Channel type heat exchangers used in cooling of electronic chips and central processing units of computers: an overview

Raghuraman DRS*, Thundil Karupparaj R, Rao BVA
School of Mechanical Engineering, VIT University, Vellore, India-632014
***Corresponding author: E-Mail: drsridhar61@gmail.com**

ABSTRACT

This paper is an overview of the various cooling technologies attempted over the past two decades to cool electronic chips and CPUs of computers. The paper also attempts to highlight the influence of channel geometry on the fluid flow and heat transfer through such devices. Finally, the factors based on which the heat sinks can be selected are highlighted.

KEY WORDS: CPUs, gases, liquids, suspensions, heat sinks.

1. INTRODUCTION

Electronic components serve as a site for excessive heating due to the electric current passing through them as a result of which their life may be short. Since trillions or even higher astronomical number of transistors are packed into a small chip the size of a finger nail or even smaller, the heat generated by them per unit volume is very high and comparable to those produced even by the surface of the sun and nuclear reactors. So naturally higher the temperature, the failure rate of electronic equipment increases exponentially with increase in its temperature.

Temperature control has become necessary with increasing heat generation. The various technologies which have evolved over the years are being discussed in this review paper.

Objectives: Therefore the present review paper aims to identify the technologies available in the past to the enabling technologies of today for cooling the earlier CPUs to present day modern cloud computing systems. Therefore the objectives of the paper are put forth as follows:

a) Selection of literature on single phase heat transfer through electronic ICs.
b) Identification of reasons for inaccuracies in analyzing the thermal performance of heat exchangers used in the above.
c) Finally to give an idea on selection of the type of heat exchangers to be used based on the heat generated in electronic chips.

Evolution of channels as transport devices: Fluid flow normally means mass or volumetric flow transfer but it can also include heat transfer through various systems in the human body like blood vessels, lungs, kidneys, intestines, brain etc. In man-made systems, the fluid flow takes place through refrigeration units, separation and filter units, desalination units, mixers, nuclear reactors etc. It is a well-known fact that the rate of fluid flow depends on the surface area which changes with the internal diameter of the tube if circular and the flow rate varies as the square of the diameter. Heat and mass transfer processes occur across the lungs and kidneys through capillaries as small as 4 microns.

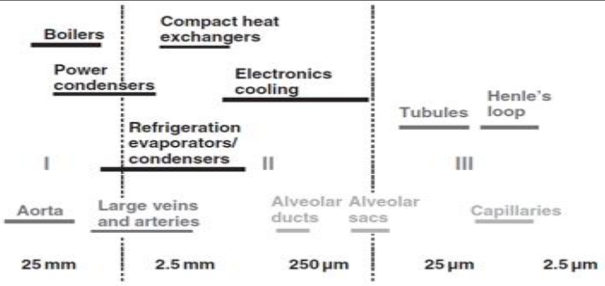

Fig.1. Channel sizes used in different applications

Table.1. Channel dimensions for different types of flow for gases at one atmospheric pressure

Gas	Channel dimensions (μm)			
	Continuum flow	Slip flow	Transition flow	Free molecular flow
Air	>67	0.67-67	0.0067-0.67	<0.0067
Helium	>194	1.94-194	0.0194-1.94	<0.0194
Hydrogen	>123	1.23-123	0.0123-1.23	<0.0123

Various methods of cooling:

Single phase cooling using gas flow: Yu and Ameel (2001), in their work talked about heat transfer in channels involving gaseous flow. They have considered slip flows and rarefaction effects in their analytical work. Kohei and Yutaka (2010), in their experimental work on gas-to-gas parallel flow heat exchangers have studied the heat transfer and pressure drop characteristics. They have found during their experimental investigations that the pressure drops were ten times that of the theoretically calculated pressure drop. Wu and Little (1984), in their work on micro heat exchangers used in miniature refrigerators with nitrogen gas as the coolant, found that Nusselt Number depends on Reynolds number in the laminar flow region. Also they found that the average Nusselt numbers calculated experimentally were higher than the theoretical. The rough walls of the micro channels improved heat transfer coefficient.

Alessandro (2006), in their work on polymeric micro channel heat exchangers made of nylon used gas as a medium for cooling. The geometry of the micro channels is a circular duct embedded in a solid substrate of rectangular cross-section. A numerical solution was obtained using finite element techniques based on Rayleigh-Ritz-Galerkin method. They have found that the Nusselt number obtained from their numerical work matched the experimental work done by Chignoli (2004), on a polymeric heat sink with both Helium and Nitrogen flows under low Reynolds, Prandtl, Knudsen, Mach and Brinkman numbers.

Single phase cooling using liquid flow: It has been observed by certain researchers and authors that at heat fluxes being generated greater than 100 W /cm^2 ,use of forced convection with air would not be sufficient to remove the hence heat sinks with liquids such as water would have to be used. Liquids like water could remove high amount of heat flux from electronic devices. If dielectric liquids like fluorochemicals (refrigerants) were to be used, the electronic devices could be immersed in them to remove large heat fluxes.

Garimella and Singhal (2010), reported the results obtained from the work performed by Liu and Garimella (2002), on micro channel heat sinks and micro pumps to understand fluid flow and heat transfer and the power needed to push the flow and the type of mechanism needed for pumping. They have studied mciro channels as large as 250 microns to 1000 microns and their experimental results confirmed the theoretical correlations. They have even attempted flow visualization by passing a dye streak through a pressure tap.

Steinke and Khnadlikar (2005), have generated a collection of literature of experimental works done by researchers and compared them in order to find out the variations and the mismatches in the literature surveyed. The reviewers have rightly concluded that efficiencies, developing flows, inaccuracies in measuring channel geometry and experimental uncertainties were not considered in the papers which they reviewed.

Kalaivananan and Rathnasamy (2011), have investigated the heat transfer characteristics in micro channels based on their experimental work with two test sections of 47 and 50 micro-channels in number with hydraulic diameters 387 and 327 μm respectively . The coolants used were ethanol, methanol and an ethanol-methanol mixture.

Silicon wafer built micro sinks, experimentally measured the pressure drop and heat transfer coefficient with water as coolant. The above measurements helped in the estimation of the local and the average Nusselt number as well as the coefficient of friction for different flow rates, channel sizes and configuration.

Omar Mukhrani (2009), in their experimental work on rectangular micro channels with large aspect ratio have studied the fluid flow and convective heat transfer characteristics for varying hydraulic diameters of the micro channel from 1 mm to 100 microns. So according to the authors, for smooth walls of the micro channel ranging with hydraulic diameter equal to or greater than 100 microns hydraulic diameter, continuum flow was valid.

Interestingly Iyengar and Garimella (2006), have focused on optimizing the entire cooling system for CMOS microprocessor driven computers using MATLAB. The authors of this work have suggested a liquid-air hybrid system instead of either air or liquid cooling technology using copper microchannel heat sink and heat exchanger materials, using water as the liquid-side coolant, having a commercial pump and fan for circulating the liquid.

Clemens (2005), in their review work on High Performance Cooling for Electronics have talked of a number of promising thermal technologies for cooling electronic devices. The authors have discussed techniques like air cooling, piezo fans, synthetic jet cooling, nanolightning, the more popular liquid cooling, heat pipes, cold plates, micro channels and minichannels, electrohydrodynamic and electro wetting cooling etc. While concluding the authors are of the opinion that for heat fluxes up to or even higher than 50 W/cm^2 air cooling is the choice. For 100 W/ cm^2 and above heat fluxes, the obvious choice is liquid coolants.

Ellsworth (2008), in their paper have reviewed the latest in cooling technology for large size IBM servers from S36091 to the IBM Power 575 supercomputing system. Increasing CPU power resulting in increased heat loads, asking for increased cooling effectiveness resulted in the reuse of water as a coolant. A coolant distribution unit was first installed in 1968 on Model 91at Colombia University. In other words, according to the reviewers of this paper, it dissipates 72 kW with 80% rejected to water and 20% to the room air.

Gina Luca Morini (2004), has bibliographically reviewed works on experiments performed on single phase convective heat transfer through micro channels. The results obtained on the friction factor, laminar-turbulent transition and the Nusselt number are examined and compared.

Peng and Petersen (1995), studied the varied properties of the coolant liquids (ethanol and water mixture) which affect the heat exchange. In other words, the data generated by the experiments conducted by them showed that the micro channel aspect ratio, Reynolds number, the velocity and temperature of the liquid affected the convective heat transfer. Their studies have also proved that the convective heat transfer was also dependent on the ratio of the hydraulic diameter to the center-to-center distance of the micro channels.

Cuta (1998), in their experimental work on MCHS found out the Nusselt number ranging from 5 to 12 for rectangular micro channels. Micro heat exchangers with an array of 54 parallel micro channels with rectangular micro channels, 1.0 mm depth and 0.27 mm wide with an aspect ratio of about 4 and a hydraulic diameter of 425 mm were tested with a refrigerant as a cooling fluid. For Reynolds number ranging from 100 to 570, a uniform heat flux of 40 W/cm^2 and wall surface heat ranging from 0 to 65 K, for single phase and two-phase flow.

Ravigururajan (1996), studied the convective heat transfer coefficient in their experimental work on micro channels using the same setup as Cuta (1998). Same fluid was used. The flow rate was controlled between 35 ml/min to 300 ml/min, heat flux was from 10 W/cm^2 to 100 W/cm^2. In conclusion, the authors of the work were of the view that though surface area increased the heat transfer, the increase in heat transfer was more likely due to thinning of the boundary layer in the narrow channels, which lowered the thermal resistance.

Single phase convection heat transfer enhancement: The necessity of a faster heat removal rate when compared to the above, made researchers think of alternate methods of heat transfer enhancement by way of channel roughness, turbulent flows and extended surfaces inside the channels.

Silicon wafer built micro sinks, experimentally measured the pressure drop and heat transfer coefficient with water as coolant. He had created two ways of heat exchange, one in a series way and another in a parallel method. As to laminar flows in the previous works reviewed, the Nusselt numbers are very high in case of turbulent flow when compared.

Yu (1995), in their experimental and theoretical work on fluid flow and heat transfer and fluid flow in micro tubes have studied the convective heat transfer in micro tubes but in the region of turbulent flow. They have found that the Nusselt numbers were larger in the turbulent region than theoretical predictions.

Adams (1998), in their experimental work have investigated turbulent, single-phase forced convection of water in circular micro channels with diameters of 0.76 and 1.09 mm. Their results show that the Nusselt numbers for the microchannel are higher than those estimated by traditional large channel correlations. Therefore based on the data generated in their work and earlier data for smaller diameter channels, the researchers (Adams, 1998) have developed a generalized correlation for the Nusselt number for turbulent, single-phase, forced convection in circular microchannel.

Kandlikar (2003), in their work on effect of surface roughness on heat transfer and fluid flow through small diameter tubes have undertaken a detailed experimental study to investigate the roughness effects in such tubes. The roughness of the inside tube surface was changed by etching it with an acidic solution. Two tubes of 1.032 mm and 0.62 mm inner diameter were treated with acidic solutions to provide three different roughness values for each tube. The Reynolds number ranged from 500-2600 for 1.067 mm tube and 900-3000 for 0.62 mm tube.

Bucci (2003), in their experimental work on fluid flow and single phase heat transfer of water as it flows through stainless steel capillary tubes. The tube diameters of 172 microns, 290 microns and 520 microns are exposed to flows corresponding to Reynolds number ranging from 200 to 6000.The authors found from their investigations that while the friction factor was in good agreement with the Haigen-Pouiselle’s theory for Reynolds number less than 800-1000, but for higher values of Reynolds number beyond turbulence, the Haigen-Poisuelle’s theory did not hold good.

Francois Debray (2001), in their work have estimated the friction factor and the forced convection heat transfer coefficient in flat mini-channels with thickness ranging from 1 mm to 250 μm. The friction coefficient measurements confirmed the classical laws. The heat transfer coefficients variations with classical correlations well-established for larger diameters could be justified by the non-uniform heat flux at the wall and the partial formation of the hydrodynamic and thermal boundary layers.

Steinke (2005), in their review paper have dwelt on the pertinence of enhancement methods utilized in heat exchangers, for single part heat transfer through small and mini channels. They were of the view that passive techniques like surface roughness could be used for each mini and small channels, whereas flow interruptions like fins, twisted tapes would work well for the larger sized mini channels.

Yet another active technique, calling for establishing small variable roughness structures in micro and mini channels, posed a technical difficulty of assembly into the heat exchangers. The passive techniques for heat transfer enhancement (mentioned in the previous paragraph) could be possible but with no additional power or actuating mechanisms.

Influence of surface roughness and hydrophobic surface: The experimental work on hydrodynamic studies of glass/fused capillary tubes from 259 microns to 31 microns ID have tried to find out if any changes were observed from the Hagen-Poisuelle’s Law (f=64 Re) in the micro-region. They are also of the opinion that fluid slip is caused by Nano bubbles on the wall surface (being hydrophobic in nature).

The average roughness height (ϵ) of the surfaces is around 3-6 microns and the relative roughness (ϵ/D) lies between 0.7% and 0.4%.It is observed in their work that the roughness has no effect on the heat transfer during the laminar flow, but the laminar-turbulent transition is seen above at Reynolds numbers greater than 2150.

Single phase convection using micro sized particle suspensions: Researches on improving the heat transfer performance of liquids were in vogue for more than a century ago. This was evident by the work done by James Clerk Maxwell a great scientist and researcher of his time. He investigated the electrical conductivity of heterogeneous solid particles. It was found by many researchers in their experimental work that the micro particles or millimeter sized particles settled very rapidly in liquids causing clogging, abrasion and high pressure drops.

Yet other researches were directed towards the use of small particles as slurries, which would contain phase change material, for heat transfer enhancement. The heat created because of melting increased the heat carrying capacity of the liquid coolant as a whole. This method of enhancement was researched analytically by Hu and Zhang (2001), in their work on convective heat transfer enhancement using micro capsulated phase change material in laminar flow through a circular tube with constant heat flux. The authors in their work have parametrically studied the heat transfer enhancement and their model agrees well with the experimental data by other researchers like Goel (1994).

Perry and Kandlikar (2006), have studied the effect of micro particles in micro channels. They pushed silica particles suspended in de-ionized water through Silicon micro channels. The significant forces for dilute solutions of silica particles ranging from 3 to 10 µm are studied in rectangular micro channels made in silicon with a hydraulic diameter of 106 µm. The authors have concluded that fouling can be minimized with solutions having higher pH Values.

Single phase convection using nano coolants: There is an advantage of using solid particles of nano sizes, suspended in liquids as emulsions in small heat exchangers. Nano powders are a new type of solid materials, which when dispersed in a base liquid tend to improve the thermal conductivity of the liquid.

Nanofluids were first developed at the Argonne National Laboratory in the U.S.A by Stephen and Choi (1998). The researchers developed a new class of liquids based on nano powder suspensions to improve the thermal conductivity of the base fluid. As a result, the first nano liquid developed at the Argonne National Laboratory contained 5% volume of nano crystalline copper oxide particles suspended in water, which resulted in an increase of thermal conductivity when compared with water.

Murshed (2008), performed both theoretical and experimental study on the thermal conductivity and viscosity of nanofluids. Their results indicated that the values of thermal conductivity and viscosity were much better than that of the base fluids and increased with rise in the volume fraction of the nanofluids.

In earlier investigations, Li and Peterson (2006), have performed experiments on two different nanoparticle suspensions, Copper and Aluminum oxide, CuO and Al_2O_3 nanoparticles blended with distilled water at 2%, 4%, 6%, and 10% volume fractions at temperatures between 27.5 to 34.7^{0}C The 6% volume fraction of CuO nanoparticle/distilled water suspension resulted in an increase in the effective thermal conductivity of 1.52 times that of pure distilled water and the 10% Al_2O_3 nanoparticle/distilled water suspension increased the effective thermal conductivity by a factor of 1.3, at a temperature of 34°C.

Ijam (2012), in their experimental work on cooling of minichannel using nanofluids have also proven that channels of small sizes, with nanofluids flowing through them, are excellent heat transfer devices for electronic ICs and chips. In their experimental study, nano fluids like Al_2O_3 water and TiO_2 water have been considered. The authors observed the highest thermal conductivity at 4% and 5% volume fraction in the nanoliquid.

Dongsheng Wen and Yulong Ding (2004), in their experimental work on convective heat transfer of nanofluids have found out the increase in convective heat transfer with Al_2O_3 water especially at the entrance region.

Nguyen (2007), in their work also studied the heat transfer improvement by using Al_2O_3 nanofluids. This was for a closed circuit cooling system meant for microprocessors and other similar electronic devices., with a particle concentration being 6.8%, naturally the heat transfer coefficient was very high as much as 40% as compared to water.

Ho (2010), in their experimental work on forced convection cooling, using Al_2O_3 water nano fluids of 2% and 4% volume fractions , have used 25 microchannel heat sinks ,of rectangular geometry with each of length 50 mm having a cross-section of 283 µm width by 800 µm height. .They deduced that the nano cooled micro channel heat exchangers performed better than the water cooled ones with respect to high average heat transfer coefficient, lower thermal resistance and lower wall temperature but at higher pumping power with problems of agglomeration and clogging.at higher concentration.

Jie Li and Clement Kleinstreuer (2008), in their theoretical work, on the thermal performance of nano liquid flow through micro channels, have studied the performance of CuO nanoparticles with volume fractions of 1% & 4% respectively. Their results also show that nanofluids increase the thermal performance of Micro channel heat sinks with a marginal increase in pumping power.

Jason Lee and Issam Mudawar (2007), in their experimental work on MCHs, while using 1% and 2% volume concentration of Al_2O_3 water nano fluids, studied both single phase and two-phase heat transfer in micro channels. They have concluded rightly, like the researchers as mentioned above, that the increase in thermal conductivity of the nanofluid leads to better heat transfer coefficient in single phase with increasing pressure drop at higher nano particle concentration. .

Jung (2009), in their experimental work on forced convective heat transfer of nanofluids in micro channels have measured the friction factor and convective heat transfer coefficient across the channels with a microsystem heat sink The convective heat transfer coefficient of the Al_2O_3 nanofluid in laminar flow regime was found to increase by 32% when compared to base fluid with increase in Reynolds number in the laminar region.

2. CONCLUSION

Different methods like active and passive cooling have been developed for CPUs, by various researchers during the past two decades or more. If heat less than 50 W is generated, then gas type micro channel heat sinks can be used. If heat more than 100 W is generated, liquid type micro channel heat sinks can be utilized.
Hybrid type heat exchangers with both liquid and gas as coolants are used to remove heat from large size CPUs where heat in kilowatts is generated due to high computing speeds... The latest type of heat exchangers have used nano liquids to remove heat from ICs used in CPUs .Different types of nanopowders like Titanium Dioxide,Magnesium Oxide, Copper Oxide, Carbon Nanotubes can be used assumptions.. It is expected that nanofluids can revolutionize the electronic cooling of ICs if their shelf life, settling time increases and the costs of manufacturing nanopowder are reduced.

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