start-up warning if it fails or is unconnected.

Using the motherboard signals has several advantages, including that it requires little extra materials, that the temperature readings are at the heat source itself and that many motherboards give the user good control over the temperature response. It is also likely that a standard circuit board for the pump can be used, perhaps even to control both pump and fans, presuming that the pump and the fans has the same voltage requirements for their respective desired speed/temperature curves.

The main disadvantage is that the user must select an appropriate fan control setting in the motherboards settings (the computer BIOS) upon installation, for which it is very difficult to supply good instructions as the procedure differs between different motherboards. If the user fails to do this, or if the motherboard does not support four-pin fans, the pump and the fans will constantly run at full speed.

C.3. COMPUTER SOFTWARE CONTROL

Computer software to control the fan speed could also be supplied with the product. This, however, requires both a data interface between the computer and the cooling system (such as an USB cable) and the development of decent multi-platform software, which the user will have to install. The temperature data could, in this case, come from either sensors built-in in the product or from the processor temperature sensors.

C.4. MANUAL CONTROL

Manual fan and/or pump control, either with a knob for the user to control the speed or with adapters setting the speed to certain levels, are cheap to produce but does not give automatic response to the computer load. While some users may prefer to manually set the speed to low during some computer applications, such as watching a movie, then manually turning it up before playing a computation-heavy game, it is presumed that most users would prefer automatic control. Since such options are cheap, it may be a good choice to include an adapter for lower speed in a kit designed for use with the motherboard signals.