Liquid immersion cooling technology with natural convection in data center

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***Abstract*— We proposed a liquid immersion cooling technology with natural convection for high power server boards used in data centers with high cooling-efficiency. The cooling performance was evaluated by CFD simulation and actual experiments. As the refrigerants, several non-conductive, thermally and chemically stable fluids were applied, including silicone oil, soybean oil, and perfluorocarbon structured liquids. The CPU temperature in the refrigerant monotonically decreases with the Rayleigh numbers of the refrigerant. The smoother refrigerant is better for cooling the high power CPU. The changes in any CPU task and any slot-removal give limited cooling effects to other slots and other CPUs. These are quite useful features for stable operation of servers in data center. As a result, this proposed technology with natural convection exhibits promising potential for low energy and space-saving board cooling which demonstrates a Power Usage Efficiency (PUE) below 1.04.**

Keywords—liquid immersion, natural convection, data center, cloud computing, power usage effectiveness, computational fluid dynamics

I. Introduction

Data center is an important business infrastructure that supports various cloud services. In addition, it will act a central role for promoting several future Internet of Things (IoT) businesses [1].

However, the electric power cost for the data center is increasing around 8 times in this 10 years. DOE reported that the power consumption of the data center worldwide reaches around 2% of the total power consumption in the world [2]. The power consumption originates from the 3 sectors in it. It includes servers, air conditioner and power supplies. In order to suppress the total power consumption, we need to increase each power-efficiency of each equipment and also increase the total management efficiency of the operation [3].

Nowadays, server power is dramatically increasing in the data center including high power computer infrastructure (HPCI) and high-end General-purpose computing on graphics processing units (GPGPU) system. For such high power data center, air-cooling technology is not effective enough to handle the heat generated.

PUE (Power Usage Effectiveness) [4] is an effectiveness of operation from the aspect of power consumption of IT equipment. The PUE in the world has been decreasing since 2006, and reaches around 1.1 at minimum [3]. When the PUE=1.0 is demonstrated, the power consumption decreases around 9% from the PUE=1.1 level. From the aspect of OPEX, the 9% is significant.

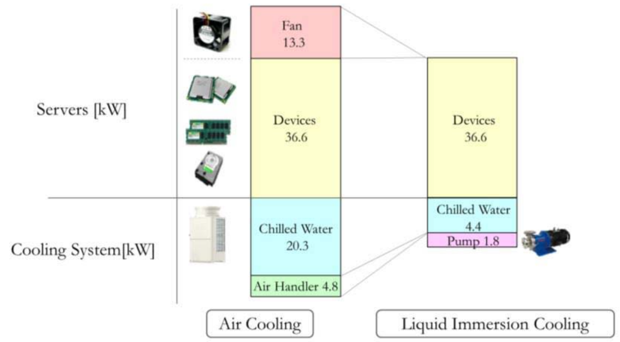

Fig.1. Example of total power consumption of data centers with air cooling and liquid immersion cooling. Liquid Immersion Cooling system can reduce total power consumption.

In this study, we proposed and demonstrated a sophisticated cooling technology for such high power consumption server board in data centers. Also, we are aiming to demonstrate the next challenging and super high level stage, PUE =1.0x (x<4). In order to demonstrate the high efficient data center for high heat density servers, the liquid immersion technology was applied in this study. Already, several trials of the liquid immersion technology were performed, including immersion with pumping to provide circulation [5,6,7] and 2 phase immersion [8]. In those systems, low PUE was demonstrated for high heat density servers, as shown in Fig. 1. Also, in a conventional data center with air cooling system, lot of space is required for effective cooling, in which air conditioners and server racks are located. On the other hand, the required space for the immersion cooling technology can be ideally suppressed below around 1/3 of that of an air cooling system, as shown in Fig.2.

On the other hand, our technology is the liquid immersion technology with natural convection, without any pumping or any fan in the bathtub for the refrigerant circulation. This system enables high efficient cooling technology for high density server with PUE= 1.0x, which is expected to be lower

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than the already demonstrated immersion cooling technologies. Because, for operation of this system, electric power required for circulating the refrigerant is unnecessary, and only electric power for circulating the cold water having a low specific gravity inside the cold plates and heat exchange of the water is required.

Also, for the conventional liquid immersion technology, floor loading level sometimes exceeds 1,000kg/m2, which is higher than the standard of conventional building. Therefore, low floor loading level is also one of our goal feature.

In this paper, computational fluid dynamics (CFD) simulation was tried at first for making basic design of the liquid cooling immersion system with natural convection, and next the actual experiment was demonstrated.

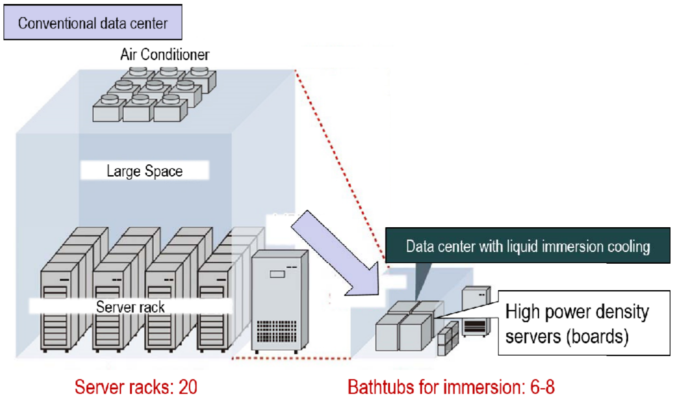

Fig.2. Comparison of space of data center with conventional air cooling technology and with immersion technology.

II. Experimental Procedures

The boards were immersed into the bathtub filled by the refrigerant without any pump or any fan for the refrigerant circulation in the bathtub. The models of the liquid immersion cooling system with natural convection and a snap shot of an actual experimental bathtub are shown in Figs 3 and 4.

For the CFD simulation, the 2 CPUs with 140 W power at maximum and 16 memory boards with 10 W power at maximum were set on a mother board. The 24 or 48 mother boards (48 or 96 CPUs) were immersed into the bathtub with 600mm X 600mm X 870mm. The 9,000,000 meshes are applied. The size of each mesh is small enough for the simulation, because the spacing between the board is smaller than the mesh size. The total power of the system reached a maximum of 14kW. Four cooling plates with 560mm X 560mm were implemented in the bathtub, three of them were placed parallel to the wall and one to the bottom, and cool water with temperature between 15 to 35 degrees C was flowed inside the plates. The heat exchanger for making the cold water is located outdoor. As mentioned above, the electric power required for circulating the refrigerant is unnecessary, and only electric power for circulating the cold water having a low specific gravity inside the cold plates and heat exchange of the water is required.

By using CFD, we achieved the natural convection without any pump or any fan inside the bathtub. For the simulation, Flow Designer Ver. 2017 of Advanced Knowledge Laboratory, Inc. was used [9]. Figure 5 shows a CFD model we constructed. Upper one is a top view of the bathtub and lower ones are side view and front view of the bathtub. The light blue part represents cold plates placed in the bathtub. Dark blue part on top of the side and front views are filled by air.

For the actual experiment, 6 server units were placed in the bathtub, each server unit consists 4 servers, and eventually 48 CPUs (Intel Zeon processor which power reaches around

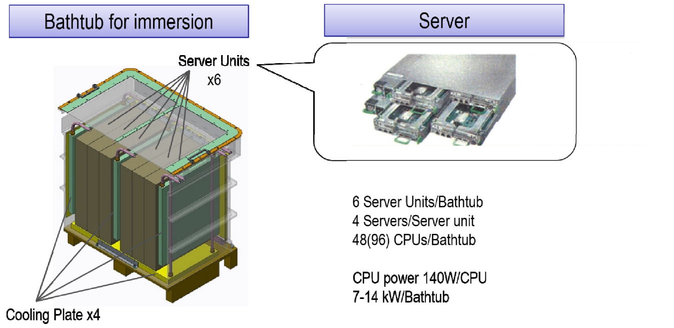

Fig.3. Experimental apparatus for liquid immersion cooling with natural convection.

Fig.4. Snap shot of liquid immersion system with natural convection.

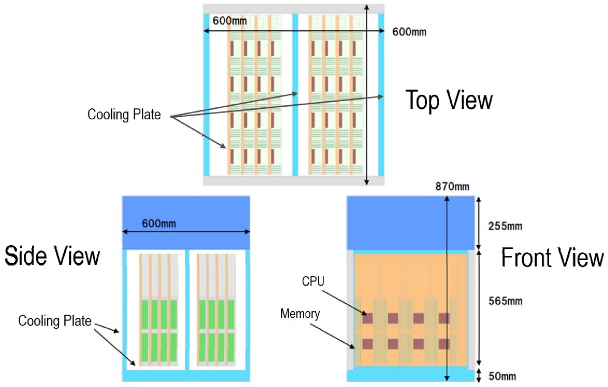

Fig.5. CFD model for liquid immersion with natural convection.

140 W at maximum task) are immersed into the bathtub. The CPU power of 100 W was applied to each CPU at maximum task. The total size of the system actually reaches around 1/3 of the conventional rack structure for air cooling, as already shown in Fig.2.

As the refrigerants, we applied several types of non-conductive, thermally and chemically stable fluids, including silicone oil, soybean oil, and perfluorocarbon structured refrigerant (*Fluorinert*) [10].

III. Results and Repare Discussions

A. CFD Simulation –Determination of Optimum Refiregrant-

Typical cooling water flows inside the cooling plates analyzed by CFD is shown in Fig.6. The water flow in 3 side cooling plates and one bottom cooling plate are clearly seen. The cooling water is flowed from the heat exchange system located outside. The temperature and the flow rate were changed from 15 to 35 degrees C and from 0.005 to 1 m/sec, respectively. A typical refrigerant circulation analyzed by CFD is shown in Fig.7. Each line represents the flow of the refrigerant. As clearly seen in this figure, no pumps and no fans to generate convection are contained in the bathtub, and the refrigerant is circulating around the board with natural convection. This convection is caused by an upward flow due to the heat generated only by the CPU. In other words, the driving force of the natural convection is the only heat of the CPUs.

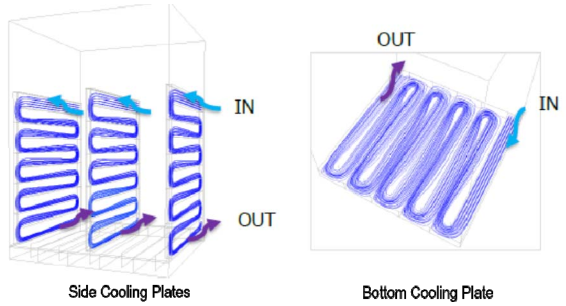

Fig.6. Typical cooling water flow in the cooling plates.

Figure 8 shows a typical snapshot of temperature distribution. As clearly seen in the image, CPUs are heated and the refrigerant heated by the CPU is circulating from the bottom to the top of the bathtub. Figure 9 also shows a snap shot of flow rate distribution of the refrigerant viewed from the front and side. The space above the middle line is the air layer, and the refrigerant is filled up to the line. As clearly seen in the image, an upward flow is generated by the heat of CPU. The flow rate is about 0.1 m/sec at 140 W. Figure 10 also shows typical temperature distributions inside the cooling plates. As shown in the figure, temperature on the top of the cooling plate is higher than that on the bottom of the cooling plate. This temperature distribution corresponds to the refrigerant circulation and heat transfer from the refrigerant to the cooling plate. These results indicate that the refrigerant circulates only based on the natural convection and the heat is removed from the CPU surface, effectively.

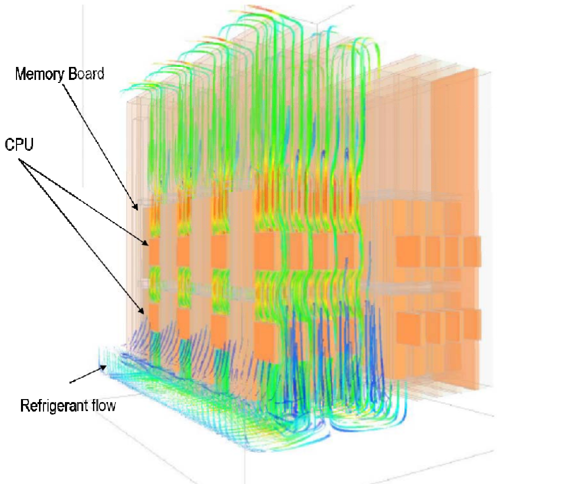

Fig.7. Typical flows of the refrigerant in the bathtub with natural convection.

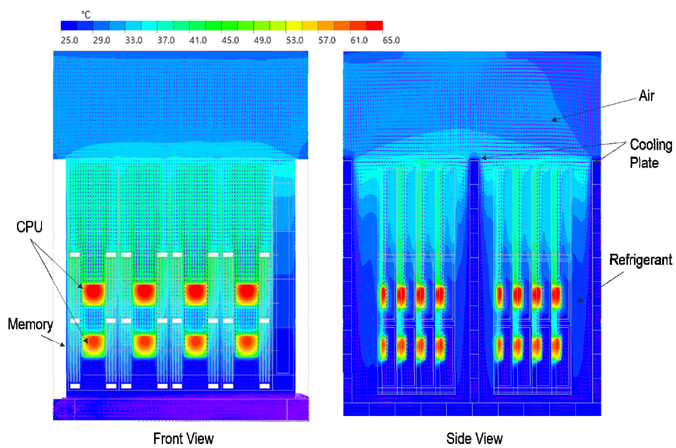

Fig.8. Typical temperature distribution inside the liquid immersion tub with natural convection. In this case, the refrigerant is 30% ethylene glycol.

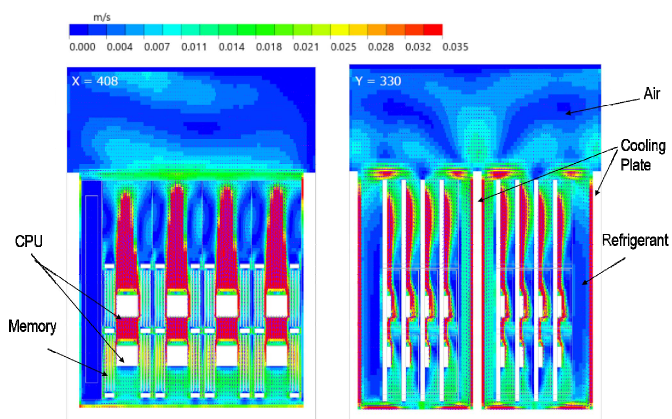

Fig.9. Typical flow rate distribution inside the liquid immersion tub with natural convection. In this case, the refrigerant is 30% ethylene glycol.

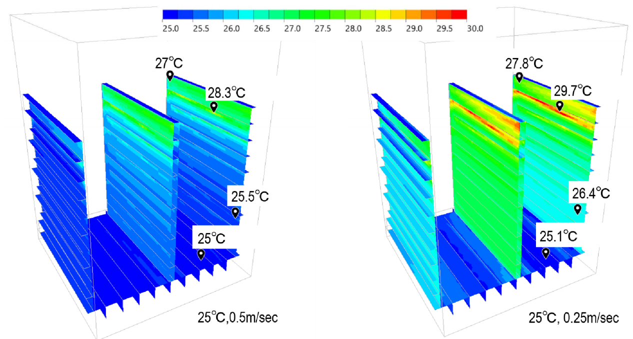

Fig.10. Typical CFD image of water flow inside the cooling plates.

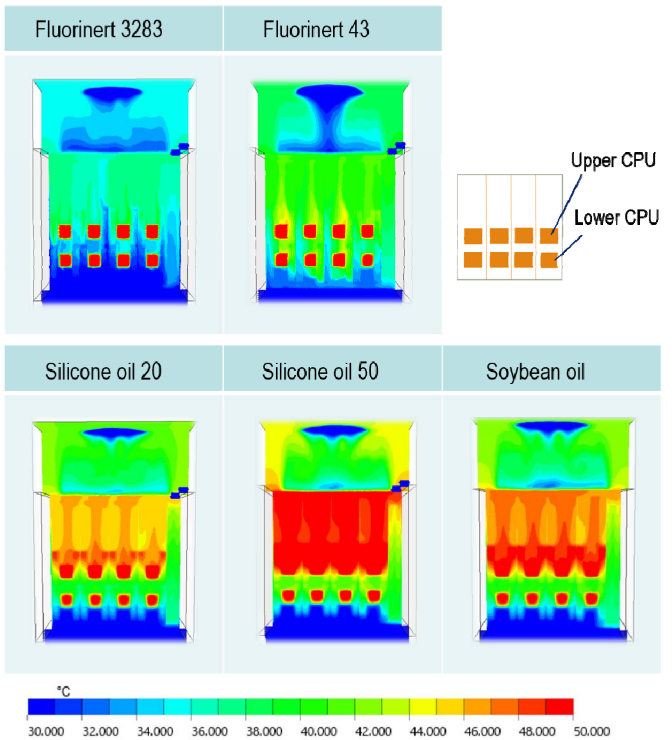

Fig.11. Typical front views of temperature distribution for several refrigerant in liquid immersion tub with natural convection.

Next, we analyze the thermal characteristics for several refrigerants. Figure 11 shows some patterns of temperature distribution for several refrigerants. From the left side, the pattern corresponds to fluorinate FC3283, and fluorinate FC43 [10], and silicon oil 20, also silicon oil 50, and last, on the right side, soybean oil. As clearly seen in the images, the temperature of the CPU reached around 50 degrees C in every case. Also, when the fluorinate was used as a refrigerant, the temperature of the refrigerant was kept lowest. When silicon oil is used, the refrigerant temperature reached around 50 degrees C. This suggests that fluorinate FC3283 and FC43 of smoother refrigerant are better than silicon 20, 50 and soybean oil of muddy or sticky refrigerants. These results indicate that the cooling effect for natural convection strongly depends on the viscosity of the refrigerant.

The more detailed simulation results are shown in Figs.12 and 13. Fig.12 represents a relationship between Rayleigh numbers of the refrigerants, a sort of the index of the viscosity, and CPU surface temperature. Also, Fig.13 represents a relationship between the Rayleigh numbers and flow rate of the refrigerant on the CPU surface. Here, the Rayleigh numbers are estimated at 25 degrees C due to the model's geometry. As seen in these figures, the CPU temperature monotonically decreases and the flow rate increases with the Rayleigh numbers. These results indicate that the smooth refrigerant, like fluorinate, is better for cooling the high power density CPU. In this model, we assumed that the heat generation in the CPU is uniform. Therefore, the temperature monotonically decreases from inside the CPU and to the CPU surface. Since, in the real CPU, heat generates only at the junction point, this model is not accurate, but as we will look at the experimental results later, the simulation results qualitatively explain the experimental results well.

The CPU temperature monotonically decreases until a certain water flow level. As long as the flow rate of the water inside the cooling plate is around 0.1 m/sec, the heat generated from the CPU is removed well at any temperature. The larger the Rayleigh number is, also the lower the water temperature inside the cooling plate is, the better the cooling performance is. When the CPU power reaches 140W, in case of FC3283, in order to keep the CPU surface temperature below 50 degrees C, the water temperature in the cooling plate should be reduced below 30 degrees C. Also, when using Si50, it is necessary to keep the cooling plate water temperature below about 20 degrees C.

It was also found that when the heat sink is attached to the CPU surface, even if the Rayleigh number of the refrigerant changes, its cooling efficiency is not greatly affected. This indicates that the heatsink with fins spaced by 6 mm (set in the CFD model) was not affected by the natural convection of the refrigerant.

B. CFD Simulation -Impact of Slot Removal-

In this section, we investigate the cooling effect on other slots when some slot is inserted or removed. Figure 14 shows a typical convection pattern when one slot is removed from the bathtub. As shown in the figure, it has little influence. Interesting thing is that the flow of refrigerant is nearly zero without refrigerant flowing backward (in this case downward flow) in the empty space from which the slot is removed. This indicates that the convection occurs only in a certain portion of the slot, so the change in convection in the portion without slots does not affect other slots. From this, it seems that as a kind of pipe model, circulation paths for the refrigerant with the same cross section is made, so that the flow velocity of the circulation flow path becomes constant. Therefore, the refrigerant does not flow backward to the empty slot. This has very advantageous features in terms of maintenance. This means that any board can be inserted and removed even during operation without change in the cooling parameters.

C. CFD Simulation -Impact of Task Allocation-

In the same way, the influence of the cooling effect on other CPUs and slots when task is given to a CPU in a certain portion. The impact of the CPU task is shown in Figs.14 and 15. As shown in the figure, the effect of the task on the other CPUs and slots is limited even when some CPU power changes dynamically. The impact of the CPU power to other CPU temperature are summarized in Figs.16 and 17. As can be seen from these figures, the higher the Rayleigh number, the lower the CPU surface temperature is as mentioned above. For any of the refrigerants, only the surface temperature of the CPU whose electric power has been changed is changing and the CPU surface temperature above or below that the electric power is not changed hardly changes. In other words, The influence on the other CPU due to the CPU power of a certain portion is limited. Since the convection which depends on the heat of the CPU occurs, the convection does not affect other CPUs and other slots. This has very advantageous features in terms of operation.

D. Experiments

Next, we performed the actual experiment. The simulation results predict well the experimental results qualitatively. The natural convection enables the effective cooling of high power density board. As described before, the 24 server boards are immersed into the refrigerant bath. No pump or no fan is placed inside this bathtub. From the CFD results, among the refrigerants we applied, we concluded that FC3283 is the best refrigerant with the best cooling performance in case of the immersion technology. Therefore, hereafter, we use the FC3283 as a refrigerant in an actual experiment.

The cooling performance of immersion technology using natural convection is analyzed by the actual experiment. The lower the temperature of flowing water inside the cooling plate, and also the higher the flow rate, the higher the cooling efficiency of CPU. In other words, it is understood from these results that natural convection technology can be used sufficiently within a practical range.

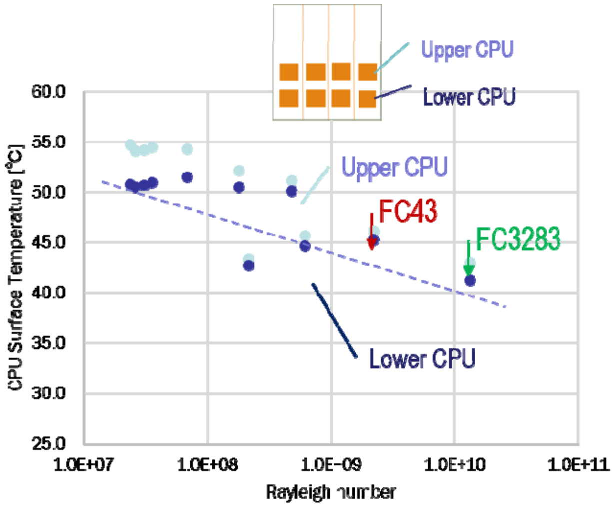

Fig.12. Relationship between the Rayleigh numbers of the refrigerant and temperature of the CPU surface. Here, the CPU power is 140 W, and water flow rate is 0.1 m/sec.

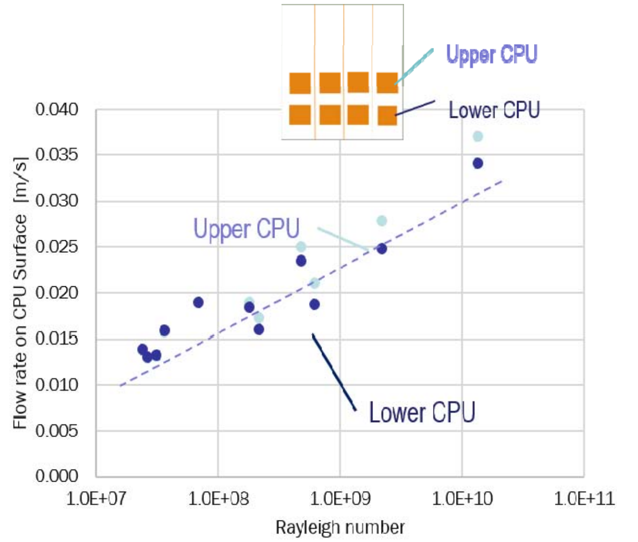

Fig.13. Relationship between the Rayleigh numbers of the refrigerant and flow rate on the CPU surface. Here, the CPU power is 140 W, and water flow rate is 0.1 m/sec.

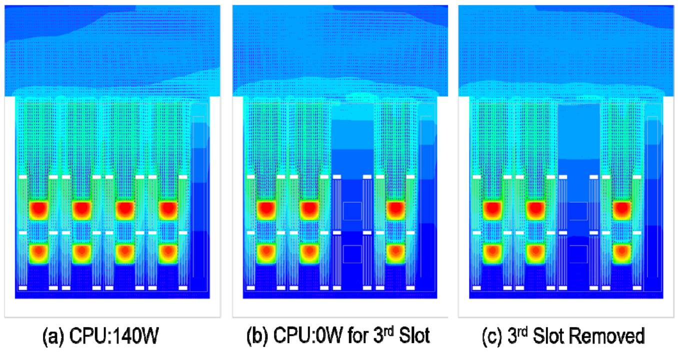

Fig.14. Typical convection pattern when task is not applied to a part of CPUs(b) and some slot is removed from the bathtub(c).

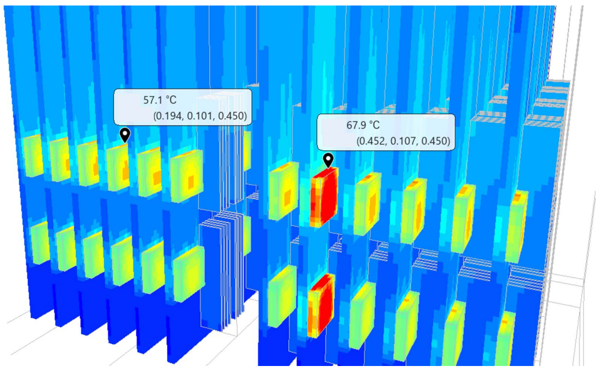

Fig.15. Typical CPU temperature distribution when over-task is applied only to CPUs of one slot. The heat of the CPU's do not affect the other CPU's temperature.

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