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EXPERIMENTAL CHARACTERIZATION OF OPTIMIZED HEAT SINKS FOR COOLING OF COMPACT ELECTRONIC COMPONENTS

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Abstract. *This work presents an experimental characterization of the optimized heat sink obtained by a proposed design methodology based on the topology optimization (TO). An implemented TO software is originally applied to find the optimal geometric configuration of the cooling channels, which are constructed in a small scale dimension. CAD design, manufacturing, and testing of experimental prototypes are carried out to the optimized heat sink, which has been studied for water cooling of compact electronic components. The heat sink prototype is manufactured with EDM process (electric discharge machining) and precision CNC milling. The manufactured prototype testing is done with pumping of liquid (water) to the channels of the heat sink with flow rate controlled. The heat source to be cooled acts as microcomputer processor. Type K thermocouples and a Data Acquisition system allow monitoring the evolution of the temperature at different points along the cooling system in real time. The results are compared with a conventional heat sink (available commercially). This allows a comparison with the current state of the art.*

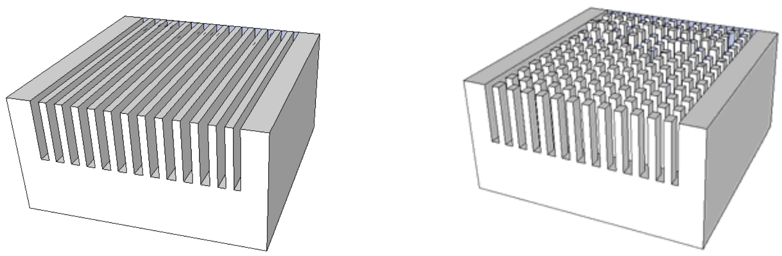
Keywords: *heat sink, small channels, topology optimization, experimental characterization*

1. INTRODUCTION

Small scale fluid flow systems found in microchannel devices have been studied over the last years as potential devices to make efficient the cooling of compact and powerful electronic devices. For instance, as a practical application, we can mention the heat sink devices for high-power LED’s (Light Emitting Diodes). This kind of LED is characterized by a high luminosity, which brings as a consequence, a high heat generation, which it is only removed by an efficient heat sink (Arik *et al.*, 2002). Another application, which is already present in some commercial products, is the water cooling systems for high-end microprocessors applied to high performance computers (Xie *et al.*, 1996). These components dissipate a large amount of heat, and need a very efficient dissipation system, to avoid malfunction or even product damage. As long as these microprocessors become more powerful and smaller, the need of efficiency in heat dissipation is even more highlighted.

As first demonstrated by Tuckerman and Pease (1981), reducing of hydraulic diameter of the channel can provide large convective heat transfer coefficient, and small mass and volume for a heat sink. Since then, microchannel technology has been studied over the last three decades as solution to increase cooling efficiency of microelectronic devices, which produces large amount of heat in a small area. In this last years, a large variety of possible micro scale enhancement structures has been studied for microchannel heat sink, such as parallel-plate fins (Fig. 1a), and staggered or aligned micro pin fin arrays (Fig. 1b). As demonstrated by many studies (Kawano *et al.*, 1998; Harms *et al.*, 1999; Lee *et al.*, 2005; Peles *et al.*, 2005; Kosar and Peles, 2006; Siu-Ho *et al.*, 2007), this enhancement structures have potential to remove high heat flux for a given volume of the heat sink and flow rate of working fluid, improving the performance of the heat-generating electronic component.

Some comparative studies have been carried out to investigate the thermal and hydraulic performance of these microchannel structures applied to heat sink design. For instance, Qu *et al.* (2008) and Jasperson *et al.* (2010) compared single-phase heat sinks constructed with both structures (micro pin fins and microchannel parallel fins) and have been found that the microchannel heat sink has a higher convection thermal resistance with a lower pressure drop at high cooling flow rates. An effective design and a performance assessment of a micro pin fin heat sink require a fundamental understanding of the complex nature of the fluid flow and heat transfer aspects of micro pin fins arrays. Renfer *et al.* (2013) investigate and illustrate the potential benefits of vortex shedding from micropin fin arrays for an integrated chip cooling. They show that the vortex shedding can produce enhanced mixing and heat transfer, however it can increase the pressure drop, thereby requiring a trade-off in the design of such cooling device. Kosar and Peles (2007), and Liu *et* *al.* (2011) investigate the pressure drop and heat transfer of cross flow over various micro scale pin fin heat sinks formed from a range of shapes, spacing, and arrangements. They conclude that the decision for using micro pin fin device is dependent on the applied performance evaluation criterion, as well as on the hydrodynamic conditions. Moreover, large spacing between pin fins and inline configurations results in lower heat transfer coefficients compared to densely populated and staggered arrangements.



(a) (b)

Figure 1. Enhancement structures for microchannel heat sink: (a) parallel-plate fins; (b) micro pin fins array

Therefore, in order to achieve better heat sink designs, it is crucial that these cooling systems have a very efficient fluid flow channel, which can be obtained by minimizing pressure drops along its extension (Qu and Mudawar, 2002). Thus, given the great potential applications inherent to microchannel devices, it is natural to aim for an optimization study in this field.

Design optimization studies have been investigated by many researchers to determine the geometric dimensions of microchannels that give optimum performance for a heat sink device (Knight *et al.*, 1992; Liu and Garimella, 2005; Li and Peterson, 2006; Shao *et al.*, 2007). In general, these studies have been carried out by using numerical analyses of the fluid flow and heat transfer in microchannels together with a parametric optimization scheme to find the optimal cross-section parameters of the microchannel heat sink.

Borrvall and Petersson (2003) gave the first steps on the application of the Topology Optimization Method (TOM) for minimum power dissipation in fluid flow channels, comparing its results with the previous Pironneau’s results (Pironneau, 1973), which considers shape optimization of minimum drag profiles under a Stokes flow. The main advantage of the TOM is the capacity of distributing material freely, inside a design domain, and systematically searching for the best-performance topology (Bendsøe and Sigmund, 2003). Besides the fluid flow problem, another field of interest to be considered in the heat sink design is the micro scale heat transfer problems. Donoso and Sigmund (2004) have applied TOM to analyze multiple physics design problems that can be described by Poisson’s equation, giving new physical insight for applying optimization in heat transfer problems.

However, few works have explored TOM applied to fluid flow and heat transfer coupled problems. Okkels *et al.* (2005) have also added the temperature field in the topology optimization Navier-Stokes flow problem, however, no more details are given about how the material model relates the design variable with the physical properties of the material in the heat dissipation problem. Yoon (2010) also studies the heat dissipation effects over the structure design, by using TOM, in which a thermal compliance minimization is considered as cost function. Recently, Koga *et al.* (2013) propose a complete cycle of development of a heat sink device designed by using TOM, in which an optimized solution for channel structure is obtained to attend a multi-objective optimization problem that involves minimization of the pressure drop of fluid flow, and maximization of the heat dissipation along the channel.

Thus, the objective of this work is to carry out an experimental characterization of the optimized structure obtained for heat sink through the design methodology proposed by Koga *et al.* (2013). CAD design, manufacturing, and testing of experimental prototype are carried out to the optimized heat sink, which has been studied for water cooling of microprocessor of high-end computers. A comparison between the manufactured prototype of the optimized heat sink and the conventional based pin-fin heat sink (available commercially) is also shown.

This work is organized as follows. In Section 2, the topology optimization algorithm and the main characteristics relevant for heat sink design are introduced. In section 3, the experimental apparatus applied for prototype characterization are described. In Section 4, the experimental characterization results are presented. Finally, in Section 5, some concluding remarks are given.

2. HEAT SINK DESIGN

The Topology Optimization Method (TOM) is a robust and efficient numerical method for obtaining the optimal distribution of a limited amount of material inside the design domain, by adding or removing it freely, aiming for an optimal design topology (Bendsøe and Sigmund, 2003). In this work, the synthesis of heat sink design is carried out by using a topology optimization (TO) algorithm developed in Koga *et al.* (2013), which aims to maximize heat transfer

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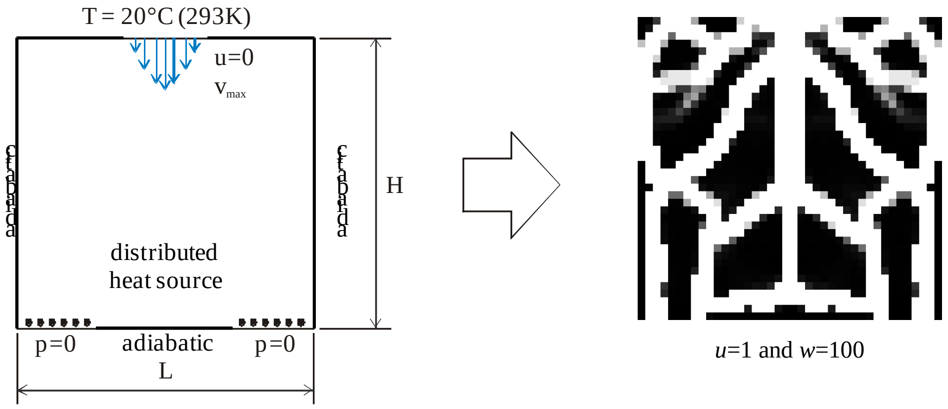
with minimum pressure drop in the heat sink design. Thus, the topology optimization problem is described as minimizing a multi-objective function, which combines two objective functions (pressure drop minimization and heat dissipation maximization), subjected to the fluid flow and heat equilibrium equations. The topology optimization formulation, as well its numerical implementation to solve the problem of finding optimum layout configurations for the heat sink design can be seen in Koga *et al.* (2013).

A multi-physics optimization is performed, considering the viscous effects of fluid and heat transfer inside the entire domain (solid and fluid regions). In the optimization process, water and Aluminum physical properties are considered. A square design domain (L = 1, H = 1), shown in Fig. 2a, is adopted as a guidance for the heat sink design, in order to evaluate the TO algorithm. At the top of this domain, it is applied a parabolic inlet velocity profile. A heat source (175 kW/m^2) is uniformly distributed all over the design domain, which has two null pressure outlet regions at the bottom. All the others external sides of the domain are prescribed with non-slip adiabatic boundary conditions.



(a) (b)

Figure 2. Topology optimization result for the heat sink design (Koga *et al.*, 2013): (a) design domain with boundary conditions; (b) result obtained for inlet velocity v_{max} = 0.25 m/s

In this multi-physics optimization, the factors *u* and *w* are applied for weighting the influence of both optimization problems (pressure drop minimization and heat dissipation maximization) through the multi-objective cost function (Koga *et al.*, 2013). The parameters that control the optimization process are q, p_1, p_2 and p_3, which are the penalty factors for the fluid flow optimization, heat conductivity (k), specific heat (c_p) and material density (ρ_m), respectively. Considering a maximum parabolic inlet velocity equal to v_{max} = 0.25 m/s, the topology obtained is shown in Fig. 2b, for q = 0.01 to 0.1; p_1 = 1 to 2; p_2 = 1 to 2 and p_3 = 1. According shown in Fig. 2b, as the method needs the fluid flow layout to maximize the heat transfer, the algorithm tries to increase the heat exchanging area by increasing the number of small channels. Some regions arise between these ramifications generates a kind of "heat islands" formation that remove and distribute the heat for the entire domain, taking advantage of the fluid flow.

Thus, the heat sink prototype has been designed and built considering the geometry of channels suggested by the obtained result, shown in Fig. 2b. A post-processing, based on the use of spline curves with the aid of a CAD software, has been done for geometric model (3D) based on the optimal topology obtained by the TO algorithm. The geometric CAD model obtained by this post-processing is shown in Fig. 3, which also shows the solid and fluid domains.

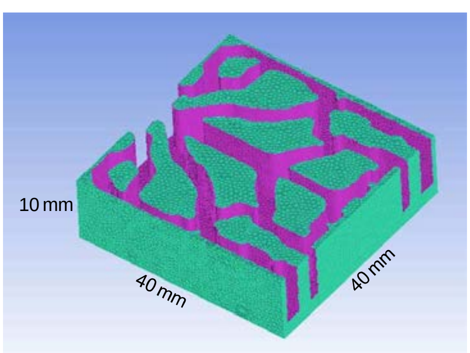


Figure 3. Geometrical model of the optimized heat sink

Manufacturing prototype of the heat sink based on optimized channel design is also carried out, in which the main body of the heat sink prototype is treated as a block of 40x40x10 mm made of Aluminum. It is observed that these dimensions are the same adopted in commercial water blocks (heat sinks with pin fin structure), used for the water cooling system of the high-end microcomputers. In this case, the temperature distribution along the flow is analyzed by evaluating the performance of the heat sink prototype. This prototype has a polycarbonate cover plate, as shown in Fig.4, and two metallic inlet and outlet small tubes. The heat sink prototype is manufactured by electrical discharge machining (EDM) and precision CNC milling.

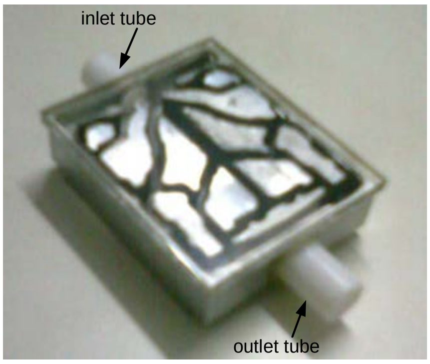


Figure 4. Manufactured heat sink prototype

3. EXPERIMENTAL APPARATUS

An experimental characterization of the heat sink with optimized channels is carried out to verify the results obtained through the topology optimization. The manufactured prototype is tested in an experimental apparatus built to supply water to the heat sink at the desired flow rate. A schematic draw of this experimental apparatus is shown in Fig.5. Basically, this apparatus consists of a water reservoir, a small flow pump, a mechanical control valve, a rotameter flowmeter, a differential pressure gauge placed between the inlet and outlet of the heat sink prototype, type K thermocouples, a voltage regulator (VARIAC), a heat exchanger (radiator with fan), and a heat source device (block of metal with a cartridge heater) designed for simulating the microcomputer heating.

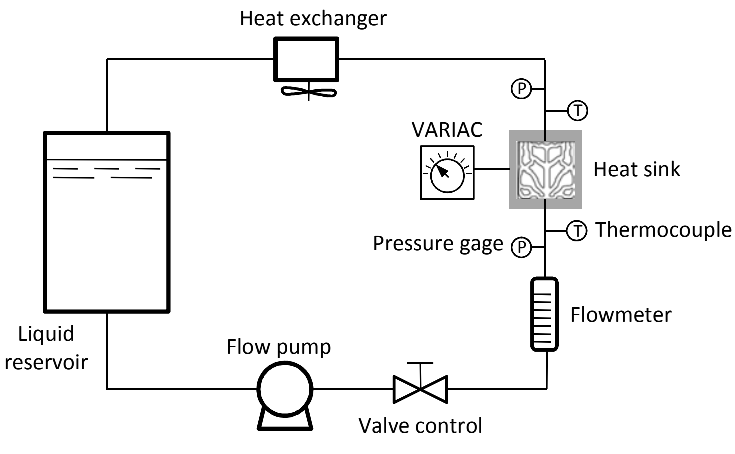


Figure 5. Experimental apparatus scheme

The water is pumped from the liquid reservoir to the channels of the heat sink prototype, which removes amount of heat supplied by the electrical cartridge heater of the heat source device, designed for simulating a microcomputer processor heating. The flow rate is controlled by a gate valve and measured with the flowmeter of the cooling system. In this experimental approach, the characterization of the prototype is performed considering a closed water cooling system. The heated liquid is cooled to the desired inlet temperature by the heat exchanger, and returns to the liquid reservoir.

The temperature of the heat source is controlled by a voltage regulator (VARIAC), which regulates the electric power in the cartridge resistance. To ensure that the power produced by the cartridge resistance is dissipated only on the surface in contact with the prototype, this heat source is thermally insulated.

The instrumental for temperature measurement in this apparatus consists of type K thermocouples, which are properly installed to measure temperatures at different points along the cooling system, such as at the water reservoir, the inlet and outlet heat sink prototype, and the contact surface between the prototype and the heat source. The

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temperature at these points is recorded by the software of a Data Acquisition driver, which allows monitoring the evolution of the temperature at the specified points in real time.

The walls of the heat sink prototype are insulated (except the surface in contact with the heat source) by using thick layer of rock wool. To ensure no fluid exchange heat with the environment, the ducts of the cooling system are insulated by using low thermal conductivity elastomeric foam.

4. RESULTS

After the first reading of temperature and pressure is established, the process is repeated for different flow rate values, in order to analyze the behavior of the heat sink prototype. For each flow rate value employed in the system, temperature and pressure drop values of specified points in the prototype are taken. The instruments used on the experimental apparatus allow performing the measurement values of temperature (^{o}C), flow rate (L/h), and pressure drop (kPa) with an uncertainty of about 1%. The plots of Fig. 6 show the flow rate and pressure drop (ΔP) versus temperature difference between fluid inlet and outlet (T_{out} - T_{in}) of the heat sink prototype.

A comparison between the results obtained from the experimental prototype and a water cooling block (available commercially) is also carried out. Figure 7 shows an illustration of this commercial heat sink, which has a pin fin channel structure and it is used for cooling the high-end microcomputers (see details in Watercooling (2013)). This commercial heat sink is placed in the experimental apparatus, and the same procedure for testing the optimized heat sink prototype has been adopted to analyze its thermal and hydraulic performance, which is also shown in the plot of Fig. 6.

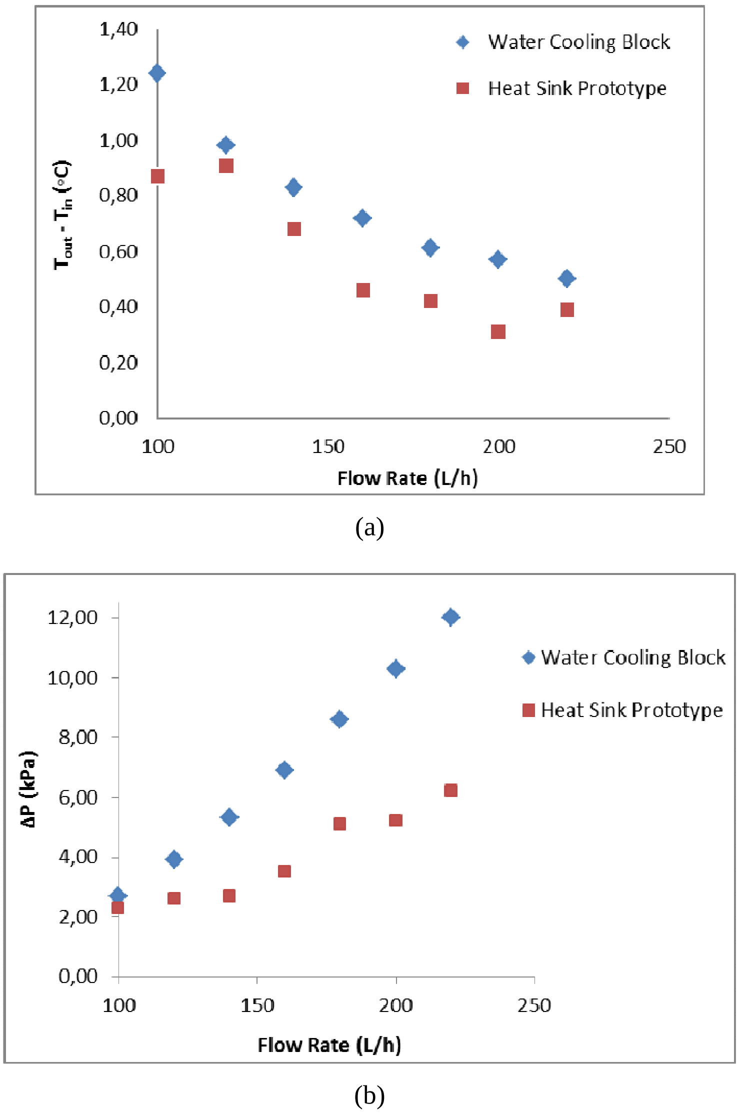

Figure 6. Comparison between results obtained by the optimized heat sink prototype and the commercial heat sink: (a) inlet and outlet temperature difference values; (b) pressure drop values

Figure 7. Water cooling block - Magicool MC Block CPU (Watercooling, 2013)

According to the plots of Fig. 6a, it is observed a certain qualitative agreement between the difference temperature curves obtained in the experimental tests of the prototype and the commercial heat sink. It is also important to emphasize that the heat sink prototype is made of Aluminum, while the water cooling block is available commercially made of Copper, which has higher thermal conductivity coefficient. Thus, this can explain the difference in the thermal performance of the heat sink prototype, shown in Fig 6a. Nevertheless, considering the pressure drop curves (Fig. 6b), it is observed that pressure drop values (ΔP) in the optimized heat sink (prototype) is smaller than the ones found in the commercial heat sink. Thus, it is conclude that thermal performance of the heat sink prototype is not very close to the performance obtained for the commercial heat sink, however, its better hydraulic performance could be an advantage in practical applications for water cooling systems, since it should require small pumping power.

5. CONCLUSIONS

The topology optimization algorithm proposed by Koga *et al.* (2013) has been applied to obtain systematically the optimal fluid flow channels layout, which is used as guidance in a complete cycle of development for the heat sink design. Experimental characterization of a manufactured heat sink prototype is carried out to evaluate the optimized fluid flow channels.

A comparison between the manufactured prototype of the optimized heat sink and the conventional based pin-fin heat sink (available commercially) has also been carried out. Several different flow rate values, applied for testing both heat sinks (prototype and commercial), show a reasonable agreement on the thermal performance behavior of both devices. However, the pressure drop curves of both show that the hydraulic performance of the optimized heat sink seems better.

Although these results be preliminaries, which it will be investigated in the next step of this work, it can be concluded that the application of the TOM in fluid mechanics field combined with heat transfer field is a very promising tool, mainly considering a conceptual design step. As future work, this design methodology will be applied to obtain very small scale devices, such as microchannel heat sinks.

6. ACKNOWLEDGEMENTS

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