Heat Transfer Analysis of a Cold Plate

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Abstract- The exponential growth of electronics and their use commercially combined with the need for better power dissipation and system cooling, has caused the need to come up with better cooling technologies at affordable costs that are viable for commercial packing. It is largely focused on high heat flux removal from computer chips in the recent years. However, the equally important field of high-power electronic devices has been experiencing a major paradigm shift from air cooling to liquid cooling over the last decade. A detailed study about cold plate and its working under various parameters is studied. Also the dependence of cold plate on working fluid, fill ratio and surfactant concentration on heat transmission is studied. It is then followed by a series of literatures reviewed which includes a brief description of previous works done in this field & also explained the applications of cold plate till date used in electronic devices. The modification is done in design of cold plate to reduce its cost and also to increase the heat dissipation rate. The modified cold plate can use water to remove major part of heat produced and air for minor part by natural or forced convection. Further experimental setup is prepared to perform experiments at atmospheric conditions and calculated for various flow rates and power inputs.

I. INTRODUCTION

A. Cold Plate

According to the International Technology Roadmap for Semiconductors [1], heat flux from microprocessors will continue to rise and remain a great challenge in thermal management. Some electronic devices, particularly high-power defense electronics, are dissipating 1000 W/cm² and higher. With such a trend, a heat flux level of more than 2500 W/cm² or higher from some electronic devices could be reached in the foreseeable future.

To cope with the heat issues of tomorrow’s technology, more efficient cooling systems will be required. Liquid cooling is always advantageous than air cooling technique since it has high specific heat value. In liquid cooling, heat is removed either in sensible or latent heat form i.e. single and two phase flow techniques. Cold plates are widely used in electronic cooling systems. It comes under sensible heat removal technique. The cold plate is used to provide a “cold wall” to which individual electronic components are mounted [2]. The design and performance evaluation of a cold plate follows a prescribed procedure that depends on the heat loading and whether the heat loading is on one or two sides of the cold plate.

B. Rate Equation for Cold Plate

The design of a cold plate involves a consideration of the heat transfer between the walls of the cold plate and the circulating fluid as well as the pumping power expended to overcome fluid friction and to move the coolant fluid through the passages within the cold plate. For a cold plate carrying a high density fluid, the
friction loss is relatively small and it is usually not the controlling factor. But when air and other gases are employed it is not uncommon for the cold plate to quickly dissipate its allotted power.

The heat flow between the fluid and the confining surfaces in a heat exchanger can be enhanced by increasing the fluid velocity. However, the velocity increase must of necessity because the heat transfer coefficient varies almost directly with the velocity while the friction loss variation is close to the square of the velocity.

![Fig.1. Simple liquid cold plate [6]](image)

In spacecraft, aircraft and missiles, space and weight are used sparingly. It is essential that in these vehicles, on-board heat exchange duties be accomplished in equipment that is as light and compact as possible.

First consider the rate equation [2] for the cold plate which is a mathematical statement that says that the quantity of heat, \( Q \) (Watts) transferred in a heat transfer process is equal to the product of the heat transfer coefficient \( h \) in Wm\(^{-2}\)K\(^{-1}\), the surface area in the cold plate \( A \) in m\(^2\) and some temperature difference or driving force \( \theta_m \) in K or \(^\circ\)C.

\[
Q = hA \theta_m
\]

Thus for fixed heat flow and temperature driving force, this becomes

\[
\frac{Q}{\theta_m} = hA
\]

Which indicates that the heat flow per unit temperature difference is maximized when the \( hA \) product is maximized.

### C. Working

Cold plates are used to provide cooling for high heat loads. One surface of cold plate is kept in contact with the heat source surface and others are dissipating heat either by natural convection or forced convection by using fans. Also since water or other fluid having high specific heat value and boiling temperature is used to pass through channels of cold plate, its heat removing capacity is much more than conventional air cooling techniques. The cold plates are of different types depending on working conditions. The generally used cold plates are two loops types with fluid inlet and outlet on same side.
In the CPU application; operating temperatures are normally in the range of 50°C to 100°C [3]. At this temperature water is best working fluid. In cold plate the heat removed by fluid is purely sensible heat and no phase change of working fluid occurs. The flow rate of fluid in cold plate plays important role in heat removal from surface. For high heat flux applications higher flow rates are preferred while for lower heat flux moderate or lower flow rate is used.

D. Classification of cold plates

A review of the literature on cold plates as well as on the catalogs of their manufacturers reveals that there are several different types. The substrate and the fluid flow channels can be arranged in several different configurations depending on the device size and power dissipation requirement [4]. These cold plate configurations are classified into four major types as follows:

1. Formed Tube Cold Plate (FTCP)
2. Deep Drilled Cold Plate (DDCP)
3. Machined Channel Cold Plates (MCCP)
4. Pocketed Folded-Fin Cold Plates (PFCP)

II. Literature Review

Different studies carried out on cold plate and liquid cooling presented in this chapter. Many studies were reported on microprocessor for its thermal managements and power consumption reduction. An effective liquid cooling methodology and types of cold plates were discussed in different papers. The different modification cases were studied for cold plate modeling.

The Encyclopedia of Thermal Packaging with Packaging Techniques [2] is comprised of four distinct Sets dealing comprehensively with the Techniques, Tools, Applications, and Configurations of modern thermal packaging. Second set of the author-written volume presents Thermal Packaging Techniques with Air- and Liquid-Cooled Cold Plates in a uniform style. This volume describes various aspects of cold plate such as preliminary considerations, design procedure for single stacked, double stacked cold plates with symmetric loading and unequal loading. It also represents fluid selection for liquid cooling and shop fabrication process.

Satish G. Kandlikar and Clifford N. Hayner [4] classified the cold plates into four types: formed tube cold plate, deep drilled cold plate, machined channel cold plate and pocketed folded-fin cold plate. In this article they discussed selection of cold plate type and channel configuration and some of the relevant manufacturing issues such as general design issues, coolant issues, manufacturing issues etc. It was recommended that the thermal designer be involved in the early stages during the electrical design and layout of the devices.

Javier A. Narvaez, Hugh Thornburg, Markus P. Rumpfkeil, Robert J. Wilkens et al. [5] studied the temperature distribution inside a Lytron CP20 micro channel cold plate under constant heat flux. The cooling fluid was DI water. The pressure, velocity and temperature at the inlet and outlet of the cold plate were
experimentally measured in two coolant loops. In addition, the problem is modeled numerically using the Star CCM+ software. The Reynolds-Averaged Navier–Stokes (RANS) equations coupled with the realizable k-epsilon model as closure was used for this simulation. The objective was to evaluate the uniformity of the temperature profile inside the cold plate. Pressure, velocity and temperature profiles were presented and compared with experimental results. Regions of especially high or low temperature were highlighted and discussed.

Suggestions on how to obtain a more uniform temperature distribution inside the cold plate were presented. Critical details on the modeling and on the limitations of the model were also discussed. The high-performance computing facility at Wright–Patterson Air Force Base was used for this research.

Feng Zhou, Ercan M. Dede and Shailesh N. Joshi [6] described a high-performance cold plate based on single-phase jet impingement and mini-channel heat sink technologies for automotive electronics cooling. A manifold system with cylindrical connection tubes and tapered inserts is designed to distribute the coolant uniformly within an individual module and between three different modules. A two-level modeling method is adopted to design and optimize the cold plate. A unit cell model is used to analyze the sensitivity of the heat sink performance to material selection and geometric parameters. Based on numerical studies, it is found that the final cold plate design achieves flow uniformity (to within 1.5%) with a maximum to minimum base temperature difference of approximately 3 K and an average heat transfer coefficient of 34 kW/(m²K). The total pressure drop of the cold plate is 9.36 kPa. Ongoing work includes experimental testing of the cold plate including validation of the expected pressure drop and heat transfer performance.

Kanchan M. Kelkar, Suhas V, Patankar et al. [7] done analysis and design of liquid-cooling systems using Flow network modeling (FNM). The objectives in the design of these systems were to create a sufficient amount of total flow and to appropriately distribute the flow so as to maintain the electronic component temperatures at the desired level. The technique of Flow Network Modeling (FNM) is ideally suited for the analysis of flow distribution and heat transfer in liquid-cooling systems. The FNM technique uses overall flow and thermal characteristics to represent the behavior of individual components. Therefore, solution of conservation equations over the network enables efficient prediction of the flow rates, pressures and temperatures in a complete liquid-cooling system.

They described the technical basis of the FNM technique and illustrate its application in the design of a distributed-flow cold plate and of a complete water-cooled system. The study demonstrates the utility of the FNM technique for rapid and accurate evaluation of different design options and the ensuing productivity benefits in the design of liquid cooling systems.

Hsiao-Kang Ma, Bo-Ren Chen, Jhong-Jhih Gao et al. [8] developed an innovative one-side actuating piezoelectric micro-pump (OAPCP-micro-pump), which is combined with a45 mm×28 mm×4 mm cold plate chamber to drive liquid in a cooling system for a laptop. The results show that the shape and the numbers of the fins inside the cold plate chamber have strong effects on the pressure drops and flow profiles. The fluid in the pump chamber may impinge on the fins and increase the heat dissipation rate due to the oscillation by the
actuator. The measured maximum flow rate of the OAPCP-micro-pump is 4.1 ml/s and its maximum pump head reaches 9807 Pa. The new cooling system with an OAPCP-micro-pump design shows a stable performance on total thermal resistance due to the high flow rate.

Y. P. Zhang, X. L. Yu, Q.K. Feng et al. [9] proposed a cold plate for cooling of the electronic components with high heat flux and high heat dissipation. The cold-plate structure of S-type with guide plates was introduced to avoid the heat hot concentration and increase the heat transfer area. The experimental results show that the maximum chip temperature of the novel cold plate was approximately 40% lower than those of the conventional cold plate. Thermal performance optimizations were conducted, indicating that it was extremely effective to install the heat source on two sides of the cold plate. Compared with the single-side heat source, the maximum chip temperature was increased only 20%. However, the heat dissipation was doubled in the limited space for the double-sides arrangement heat source. Moreover, the integrated density of the power module was greatly enhanced by using the cold plate. Transient state temperature variation indicates that the cold plate have quick thermal response in start-up process. It was beneficial to the heat dissipation of integrated module for high power density.

Hsiang-Sheng Huang, Ying - CheWeng et al. [10] investigated the thermal performance of a thermoelectric water-cooling device for electronic equipment. The influences of heat load and the thermoelectric cooler's current on the cooling performance of the thermoelectric device are experimentally and theoretically determined. In this study they developed a analytical model of thermal analogy network to predict the thermal capability of the thermoelectric device. The model's prediction agrees well with the experimental data. The experimental result show that when heat load increases from 20Wto 100 W, the lowest overall thermal indicator increases from −0.75 K/W−1 to0.62 K/W−1 at the optimal electric current of 7 A. Besides, this study verified that the thermal performance of the conventional water-cooling device can be effectively enhanced by integrating it with the thermoelectric cooler when the heat load is below 57 W.

Uma Ravindra Maddipati et al. [11] presented study on thermal design and analysis of cold plate with various proportions of ethylene glycol water (EGW) for cooling high power dissipating Travelling Wave Tube (TWT), which was used for high power applications in Electronic Warfare (EW) systems. They found that selection of right proportion of ECW with required volume flow rate was essential to cool the TWT when it was subjected to low temperature environment. They predicted thermal performance of cold plate by theoretical and numerical approaches.

Jung - Shun Chen, Jung-Hua Chou et al. [12] examined experimentally the effects of liquid filling ratios and leakage on the cooling performance of flat plate heat pipes (FPHPs). With the size of 150 mm × 50 mm × 2.5 mm for all Al 6061FPHPs filled with acetone (99.87% pure), the results showed that the one with the liquid filling ratio of25% performed thermally the best. The corresponding maximum heat transport capability, minimum thermal resistance & maximum effective thermal conductivity were about 47 W, 0.254 K/W and 3150 W/m K respectively. In contrast, improper vacuum and leakage would decrease the maximum thermal conductivities greatly to about 200–306 W/m K and 164 W/m K respectively. The latter was similar to that of
an aluminum block and performed the worst among all FPHPs. This situation should be avoided or carefully assessed as the maximum effective thermal conductivity decreased from the best by a factor of about 19.2.

Jackson Braz Marcinichen, John Richard Thome, Bruno Michel [13] studied three micro-evaporator cooling cycles, one with a pump, one with a compressor and a hybrid of the two together, and proposed for cooling a computer blade server. The hybrid cycle is characterized by the interchangeability between the first two cycles, where the decision on the cycle to operate is based on the season (necessity or economical benefit for heat recovery) or the maintenance of cycle’s driver. The main characteristics of each cycle are presented as well as the details of the micro-evaporator cooler for the blade’s CPU. Analysis of the cycle overall efficiency and the potential for heat recovery shows that the best cycle to use depends mainly on the end application of the heat recovered. Four refrigerants were evaluated as the possible working fluids for cooling the microprocessors.

P. Sivakumar, P. Srihari, Prof. N.HariBabu et al. [14] performed optimization of liquid cold plates using computational fluid dynamics. The objective of work was comparing 3 different profiles of cooling plates to maintain the equipment in safe temperature condition. In this study, evaluation of 3 different types of cooling plates through CFD analysis by fixing the diameters of inlet and outlet portions were kept constant. The design of cooling plate placed upon 8 IGBT’s and the analysis of flow by using solid works flow simulation software. Comparing three different cooling plates i.e. the Form tube, Machined channel and Deep drilled cold plate and Optimization is done by considering weight of the cold plate and better temperature distribution.

III. EXPERIMENTAL SETUP

In this chapter, fabrication, setup installation and experimental procedures are mentioned. There are several important factors that affect the performance of the cold plate:

1. Working fluid
2. Flow rate
3. Cold plate material
4. Dimensions of the Cold plate.

Depending upon the working temperature proper working fluid is selected. For example for high temperature ranges up to 100°C deionized water is used. Deionized water is used for all flow rates i.e., for very low to high. Moderate and low flow rates are used for deionized water since it is capable of removing the given heat load efficiently.

Cold plates are made from materials having high thermal conductivity and low thermal resistances. Copper is most commonly used material for fabrication of cold plate because of its high thermal conductivity value and inertness to most of working fluids.

Cold plate is square or rectangular box of dimensions as per component to be cooled. For CPU microprocessor (4×4) cm dimension is generally preferred.
A. Fabrication of Cold plate:

The cold plate is fabricated with modifications in its design. The single channel is completely replaced by the segregated channel of tubes. The working fluid is passed through the tubes. The 40 × 40 mm copper block weighing 400gm is machined so as to make its surfaces plane and corners to be sharp. There are 6 holes in the copper plate drilled throughout having a diameter of 4mm. The holes are interconnected as lower row first then lower row to upper one. Thus the inlet is at bottom and the outlet is at top on same side of cold plate.

![Fig. 2 Cold plate with K-type thermocouple connections](image)

The thermal conductivity of copper is 390 W/mk. Also it is inert to operate with deionized water, acetone and methyl alcohol which are working fluids to be used. The thermocouples are attached at locations where the temperature is to be noted. The acrylic sheet is used for housing purpose of cold plate.

B. Setup Preparation:

The layout of setup on which experimentation is to be carried out is shown in fig. 3. The cold plate is placed on heater surface as shown in figure. The assembly is then insulated by using acrylic sheet. The thermocouples are connected to plate by drilling holes at required points and making the same holes in acrylic sheet. The control valves are provided for flow regulation.

1. Acrylic plate: It is used to hold the cold plate in its position from top surface. The top surface of cold plate and acrylic plate are coplanar. It is having a thermal conductivity of 0.2 W.m⁻².K⁻¹.
2. Backelite plate: It is used to support heater from bottom surface. Its thermal conductivity is 0.2 W.m⁻².K⁻¹.
3. Mica: It acts as interface medium between heater and cold plate. It is having a thermal conductivity of 0.71 W.m⁻².K⁻¹.
4. Fiber glass wool: It is lightweight, flexible, thermal and acoustical insulation material designed to provide the heat loss reduction. It is formed from resin-bounded borosilicate glass fibers. It is water and fire
resistant, it has low density of combustion gas and low toxicity. It’s density in non-pressed state is 5-20 kg.m$^{-3}$. Thermal conductivity is 0.04 W.m$^{-2}$.K$^{-1}$. It occupies space between acrylic and bakelile plate.

![Diagram](image)

**Fig. 3 Schematic of the set-up used for the present experiment**

**C. Experimental setup:**

It contains assembly of cold plate and heater with mica sheet as connecting medium.

i. K-type thermocouples are used having following specifications:
   a. sensitivity: 41$\mu$V/ºC
   b. Range: -200ºC to 1350ºC with good operating conditions in oxidizing atmosphere.

ii. Dimmerstat with max load of 4 A And max kVA: 1.08

iii. Water supplying tank with control valve.

iv. Water collector tank with measuring tank and control valve.

v. Glass wool as insulating material around the assembly parts.

Fig. 4 shows the schematic of the set-up used for the present experiment. The experiments are conducted for different configurations of power inputs and flow rates. The block is heated by a nichrome foil heater of the same size attached underneath of the block. The heater is supported by a bakelite plate to provide proper surface contact between the heater and the copper block. The copper block is insulated by glass to minimize the heat loss through the sides and bottom.

The heater surface provides a constant heat flux, as the driving power input is constant and the flexible heater is specifically designed to provide a constant heat flux output. The surface temperature is measured with two pre-calibrated K-type thermocouples, which are placed at two sides of the copper block 4 mm from the corner, thus providing a spatially averaged temperature over the exposed surface of the copper block. An identical thermocouple is used away from the heated surface for ambient air temperature measurement. The power supplied to the heater is measured with a multi-meter and is controlled by a Dimmerstat. Two K-type thermocouples are connected at water inlet and outlet of cold plate. Water is supplied through tank at certain head and flow rate is adjusted by controlling valve, Temperature of water both at inlet and outlet are measured.
IV. RESULTS AND DISCUSSIONS

This chapter describes the experimental measurements for cold plate. Also Experimental results of current working fluid are validated by using CFD results.

A. Heat loss Calculations

1. Heat loss from top surface:

\[ Q_1 = (T_1 - T_\infty) \]

2. Heat loss from bottom surface:

\[ Q_2 = (T_2 - T_\infty) \]

3. Heat loss from side surfaces:

\[ Q_3 = (T_f - T_\infty) \]

Results obtained regarding selection of length of tubes are:

D = Diameter of the tube (m)

T_1 = Temperature of heater plate (°C)

T_2 = Temperature of fluid at inlet (°C)

T_f = Saturation temperature of fluid at given pressure (°C)

L = Length of tube

R_{conv} = Resistance due to convection = \frac{1}{\alpha} \]

After validating the experimental setup the top surface is now kept open to surrounding for natural convection. Heat transfer coefficient is calculated from experimental values and using law of conservation of energy:

\[ P_{supp} \cdot Q_{loss} = Q_w + h \cdot A_\ell \cdot (T_\ell - T_\infty) \]

Experimentation is being carried out for two conditions:

1. Keeping flow rate constant and varying power supplied

2. Keeping power constant and varying flow rate

Reynolds number is less than 2300 for all flow rates hence laminar flow conditions are selected. For first condition with mass flow rate \( \dot{m} = 0.000019 \) kg/s results are
TABLE 1 EXPERIMENTAL RESULT FOR MASS FLOW RATE OF 0.000019 KG/S

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>$P_{act}$ (W)</th>
<th>$T_{avg}$ (°C)</th>
<th>$T_{in}$ (°C)</th>
<th>$T_{out}$ (°C)</th>
<th>$T_\infty$ (°C)</th>
<th>$Q_w$ (W)</th>
<th>$T_{surf}$ (°C)</th>
<th>$h$ (Wm$^{-2}$K$^{-1}$)</th>
<th>$Nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5579</td>
<td>40.4521</td>
<td>31.6298</td>
<td>32.3673</td>
<td>29.9075</td>
<td>0.1741</td>
<td>32.6130</td>
<td>88.6690</td>
<td>147.78</td>
</tr>
</tbody>
</table>

CFD analysis is carried out by using STAR-CCM+ software with 9.04 version. Results are validated using this software are shown in figure.

Figure 4 and 5 shows the 3D model and volume meshing with base size 1mm of cold plate and CFD analysis of experimental result.

Figure 4

![3D model and volume meshing scene (base size 1mm) of cold plate](image)

**Fig.4 3D model and volume meshing scene (base size 1mm) of cold plate**

Figure 5

![Scalar scene of cold plate for $P = 0.5579W$ and $m = 0.000019kg/s$](image)

**Fig.5 Scalar scene of cold plate for $P = 0.5579W$ and $m = 0.000019kg/s$**

V. SUMMARY

Electronics cooling research has been largely focused on high heat flux removal from computer chips in the recent years. However, the equally important field of high-power electronic
devices has been experiencing a major paradigm shift from air cooling to liquid cooling over the last decade. Various authors have done detailed study about cold plate and its working under various parameters. Also the dependence of cold plate on working fluid, fill ratio and surfactant concentration on heat transmission is studied. A series of literatures is reviewed which includes a brief description of previous works done in this field & also explained the applications of cold plate till date used in electronic devices. The modification is done in design of cold plate to reduce its cost and also to increase the heat dissipation rate. The modified cold plate uses water to remove major part of heat produced and air for minor part by natural or forced convection.

VI. REFERENCES


