# Micro-channel Cold Plate Units for Cooling Super Computer

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*In recent years, there has been a growing demand for an effective high-performance cooling solutions especially in data-centers and super computers because of an increased amount of power consumption there. Water cooling systems have once again been considered as effective means for large scale computer facilities. We have been developing an advanced cold plate technology to build an effective high-performance cooling module of a super computer. In collaboration with a customer, we completed a water cooling unit assembled on the system board of a supercomputer (the K computer). The cold plate units contributed to the computer achieving a high-level of performance (the world's fastest computing) and cutting down on power consumption of CPUs. We will continue to improve and apply this cooling technology to not only super computers but also other electric and industrial products.*

## 1. Introduction

Water cooling systems have become more favorable than conventional air-cooling systems for the cooling of power modules and data-centers with upward trends of performance, power consumption, and downsizing. Increases in consumed power at data-centers, in particular, are expected with increases in the amount of data processing. [1)2)]

Schematics of an air cooling system and water cooling system of servers in a data-center are shown in Fig. 1 and Fig. 2, respectively. Table 1 compares the advantages and disadvantages between the air cooling system and the water cooling system. Air cooling systems are easy to install and re-structure in server racks compared with water cooling systems. However, with increases in heat dissipation, air cooling systems require large-size heat sinks, and hot spots occur during cooling. The cooling is insufficient because CPUs of the server rack are cooled by air, which has low heat capacity and thus requires large air flow and fan power. Then, water cooling systems are more effective than the conventional air cooling systems. Water cooling systems can reduce the size of heat sinks due to high heat transfer coefficients which can further reduce the temperature of a CPU. Ultimately, water cooling systems provide effective cooling while consuming less power. The disadvantage of water cooling is the need of leak-proof water piping connections. Consequently, it is needed to develop and improve not only thermal performance of cold plate, but also leak-proof pipe joint technology of the water cooling systems.

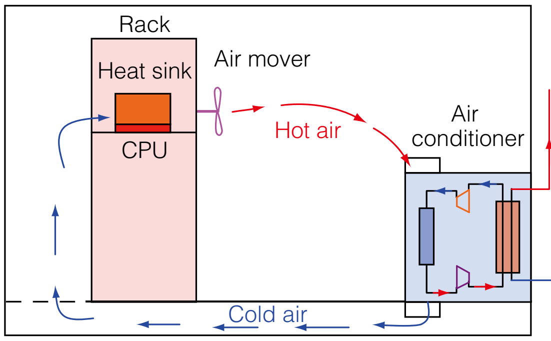


**Fig. 1. Air cooling system.**

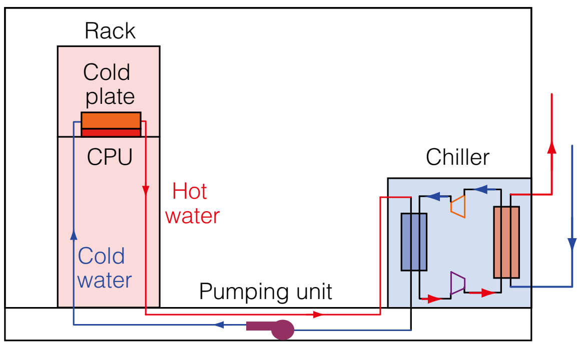


**Fig. 2. Water cooling system.**

**Table 1. Comparison between air cooling system and water cooling system of server.**

| | Air Cooling | Water Cooling |
|---|---|---|
| Advantage | Easy to assembly (Changing position, restructure) No piping of water | High cooling capacity High density of assembly Saving Power |
| Disadvantage, Countermeasure | Need the space of heat sink module. Noisy air flow Hot spot and limitation of cooling capacity. | Need water piping, Leakage of water |

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In this paper, we describe the design calculations for cold plates and the thermal test results, and the development of a cold plate with micro-channels conforming to customer requirements (0.05K/W, withstand water pressure of 1MPa ) for a super computer. The CPUs need to be cooled to a lower temperature. The reason is not only for efficient high performance computing but also for the improved reliability of the CPUs.

## Nomenclature

A : Heat transfer area [$m^2$]
Cp : Specific heat capacity [kJ/kg-°C]
F : Flow rate [kg/s], [L/min]
L : Length of micro-channel fin of cooling module [m]
P : Pressure [MPa]
Pr : Prandtl number
Q : Heat dissipation [W]
R : Thermal resistance [°C/W]
Re : Reynolds number
T : Temperature [°C]
$\alpha$ : Heat transfer coefficient [W/$m^2$-°C]
$\lambda$ : Thermal conductivity [W/m-°C]
$\varphi$ : Thermal efficiency of fin

## Subscripts

b : Base of cold plate
c : Case of CPU
cp : Cold plate
f : Fin
sp : Spreading resistance
w : Water
wi : Inlet of water
wm : Midpoint of water
wo : Outlet of water

## 2. Structure and design of cold plate with micro-channel

1) STRUCTURE AND DESIGN OF COLD PLATE

To improve the thermal performance of cold plates, a micro-channel fin structure is very useful to provide high thermal performance in a compact size.[1), 2)]

Figure 3 shows a schematic structure of a cold plate with micro-channels and definition of temperatures for the cooling design. Micro-channels are formed on the top side of the base of the cold plate. The cold plate is made by brazing a cover onto the base. The water inlet pipe and the outlet pipe are also connected to the cold plate by brazing. The micro-channel fins on the top side of the base part enable the cold plate to cool effectively.

Thermal resistance of cooling module (Rt) is generally defined as follows :

$$R_t = (Tb - Twi)/Q = \Delta Tw/2Q + R_{cp} \quad \cdots\cdots (1)$$

Here,

Tb : Temperature of base of cold plate (°C)
Twi : Temperature of Inlet of water (°C)
$\Delta$Tw : Temperature difference between inlet and outlet (°C)
Q : Heat of CPU (W)

$$R_{cp} = R_{sp} + R_f \quad \cdots\cdots (2)$$

$$R_f = 1/(A_f \ \varphi_f \ \alpha_w) \quad \cdots\cdots (3)$$

$R_{(sp)}$ : Spreading resistance (°C/W)
$R_f$ : Thermal resistance between fin and water flow (°C/W)

For sets of parallel plate fins, the heat transfer coefficient is expressed as the following formula :

$$\alpha_w = 0.664\ (\lambda/L)\ (Re)^{1/2}\ (Pr)^{1/3} \quad \cdots\cdots (4)$$

If the heat loss from a CPU and a cold plate to the surrounding area is negligible, the relation between the increase of water temperature and the flow rate (Fw) of water is expressed by the following expression :

$$Q = (Two - Twi) \cdot Fw \cdot Cp = (T_f - T_{wm}) \cdot A_{fin} \cdot \alpha_w \quad \cdots (5)$$

In the design of a cold plate with micro-channels, there are many parameters affecting the thermal performance such as the area (L x W) of micro-channel fins, the fin height and gap. In this case study, calculations were based on our customer-required configuration. We estimated the heat transfer coefficient by mainly changing the fin gap and height. Figure 4 shows the estimated relation between the micro-channel fin gap, the water flow velocity and the heat transfer coefficient for a constant fin height ($H_f$=3.5mm, $T_f$= 0.5mm). In this design, the fin gap was determined on the basis of stable manufacturing processes and quality.

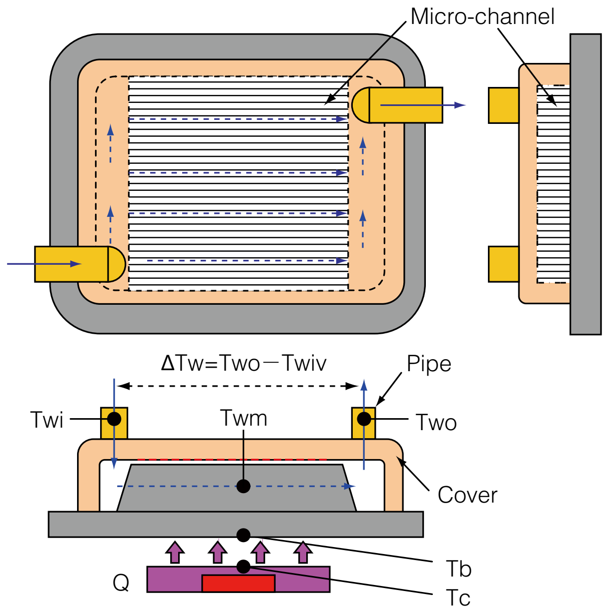


**Fig. 3. Schematic structure of a cold plate with micro-channels.**

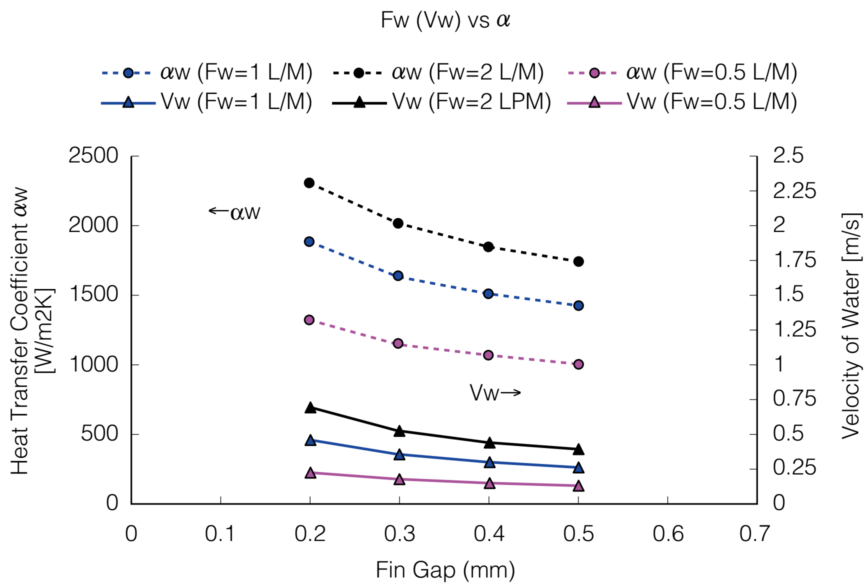


**Fig. 4. Relation between fin gap of micro-channel, water flow velocity Fw, and heat transfer coefficient.**

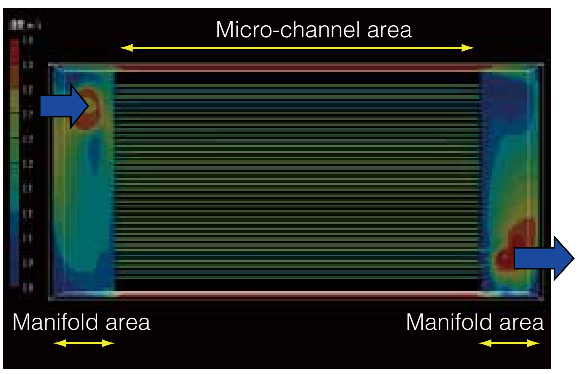


**Fig. 5. Simulation of hydrodynamic flow inside micro-channel.**

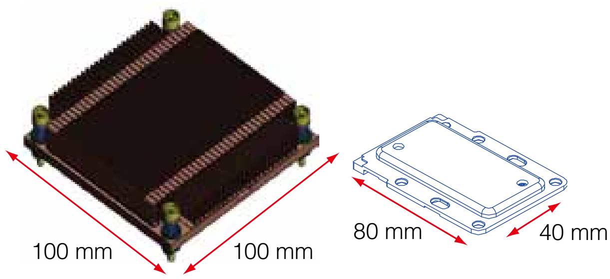


**Fig. 6. Comparison of cooling modules between air cooling and water cooling.**

**Table 2. Estimated comparison of heat sink design in air cooling and water cooling.**

| Parameters | | Heat sink of air cooling | | Heat sink of water cooling | | Ratio of Air/Water |
|---|---|---|---|---|---|---|
| Area of Fin (L × W) | cm | 10.0 × 10.0 | | 8.0 × 4.0 | | – |
| Fin height | cm | 5 | | 0.35 | | – |
| Volume of fin area | $cm^3$ | 500 | | 11.2 | | 45 |
| Fin thick and pitch | mm | 0.5 | 2 | 0.5 | 0.9 | – |
| Heat transfer surface | $m^2$ | 0.5 | | 0.022 | | 23 |
| Flow rate of fluid (Fi) | L/min | 900 | (600 – 1200) | 1 | (0.5 – 2.0) | 900 |
| Velosity rate of fluid (V) | m/s | 3 | (2 – 4) | 0.3 | (0.15 – 0.6) | |
| Heat transfer coefficient | $W/m^2C$ | 30 | (25 – 37) | 1500 | (1050 – 2050) | 0.020 |
| Thermal resistance Rf | C/W | 0.08 | | 0.039 | | 2.1 |
| Thermal resistance dT/2Q | C/W | 0.028 | | 0.007 | | 4.0 |
| Thermal resistance Rt | C/W | 0.108 | | 0.046 | | 2.3 |

In order to obtain designed cooling performance, a uniform flow rate distribution for each channel is indispensable. CFD software is used to validate the effect of the flow rate distribution. Figure 5 shows the calculation results of the simulation at a flow rate of 0.8 L/min. The resalts show that the flow distribution is uniform for this design and condition.

2) Comparison of cooling modules

Table 2 and Fig. 6 compare the estimated thermal performance and the sizes between heat sink for air cooling and cold plate for water cooling in the design condition of cooling CPU of 100 W. The heat transfer coefficient (αa) of air cooling is approximately 30 W/m²°C for a given acceptable air velocity and acoustic noise level. On the other hand, the heat transfer coefficient ($\alpha w$) of water cooling is approximately 1500 W/m$^2$°C, which is 50 times higher than that of air cooling. With the significantly high heat transfer coefficient for liquid cooling, the cold plate design achieved the target thermal resistance ($R_f$) of 0.05 °C/W, and also more compact size.

## 3. Application of cold plate for cooling CPUs of super computer [2)3)]

We designed a cold plate with micro-channel fins for heat transfer to meet the requirements such as high thermal performance (0.05°C/W thermal resistance), mechanical strength integrity (1MPa pressure resistance) and downsizing for a cooling module of high-density assembly. We also adopted a special machining method to manufacture the micro-channel fins.

The cover and base of the cold plate were brazed together for mechanical strength integrity as shown in Fig. 7. However, after brazing, these parts were annealed and the mechanical strength decreased. To increase the mechanical strength, a new brazing process was developed to bond the tips of the micro channel fins to the inside of the cover and the cover to the base.

Prototypes of the CP were fabricated to verify sufficient thermal performance at a heat input of 100 W for various flow rates. Figure 8 shows experimental results of thermal resistance Rt in total and Rcp of the cold plate, and compares them to the calculation results. The experimental thermal resistance results were very close to the calculation values for higher water flow rates (Fw >0.8L/min). Figure 9 shows the experimental results for a relationship between the water flow rate (Fw) and the pressure drop ($\Delta P$) of the cold plate. These test results satisfied the customer's requirement.

Figure 10 shows the final design of the cooling module assembled on the fixing board. The completed cooling module consists of 8 cold plates, pipes and a manifold, all brazed together.

In high volume manufacturing, the cooling module was subjected to a rigorous inspection consisting of helium leakage test, nitrogen pressure test and water flow pressure drop test. In the manifold, there were

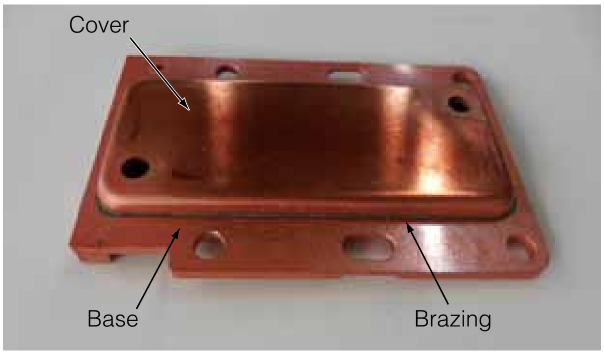


**Fig. 7. Improved brazing of a cold plate.**

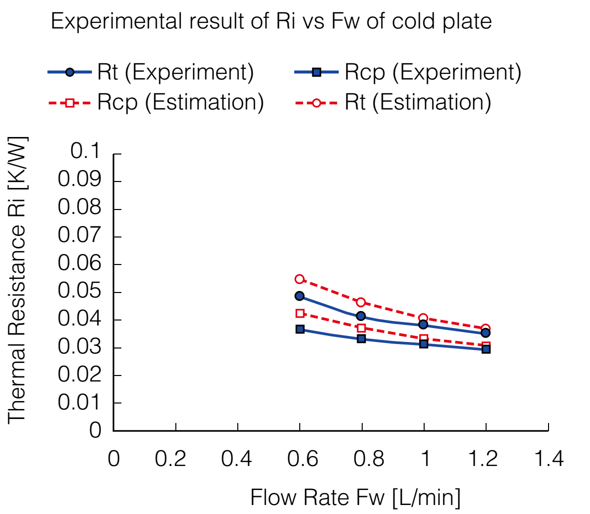


**Fig. 8. Experimental results for the relationship between water Flow rate ($F_w$) and thermal resistance ($R_t$) of the cold plate in comparison to estimated values.**

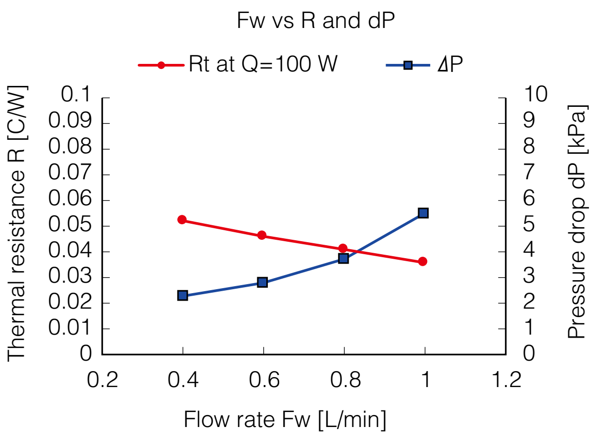


**Fig. 9. Experimental results of water Flow rate ($F_w$) and Pressure drop ($\Delta P$) of the cold plate.**

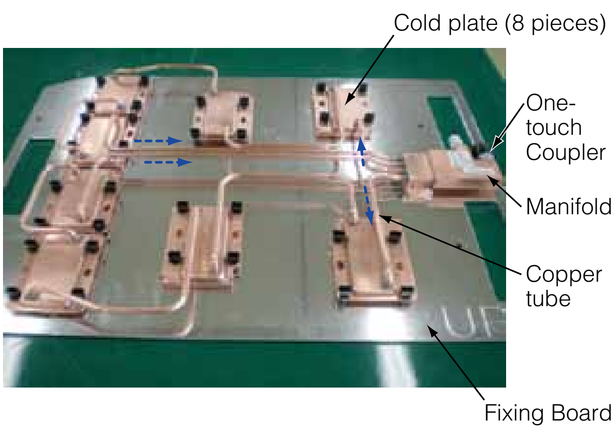


**Fig. 10. Cooling module assembled on fixing board.**

**Fig. 11. Photo of cold plate module assembled on system board of super computer.**

**Fig. 12. Rack of Fujitsu's super computer "K" equipped with cold plate unit.**

two water flow lines arranged in parallel. The total pressure drop of this cooling module was approximately 15 to 20 kPa.

To prevent the cooling module from being damaged during transportation, the module was mounted on a fixing board and shipped to our customer, who will remove it from the fixing b

oard and assemble the cooling module to system boards and server racks.

Figure 11 shows a photo of the cold plate module assembled on customer' system board. Each rack of the super computer manufactured by our customer consists of 30 system boards placed in the top and bottom portions of the rack. Each system board is connected to the cooling system with pipes. The evaluation by the customer has proved that the newly developed cold plate module drastically decrease the temperature of the CPU and also lower its power consumption.

## 4. Other applications of cold plate

Application to laser diode cooling

Laser machining such as welding and cutting has attracted much attention recently. Among lasers for machining, a fiber laser usually uses a set of semiconductor laser diodes for pumping, which requires efficient heat dissipation. The conventional cold plate shown in Fig. 13 has less capability to cool down the diodes to 45°C or lower. In contrast, the novel cold plate with micro channels has easily cooled the laser diodes to 30°C at a water cooling temperature of 20°C and at a flow rate of 8 L/min. In the cooling system for the laser diodes, each cold plate and the connecting pipes are arranged to minimize pressure drop and flow imbalance.

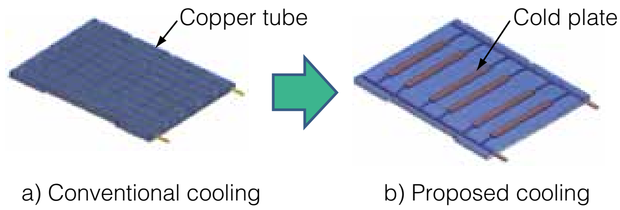


**Fig. 13. Requirement of cooling fiber laser diodes.**

## 5. Conclusion

We have developed a cold plate technology to build a high-performance cooling module. The module has a micro-channel fin structure to efficiently transfer heat and has met customer requirements such as high thermal performance and downsizing for high-density servers of the super computer. The experimental results of the thermal performance were in good agreement with the calculation results. We also have developed a new brazing process for mechanical durability under high pressure to respond to the requirement of high mechanical strength of the brazed cold plate. Finally, we have established manufacturing and inspection processes of the high quality products. We will continue to improve and apply this micro channel cold plate technology to other products on the market.

## References


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