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DESIGN OF A LIQUID REFRIGERATION SYSTEM FOR MICROPROCESSORS

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Abstract. *This work aims to present an alternative model of liquid cooling for microprocessors in desktops that is more efficient than the typical commercialized. From an experimental analysis it was possible to compare the temperature behavior of the processor using the liquid system with the conventional (air) system, under different conditions of request of the component. The described theme is very useful for users with problems of processor overheating, and presents a satisfactory result for solving the problem, with a temperature reduction of up to 24.7 ° C when overloaded.*

Keywords: *Cooling, Microprocessors, Temperature, Overheating.*

1. INTRODUCTION

Simultaneous to the technological advancement of processors, the increase of frequencies reaching large processing capacities, the need arises to maintain the appropriate temperature of its components. As processors improve their electronic appearance, they emit increasing heat fluxes across their surfaces, so there is a need to integrate cooling systems with processors.

Most computers have a cooling system on the processor, the source, and the video card. The processor cooling system consists of a cooler and a heat sink block formed by several fins. Cooler cooling systems perform heat transfer from the device to the medium and as a consequence, this type of system takes warm air to other components of the computer (SOUSA JUNIOR, 2009).

The heat generated by the components, mainly by the processor, needs to be dissipated to the outside of the cabinet. If this transfer process is not carried out properly several problems will arise, the main ones being the reduction of the processing power (locking of the operating system), the reset of the machine and damages to the electronic components of the computer shortening its useful life.

In the search for high performance, several scientific lines appeared with the objective of maximizing the heat exchange with a medium that had better convective properties than air. This led to the massive study of liquids as a possible source of microprocessor cooling. (PEREIRA, 2012), (SANT'ANA, 2016).

The purpose of the liquid cooling system presented is to better manage the heat of the components. At lower temperatures, the computer works even better in cases where the components are taken to the extreme. New studies are being developed in order to improve performance and optimize the proposed system (Sakurai, 2014) (THORÉN, 2011), (CARR, 2014), (KHONSUE, 2012).

2. DEVELOPMENT

The proposed design is one of the most popular cooling systems for high-powered computers. This system allows a better cooling of the components, allowing the processors to maintain high processing rates for longer, avoiding problems of damage.

Figure 1 represents a typical liquid cooling system for microprocessors, such a system is best detailed throughout this paper. The fluid used is distilled water, which, after leaving the reservoir, is pumped to a block of copper, which is located on top of the surface of the processor. The water gets colder in the block and after contact with the hot surface of the processor heats up leaving at a higher temperature. Subsequently the liquid will pass through the radiator where it will be cooled by the fan. After cooling in the radiator, the cold water returns to the reservoir and will cycle again.

As shown in Figure 1, the system is composed of the following components: heat sink block, responsible for heat transfer by conduction of the processor to the water. Radiator, responsible for transferring heat from water to the environment. To optimize heat dissipation, a fan is used which blows air at room temperature against the fins and ducts of the radiator. A common water reservoir, and a pump to force the circulation of water through a closed loop connected through silicone hoses.

The main advantage of a liquid cooling system is better component heat management. This system arose in order to overcome the limits of conventional air cooling, thus allowing a better performance of the components, achieving higher clock values in the different types of hardware.

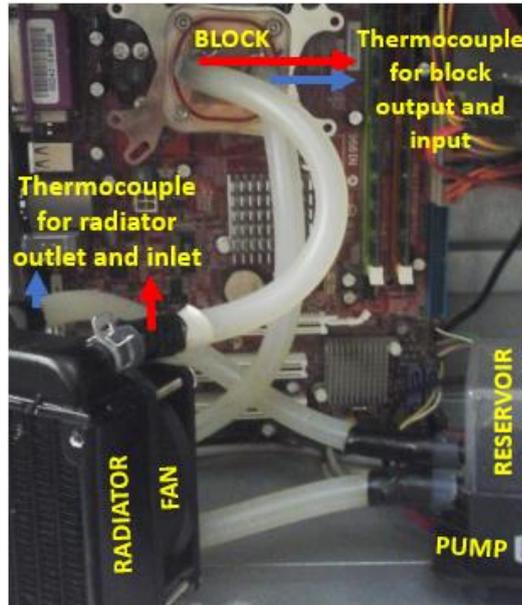


Figure 1. Cooling cycle installed

It is important to emphasize that during the whole experiment the radiation transfer was not counted. It is also expected that this condition does not significantly alter the results due to the low temperature.

2.1 Methodologys

2.1.1 Heat conduction

According to Incropera and DeWitt (2005), when talking about thermal conduction one must immediately consider the concepts of atomic and molecular activity. The conduction can be seen as the transfer of energy from the most energetic particles to the particles of lower energy, in a medium that has interaction between them.

It is possible to quantify heat transfer processes in terms of appropriate rate equations. These equations can be used to calculate the amount of energy being transferred per unit time. For thermal conduction the transfer rate equation for the one-dimensional flat wall is represented by Eq. (1).

$$q_x = -k A \frac{dT}{dx} = \frac{\Delta T}{R_{cond}} \quad (1)$$

Where \mathbf{k} represents the thermal conductivity of the material [W/mk]; \mathbf{A} is the area of the section through which heat flows by conduction (measured perpendicular to the direction of flow) [m^2]; $\mathbf{dT/dx}$ is the temperature gradient in the [K/m] section.

2.1.2 Convection

Natural convection is based on the movement of the fluid caused by the variation of its density due to a temperature difference. A fluid expands when heated and becomes less dense. By gravity action the lighter (less dense) fluid rises, this initiates a movement in the liquid called natural convection currents. Natural convection cooling is most effective when the fluid path is relatively free of obstacles, which tends to decelerate the fluid, and less effective when the fluid has to pass through narrow flow passages and along many obstacles.

The magnitude of the natural convection heat transfer between a surface and a fluid is directly related to the flow rate of the fluid. The higher the fluid flow rate, the higher the heat transfer rate. In natural convection, ventilation equipment

(fans and fans) is not used, therefore the flow rate cannot be controlled externally. The greater the temperature difference between the fluid adjacent to a hot surface and the fluid away from it, the stronger the convection currents and the higher the rate of heat transfer.

The convection heat transfer per unit of time between a solid surface at temperature T_{sup} and a fluid at temperature T_f can be calculated from Eq. (2).

$$\dot{Q}_{cv} = h \cdot A_s \cdot (T_{sup} - T_f) = \frac{\Delta T}{R_{conv}} \quad (2)$$

Where \dot{Q}_{cv} is the amount of heat absorbed by convection [W]; h is the convective coefficient of heat transfer [W / (m².K)]; A_s is the heat transfer surface area [m²]; T_{sup} is the surface temperature [K]; T_f is the temperature of the fluid, given in [K].

The value of h depends on the geometry of the surface and the type of fluid flow, among other things. Natural convection currents begin to laminate (smooth and orderly) and become turbulent when the size of the body is extensive and the temperature difference between hot surfaces and fluid is large. (Sanches Durval, 2005).

The coefficient h is a complex function of a series of variables related to system conditions and characteristics. So, h is a function of the type $h = f(D, \mu, c_p, \delta, V, g, \Delta T)$ where D is the dimension that dominates the convection phenomenon. Ex: diameter of a tube, height of a plate. μ is dynamic viscosity of the fluid; ρ fluid density; C_p fluid specific heat; k thermal conductivity of fluid; δ coefficient of volumetric expansion, V fluid velocity; g fluid velocity; ΔT temperature difference between surface and fluid

A formula that takes all these parameters into account would be extremely complex. The problem is then circumvented by dividing the study into particular cases. For each case empirical equations are obtained through the technique of dimensional analysis combined with experiments, where the film coefficients are calculated from empirical equations obtained by correlating the experimental data with the aid of dimensional analysis. The results are obtained as dimensional equations according to the flow regime.

2.1.3 Method of Effectiveness – NTU

In certain types of problem, it is desired to determine the heat transfer rate and the outlet temperatures of the hot and cold fluids for the mass flow rates of the fluids and the specified inlet temperatures, since the type of heat exchanger and its size is specified. That is, what is sought is to determine the heat transfer performance of a particular heat exchanger or to determine if an available heat exchanger can be used. (Çengel and Ghajar, 2012).

To eliminate a large number of iterations in the solution of these problems, in 1955 Kays and London presented a new method, called effectiveness-NTU, simplifying the analysis of heat exchangers. In this method, the heat transfer effectiveness is defined by Eq. (3).

$$\varepsilon = \frac{\dot{Q}}{Q_{max}} = \frac{\text{Actual heat transfer rate}}{\text{Maximum heat transfer rate}} \quad (3)$$

In which the actual heat transfer rate can be determined from the energy balance in the heat exchange, by Eq. (4).

$$\dot{Q} = \dot{m} \cdot C_p \cdot \Delta T \quad (4)$$

Where \dot{Q} is the absorbed thermal flow [W]; \dot{m} is the mass flow [kg / s]; C_p is the specific heat of the fluid at constant pressure [kJ / kg. K] and ΔT is the temperature gradient [K]. Meanwhile the maximum heat transfer occurs when the cold fluid is heated to the inlet temperature of the hot fluid or the hot fluid is cooled to the cold fluid inlet temperature. When the thermal capacity of the fluids is different, the fluid with lower thermal capacity will limit the heat transfer, so the maximum possible heat transfer rate is represented in Eq. (5).

$$Q_{max} = C_{min}(T_{h,in} - T_{c,in}) = \dot{m}_c c_{p,c}(T_{h,in} - T_{c,in}) \quad (5)$$

2.1.4 Radiator heat transfer

The convective coefficient of heat transfer in the radiator is estimated for air as well as it flows over the radiator tubes. Using Eq. (2) it is possible to quantify the cooling done by the cooler on the radiator.

According to the methodology of Çengel and Ghajar (2012), the first law of thermodynamics requires that the heat transfer rate of the hot fluid equals the heat transfer rate for the cold fluid. The following hypotheses were considered:

- There is no work performed by or about the system;

- Permanent regime;
- Variations of negligible kinetic energy and potential;
- Uniform properties;

Equation (4) describes the amount of heat per unit of time lost by the water circulating in the radiator. It is noted that the mass flow of both fluids as well as the inlet and outlet temperatures need to be determined for this analysis. Considering that the energy lost by the fluid (temperature drop) comes from the air-fan, it is possible to estimate the convective coefficient of experimental heat transfer of air according to Eq. (6).

$$h_{exp} = \frac{\dot{m}_{water} c_{p,water} (T_{in,water} - T_{out,water})}{A(T_{room} - T_{sup})} \quad (6)$$

Where h_{exp} is the experimental convection coefficient [$W / (m^2.K)$]; \dot{m}_{water} is the rate of mass flow through the radiator [kg / s]; c_p is the specific heat of the fluid at constant pressure [$kJ / kg. K$]; A is the peripheral area of radiator tubes also considering the fins [m^2]; $T_{in,water}$ and $T_{out,water}$ are the water inlet and outlet temperatures in block [K]; T_{room} is the ambient temperature of the air moving over the radiator [K]; T_{sup} is the tube wall temperature [K].

2.2 Experimental procedure

The proposed experiment is a comparison between the conventional (air) and liquid system. Processor temperature monitoring was done through thermocouples attached to the base of the component, capable of measuring the temperature under two operating conditions, simulating low and high processing load. It was also followed the temperature variation of the fluid (water) circulating inside the system in the points highlighted in Fig. 1.

To simulate situations of low and high processing load, CPU-Z® software was used for analysis of operating temperature for both systems. The experiment simulated operations where the processing was less than 10% of the maximum limit characterizing low load, and above 90% of the maximum limit for high processing loads.

The temperature variations presented at the inlet and outlet of the fluid in the radiator were collected in order to quantify the heat transfer on it. It was considered that all energy withdrawn from the water circulating inside the radiator through the fan happened by convection. From these considerations it is possible to estimate the efficiency of the heat exchanger in question.

According to (THORÉN 2011) it is possible to identify the arrangement of the fan that presents better performance for configuration of the air flow. This same setting is used in the experiment.

According to Incropera and De Witt (1996), heat transfer is the thermal energy in transit due to an imbalance of temperatures, the forms of heat transfer can be described by: conduction, convection and thermal radiation.

In the proposed project, experimental data (temperature and fluid flow) were collected to apply them in physical models to quantify the thermal exchange of the system. Thermal conduction Eq. (1) was considered for the copper surface of the block, and the thermal flux through the thermal paste film. The convection model (GARIMELLA, 2001) of colliding jets Eq. (7) for the fluid in the block is used.

$$Nu = 0,69Re^{0,555}Pr^{0,452} \left(\frac{L_n}{d}\right)^{-0,07} \left(\frac{D_e}{d}\right)^{-0,348} \quad (7)$$

The Figure 2 details the parameter parameters of the block used according to Eq. (7). L_n represents the height of the nozzle 25.1 [mm]; d represents the section diameter at which the fluid enters the block 9.4 [mm] and D_e is the effective diameter of the heat source 55.74 [mm] (not shown in the figure).



Figure 2. Dimensions of the cooling block

The cooling block in contact with the thermal paste is capable of transferring heat through its base and the fluid which maintains the flow through its interior. The thermal resistances of this set and its impact on the temperature of the processor are given as a function of Eq. (8).

$$T_{Processor} = T_{Water} + q(R_{cond,block} + R_{conv,liq} + R_{Thermal\ paste}) \quad (8)$$

The T_{case} represents the temperature measurement with the use of a thermocouple embedded in the center of the heat exchanger. The initial measurement is done at the factory. This temperature refers to the maximum processor "casing" temperature and is provided by Intel for each processor model in order to have an operating parameter. For the model used in the experiment is defined as maximum of 74.1 ° C. The experiment was performed using the Intel® Pentium® Processor E5400 (2M Cache, 2.70 GHz, 800 MHz).

In order to evaluate the consistency of the results regarding the data collection in the laboratory, three experiments were carried out under the same conditions and a statistical descriptive analysis for each experimental parameter and calculated: maximum processor temperature, thermal processor-block flow, heat absorbed by the radiator, convective coefficient and efficiency of the radiator. (GUEDES, 2008), (TOLEDO, 1985).

2.2 Analyzes and results

2.3.1 Processor

According to Figure 3, analyzing the curve described by the air system, in the initial 200 seconds the system was maintained with low processing load in order to obtain a balance of the system. From a certain point the surface temperature of the processor begins to increase until reaching maximum due to the requested processing load. Because the temperature recorded is above the limit provided by the manufacturer, it was necessary to reduce the stabilization time for component safety. The safety system of the component is responsible for the drop-in temperature at the instant of 450 seconds, as well as the reduction of its performance in that same time interval.

By analyzing the curve described by the liquid cooling system (Figure 3), in the first part of the experiment (up to 300 seconds) no processing load was applied, so the processor remained at a lower temperature. After a certain time (after approximately 320 seconds of measurement), a higher processing load was requested, a fact that justifies the increase in temperature.

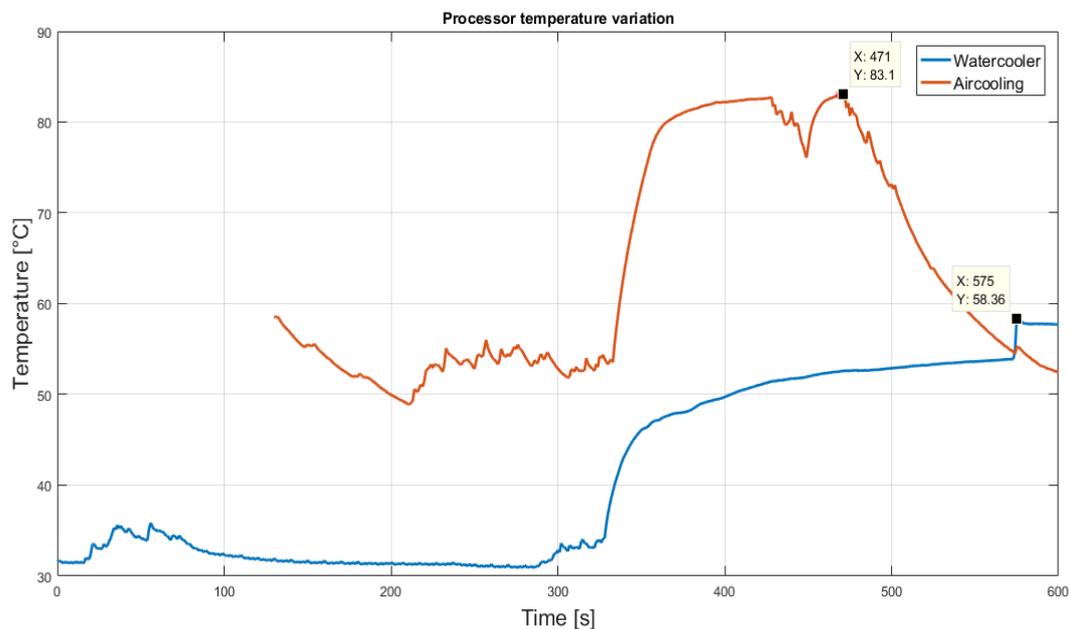


Figure 3. Processor temperature variation

2.3.2 Radiator

During the experiment the temperature variations of the cooled water were minimal. This is justified by the fact that the processor under test does not have a high thermal load sufficient to heat the fluid considerably. Figure 4 illustrates the variation of water temperature during the experiment. The red and blue color curves represent the input and output respectively.

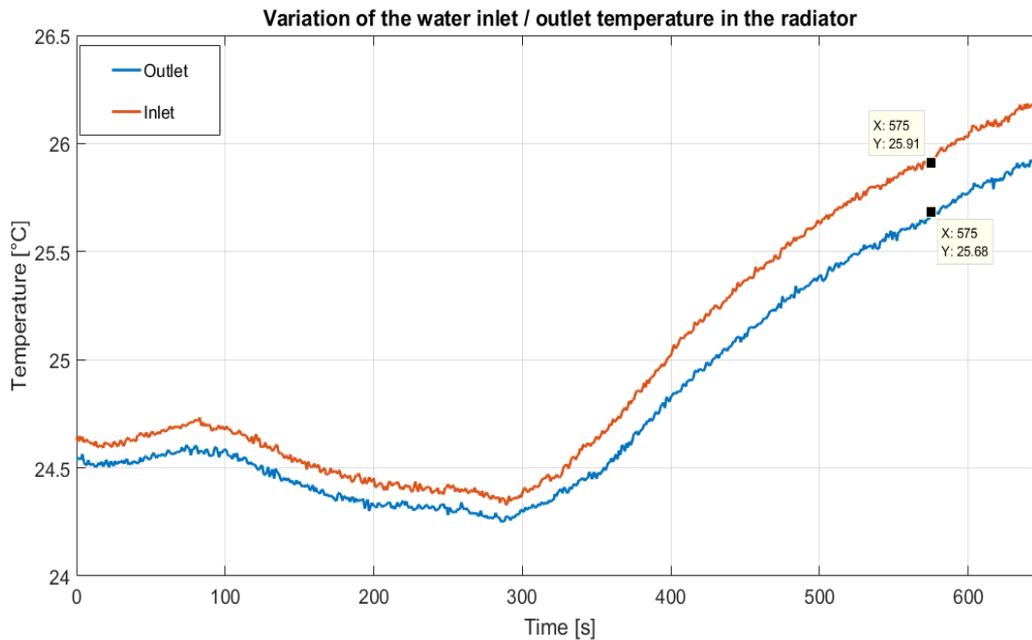


Figure 4. Variation of the water inlet/outlet temperature in the radiator

According to Figure 4 it is possible to identify the energy withdrawn from the system by the radiator at each instant of time. It was calculated from the instantaneous water temperature variation and so the heat can be monitored throughout the experiment. The highest heat removed, also characterized by the time when the highest temperature gradient was 106.23 W, while the average during the experiment was 86.47 W. Once the processor reached the highest temperature at the instant 575 seconds, according to Figure 3, the heat withdrawn at that particular time was 79.16 W.

To analyze the efficiency of the radiator, it was necessary to use the anemometer to identify the air flow velocity, and subsequently the air flow involved in the convection heat transfer process. Through a pachymeter it was possible to obtain the area of the radiator that was exposed to the forced airflow by the fan (fins and tubes). All these parameters are necessary to use the convection equation and are fundamental to determine an estimated convective coefficient for the forced flow through the fan.

In view of the surface temperature of the measured radiator tubes of 24 °C and ambient temperature of 17 °C, it is possible to calculate the data obtained described in Table 1. The values found below are related to the maximum heating point of the processor, the ones underwent significant variations during the experiment as a function of the measurement time.

Table 1. Radiator Measurement Parameters

Air flow	0,0176	kg/s
Thermal exchange area (tube + flap)	0,01	m ²
Front radiator area	0,0064	m ²
Airflow velocity	2,3	m/s
Convective air coefficient (h)	109,13	W/m ² . K
Efficiency of the heat exchanger	71,4	%

2.3.3 Block

Figure 5 represents the inlet and outlet temperatures of the water in the cooling block. Even analyzing a specific point (t = 575 seconds) it is possible to quantify the heat that the water absorbs according to Eq (4). Table 2 describes some calculated parameters.

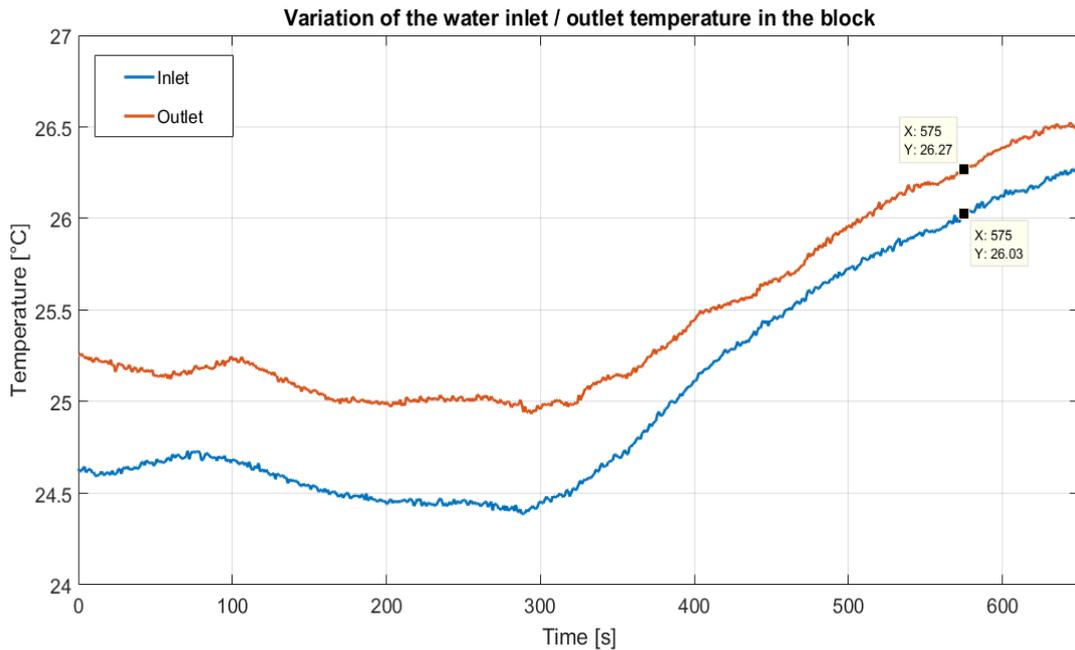


Figure 5. Variation of water inlet/outlet temperature in the block

In another analysis, using the equivalent thermal resistance method it is possible to quantify the thermal flow of the processor to the water. The thermophysical properties of air, saturated water and copper are specified according to Incropera (1996) at the respective temperatures shown.

Table 2. Parameters calculated for the block

Variables	Values
Reynolds [<i>Re</i>]	13162
Prandtl [<i>Pr</i>]	5,83
Nusselt [<i>Nu</i>]	148,7
Coeficiente convectivo jato [<i>h</i>]	9695
Thermal Resistance	
Block thermal resistance [K/W]	0,0025
Thermal grease resistance [K/W]	0,1361
Convection water heat resistance [K/W]	0,0421
Total equivalent thermal resistance [K/W]	0,1807

Thermal resistance related to thermal paste was calculated using the conduction heat transfer model, where a thickness of 0.5 mm was preset for a thermal conductivity of 1.5 W / m K according to the manufacturer Würth®.

The amount of heat calculated according to the equivalent resistance methodology quantifies the thermal flow from the processor chip to the water. This value is calculated according to equation (8). The maximum temperature of the processor measured by the thermocouple was 58.36 °C, by which time the average inlet and outlet temperature of the block was 26.15 °C, which results in a thermal flow ($\Delta T/R_{eq}$) equal to 178.3 W.

It is important to emphasize that the calculated values for heat and heat flux, despite being related, must be interpreted in a different way. The thermal flux, 178.3 W symbolizes how much heat is coming out of the processor housing and reaching the top surface of the block, that surface is in contact with water. The heat absorbed; 82.41 W means how much water absorbed from the thermal flow explained above. The remaining value (difference) was possibly dissipated by the walls of the block, and also heat exchange by radiation.

2.3.4 Cost

It is clear that liquid cooling systems, although more efficient in relation to the air cooler, are more expensive, most of the time the cost accompanies their performance.

According to Table 3, the cost analyzes were made for both processing situations, low and high load. In order to establish the cost benefit of both cases, a ratio of the total cost of the components of the liquid refrigeration system was made by the temperature difference of the component under the same processing condition for different cooling means.

Table 3. Cost benefit table for different refrigeration systems

Cost Benefit			
Cooling	Minimum temperature [°C]	Maximum temperature [°C]	Cost [R\$/°C]
Aircooling	45,59	83,09	24,15
Watercooler	30,89	58,36	14,35

The results have a lower cost analyzing the processor on higher work requirement. Therefore, the need for this type of system is relative, for users of high demand who tend to request their systems to the maximum or those who work in excessively hot environments, liquid cooling is a solution for maximum stability of the components. For users who need the quietest possible system, the almost always silent operation of water cooling is also probably the best choice.

2.3 Conclusion

It is concluded that the proposed liquid cooling system performed satisfactorily in what was expected compared to the conventional system (air), which is consistent with the objective of presenting an effective solution to overheating problems. For users who need high performance with high processing load the design presented is important in intermittent component temperature maintenance, which directly affects their performance and service life. It is still possible to further optimize the system described by testing new fluids, or even with programs of automatic pump activation / shutdown for certain situations in order to save energy at specific times. Regarding the cost-effectiveness of the liquid cooling system, for users who work with high processing loads the lowering of the maximum processor temperature will surely bring a longer useful life of the component that will compensate the initial investment made in this type of cooling.

3. ACKNOWLEDGEMENTS

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