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# Numerical Study on the Thermal Characteristics of the Various Cooling Methods in Electronic Equipment

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**Abstract** : Thermal characteristics of the various cooling methods in electronic equipment are studied numerically. A common chip cooling system is modeled as a parallel channel with protruding heat sources. A two-dimensional model has been developed for the numerical analysis of compressible, viscous, laminar flow, and conjugate heat transfer between parallel plates with uniform block heat sources. The finite volume method is used to solve this problem. The assembly consists of two channels formed by two covers and one printed circuit board that is assumed to have three uniform heat source blocks. Various cooling methods are considered to find out the efficient cooling method in a given geometry and heat sources. The velocity and the temperature fields, the local temperature distribution along the surface of blocks, and the maximum temperature in each block are obtained. The results are compared to examine the thermal characteristics of the different cooling methods both quantitatively and qualitatively.

**Key words** : Thermal characteristics, Cooling method, Electronic equipment, Protruding heat source, Numerical analysis

## Nomenclature

| | |
|---|---|
| $H$ | height [m] |
| $k$ | thermal conductivity [W/m · K] |
| $L$ | length [m] |
| $n$ | normal coordinate |
| $Q$ | heat generation rate per unit length [W/m] |
| $T$ | temperature [K] |
| $t$ | time [s] |
| $u$ | velocity in $x$-direction [m/s] |
| $v$ | velocity in $y$-direction [m/s] |
| $x$ | horizontal coordinate |
| $y$ | vertical coordinate |

Greek symbols

| | |
|---|---|
| $\theta$ | dimensionless temperature |

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Subscripts

$f$ fluid
$LC$ lower channel
$PCB$ printed circuit board
$s$ solid
$UC$ upper channel
$\infty$ surrounding

## 1. Introduction

Recent trends in the electronic equipment indicate that the power consumption and heat generation in a chip increase as the components are miniaturized and the computing speed becomes faster. The rapid progress in the electronic equipment has triggered the demand for more reliable and efficient cooling technology[1]. Suitable heat dissipation has become one of the primary limiting factors to ensure the guaranteed performance and reliable operation of the electronic devices. Hence the development of efficient cooling technologies to maintain the electronic device under allowable temperature has become an important issue.

The cooling technologies in electronic equipments are classified as follows according to the heat transfer mode and the cooling media. Conduction cooling is based on the heat diffusion through solid. Conduction block or TCP (tape carrier package) for notebook computer and TCM (thermal conduction module) for high heat flux CPU and multi-chip module are commonly used[2],[3]. Natural convection cooling is used for low heat flux and low capacity devices[4]. Forced convection cooling is applied to high heat flux equipments where the safe working temperature is not guaranteed by natural convection cooling[5],[6]. Liquid cooling uses higher specific heat liquid as cooling media. Direct immersion cooling and indirect liquid cooling are used[7],[8]. Cooling with phase change uses latent heat through boiling and condensation processes, which could expect the highest cooling effect[9].

Previous studies provided the information for individual cooling characteristics, but didn't offer which is the most efficient cooling technology for given conditions such as geometry and heat generation, etc. In this study, each cooling technique is identified and compared to find out the effect of each method on the cooling characteristics and the most efficient cooling method. The system is modeled as uniform block heat sources on a printed circuit board (PCB) with upper and lower parallel channels. Six different cooling methods are applied. Conjugate heat transfer problem is solved for the cases of forced convection in the upper channel with natural convection, forced convection, liquid cooling, and conduction block in the lower channel. Forced convection cases with 1 and 2 baffles installed in the upper channel are considered to check the possibility of the heat transfer enhancement.

## 2. Numerical Analysis

### 2.1 Analysis model

The considered assembly consists of one PCB that has three protruding uniform heat source blocks and two channels formed by two covers on the upper and lower side of the PCB. Protruding heat sources are installed in the upper channel, and the conduction block is considered in the lower channel for one case. Lee and Park[10] analyzed the effects of the shape and position of the protruding heat sources on the flow and heat transfer numerically. They proposed the optimum design conditions, on which the geometric shape and dimension are based in this study. The shape and dimension of the model with conduction block in the lower channel are shown in Fig. 1.

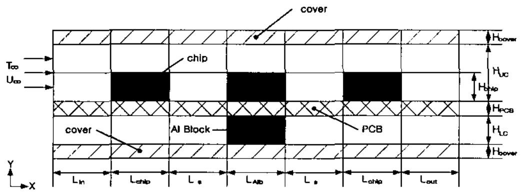


**Fig. 1 Coordinate system and geometry.**

### 2.2 Governing equations and boundary conditions

The flow field and convection heat transfer of the cooling fluid in the upper and lower channels, and conduction heat transfer through the solid state PCB, heat source blocks, and the covers are analyzed numerically. Mass, momentum and energy conservation principles are applied to obtain the velocity and temperature. The governing equations are those of two-dimensional continuity, Navier-Stokes and energy in their compressible and variable-property form and two-dimensional heat conduction equation[11].

In the upper channel, where forced convection is applied, uniform velocity and temperature, $u_\infty$ and $T_\infty$, are given as inlet boundary conditions, and normal velocity component, $v_\infty$, is set to zero at inlet. The $x$-direction gradients of the temperature and velocity, $\partial T/\partial x, \partial u/\partial x, \partial v/\partial x$, are set to zero at exit[12].

The boundary conditions in the lower channel are different in each case. The same boundary conditions as the upper channel are used in the lower channel for the forced convection and liquid cooling cases. However, when using natural convection in the lower channel, the x-direction velocity gradients, $\partial u/\partial x, \partial v/\partial x$, are given to zero at both inlet and outlet. At inlet and outlet, the surrounding temperature, $T_\infty$, is given for incoming flow or temperature gradient, $\partial T/\partial x$, is set to zero for outgoing flow.

At the left and right boundaries of the solid PCB and cover plates, velocities, $u, v$, and temperature gradient, $\partial T/\partial x$, are set to zero. The top and bottom boundaries are assumed to be adiabatic. Interface between solid and fluid has no slip condition. At the interface between solid and solid or solid and fluid, $k_s \frac{\partial T_s}{\partial n} = k_f \frac{\partial T_f}{\partial n}$ is applied to match the heat flux.

### 2.3 Numerical method

Finite volume method[13] is used to solve the governing equations with boundary conditions. The continuity equation is utilized to develop pressure and pressure correction equations following the SIMPLEC(SIMPLE Corrected) algorithm[14].

Non-staggered grid system is used, and momentum interpolation is used to determine the interfacial values of the conserved variables. An iterative approach using the ADI method[15] in conjunction with the TDMA algorithm is used to solve the discretized equations.

A converged solution is assumed to be obtained when the residuals at all grids for all equations are less than $10^{-4}$. To obtain a converged solution, $t$ = 4000~8000 seconds of computation time is required, and 40~80 hours of run time on Pentium IV PC for each case.

## 3. Results and Discussion

To confirm the validity of the program developed in this study, the results were compared with those of Davalath and Bayazitoglu[16], which numerically analyzed the forced convection cooling in a horizontal channel with three protruding heat source blocks. The results were in good agreement with the maximum difference of 5% considering the block surface temperature as well as the flow and temperature fields.

Grid and time step independence studies have been performed to select appropriate number of meshes and time step guaranteeing accuracy and efficient computation time. The number of mesh is chosen to be 350x115 and time step is set to 0.05 second.

Six different cooling methods, which are summarized in Table 1, are considered to analyze and compare the cooling characteristics of each method. Three protruding uniform heat source blocks are placed on a PCB, and the heat generation rate in each protruding heat source block is 5 W for all cases. Inlet velocity is 0.794 m/s when forced convection is used, which corresponds to laminar flow regime with Reynolds number of 1000. In each case, flow and temperature fields, temperature along the three heating block surfaces, and the maximum temperature of each block are obtained. Dimensionless temperature is defined as follows.

$$\theta = \frac{T - T_\infty}{Q/k_f} \tag{1}$$

where $T$ is temperature, $T_\infty$ is surrounding temperature, $Q$ is the heat generation rate in each block, and $k_f$ is the thermal conductivity of the fluid.

Dimensionless temperature distributions are shown in Figs. 2~7 for each case. Case 1 (Fig. 2) shows that the isotherms

**Table 1 Cooling methods in each case.**

| | Upper channel | Lower channel |
|---|---|---|
| Case 1 | Forced convection | Natural convection |
| Case 2 | Forced convection | Forced convection |
| Case 3 | Forced convection | Liquid cooling |
| Case 4 | Forced convection | Conduction block |
| Case 5 | Forced convection with 2 baffles | Natural convection |
| Case 6 | Forced convection with 1 baffle | Natural convection |

are widely distributed due to the effect of natural convection in the lower channel. However, the temperature varies sharply around the top surfaces of the blocks due to the forced convection in the upper channel. The temperature of the first block is the lowest due to the vigorous heat transfer near the first block, and the block temperature increases along the passage.

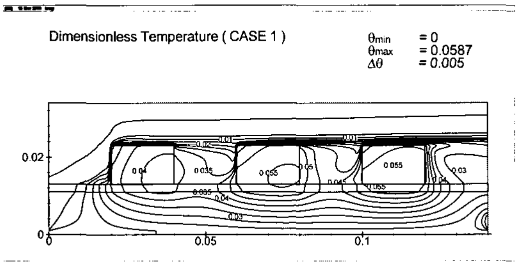


**Fig. 2 Dimensionless temperature distribution (case 1: forced convection/natural convection).**

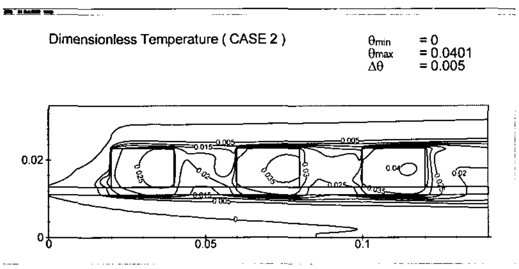


**Fig. 3 Dimensionless temperature distribution (case 2: forced convection/forced convection)**

Thermal boundary layer is formed and temperature varies sharply near the bottom surface of the PCB in the lower channel due to the forced convection in case 2 (Fig. 3). The similar results are shown in the upper channel due to the forced convection. The temperature of the first block is the lowest due to the vigorous heat transfer as in case 1. Overall temperature distribution in case 2 is lower than case 1. Therefore, case 2 using forced convection in both channels seems to be more effective in cooling compared to case 1 using natural convection in the lower channel due to the heat transfer enhancement in the lower channel.

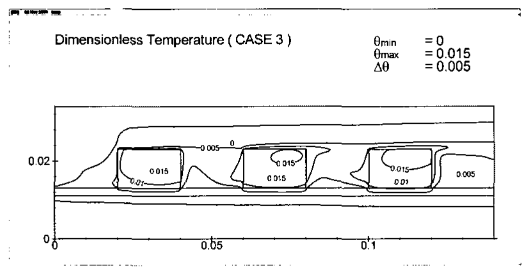


**Fig. 4 Dimensionless temperature distribution (case 3: forced convection/liquid cooling).**

Case 3 (Fig. 4) uses liquid cooling with water in the lower channel. The water flows through a tube made of high thermal conductivity material to prevent direct contact with the PCB. No steep change in temperature exists and the block temperature is quite low compared to those of cases 1 and 2. This is conjectured from the better cooling performance of liquid than that of gas. The temperature distribution of each block is similar. Therefore, it can be found that the liquid cooling effect in the lower channel rather than the forced convection effect using gas in the upper channel prevails the overall cooling characteristics.

Conduction block made of high conductivity material, aluminum, is used in the lower channel in case 4 (Fig. 5). Temperature distribution around the conduction block is nearly uniform, and the temperature layer by natural convection is formed under the first and third blocks. Especially the third block shows this effect more clearly due to the relatively higher temperature than the first block.

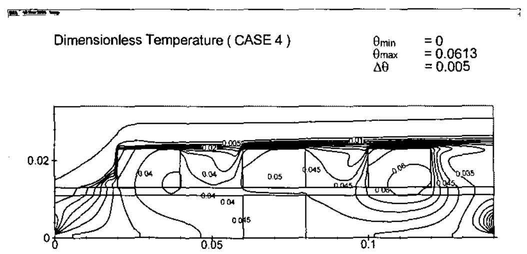


**Fig. 5 Dimensionless temperature distribution (case 4: forced convection/conduction block).**

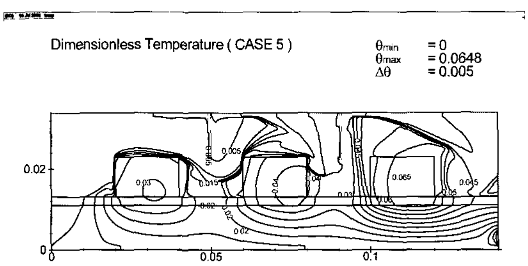


**Fig. 6 Dimensionless temperature distribution (case 5: forced convection with 2 baffles/natural convection).**

Case 5 (Fig. 6) shows the effect of two baffles installed between blocks in the upper channel. Other conditions are same as those of case 1 (forced convection/ natural convection). The thermal boundary layer develops along the top surface of a block and then decreases as the flow direction is changed to the side of a block by the baffle. When the results are compared with case 1 with no baffle, the temperatures of the first and second blocks decrease due to the change of flow direction by the baffles. However, the temperature of the third block increases because downstream velocity decreases due to the baffles and the fluid temperature increases due to the heat transfer enhancement near the upstream blocks. Therefore, when two baffles are installed between blocks in the upper channel, cooling performance is enhanced in the upstream blocks of the baffles (first and second blocks) but the baffles show a negative effect on the downstream block (third block).

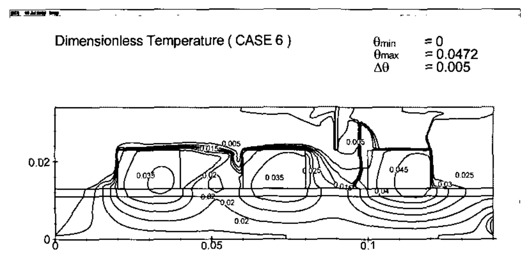


**Fig. 7 Dimensionless temperature distribution (case 6: forced convection with 1 baffle/natural convection)**

To study the effect of baffle number on the cooling performance, only one baffle is installed between the second and third blocks in the upper channel in case 6 (Fig. 7). When the results are compared with case 5 with two baffles, it can be seen that the temperatures of the first and second blocks are similar but that of the third block decreases.

To compare the effect of six different cooling methods on cooling performance and to find efficient cooling method, dimensionless temperature along the block surface and the maximum temperature at each block are compared. Block surface temperature shows the one from bottom to top along left surface, from left to right along top surface, and from top to bottom along right surface of each block successively. The temperature of the PCB between the blocks is not included.

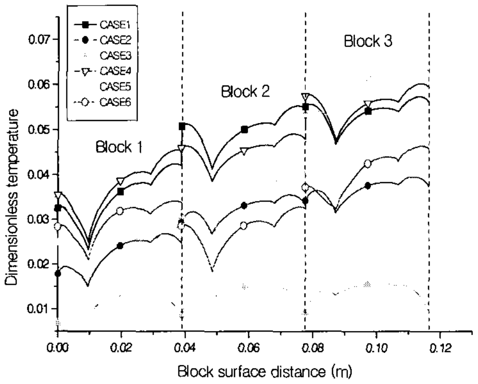


**Fig. 8 Dimensionless temperature along block surface for each case.**

Figure 8 shows the dimensionless temperature along the block surface for each case. The most efficient cooling performance is shown in case 3 (forced convection/liquid cooling) and the worst one in case 1 (forced convection/natural convection). Conduction block seems to be efficient cooling method for the high heat dissipating chips considering low temperature at the second block equipped with it in case 4 (forced convection/ conduction block). However, the temperature of the other blocks increases slightly because the conduction block disturbs natural convection in the lower channel. Surface temperature of each block is nearly same in case 3, and this is advantageous when overall system performance is important.

Cooling performance is enhanced in the upstream blocks of the baffles (first and second blocks) in case 5 (forced convection with 2 baffles/natural convection). However, the baffles show a negative effect on the downstream block (third block). When the upstream baffle is removed in case 6 (forced convection with 1 baffle/natural convection), the problem of deterioration of cooling performance at the downstream block can be prevented.

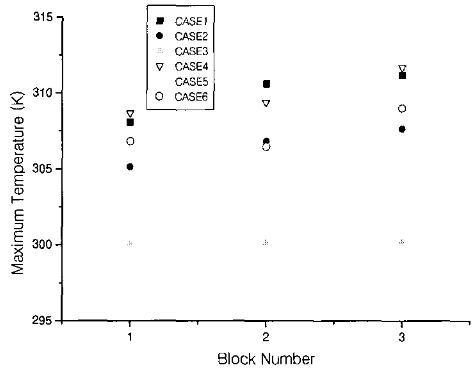


**Fig. 9 Maximum temperature at each block for each case.**

The maximum temperature at each block for the six methods is shown in Fig. 9. Case 3 using liquid cooing in the lower channel is the most effective in cooling performance, and the next is case 2 using forced convection in the lower channel. Case 1 using natural convection in the lower channel shows the worst cooling performance.

To find the method of enhancing cooling performance, cases 4~6 are considered on the basis of case 1. When case 4 using conduction block in the lower channel is compared with case 1, only the second block equipped with conduction block shows lower temperature. Other blocks show higher temperature because the conduction block disturbs the natural convection heat transfer in the lower channel. Two baffles in the upper channel (case 5) show enhanced cooling performance in the first and second blocks but negative effect on the third block. Case 6 using only one downstream baffle in the upper channel shows lower cooling effect in the first block compared to that of case 5 and considerably enhanced cooling performance in the second and third blocks.

## 4. Conclusions

In this study, each cooling technique is identified and compared to find out the effect of each method and the most efficient cooling method for given conditions in a typical electronic equipment system which is modeled as two parallel channels with protruding uniform block heat sources on the middle plate. The following results are obtained by analyzing and comparing six different cooling methods.

1. Forced convection is better than natural convection, and liquid is better than gas in cooling performance as well known. Therefore, it is required that the proper choice of cooling media and cooling method to ensure cooling performance considering the geometry and the heat dissipation required case by case. Liquid cooing in the lower channel prevails the overall cooling characteristics, and it is the most effective cooling method when overall system performance is important.

2. Conduction block offers enhanced cooling performance for the high heat-dissipating chip even though other blocks show slightly higher temperature compared to the case of without conduction block. It is advantageous in cooling to attach conduction block under the high heat-dissipating chip if the structure is not favorable to the forced convection in the lower channel. However, heat transfer analysis is essential to ensure reliable operating temperature because the temperature of other blocks may increase slightly.

3. Baffles in the upper channel offer the better spot cooling performance by inducing the cooling media to the heat source. The cases of two baffles installed between blocks and only one downstream baffle installed in the upper channel show different cooling performance. Baffles can enhance cooling performance in the upstream chips, however, they can give the negative effect on the downstream chips. Therefore, the position and the number of baffles could be very important design parameters to maintain the chip under allowable temperature.

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