PERFORMANCE IMPROVEMENT OF AN INDUSTRIAL CONTROL ENCLOSURE COOLING SYSTEM

by

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Original scientific paper
https://doi.org/10.2298/TSCI201205177C

Following the trend of high accuracy machining, thermal management of industrial control enclosures become a critical issue. Therefore, a well-designed enclosure cooling system is essential to manage the heat generation inside the enclosure. In this study, to improve the performance of cooling system and the air-flow distribution inside the enclosure, CFD simulation has been used to evaluate the application of using the auxiliary circulation fan and air baffler. Furthermore, this study also investigates the lay-out design for both supply air vent and return air vent arrangement by two types of commercialized cooling systems through field measurements. The simulation results show the short circulation of air-flow is improved when the air baffler is installed. It also shows that the auxiliary circulation fan is suggested. Besides, air baffler is used to enhance the temperature distribution. The experimental results reveal the upper supply vent arrangement will cause the short circulation of air-flow slightly. The auxiliary circulation fans can improve the heat dissipation of cooling systems. There is no short circulation of air-flow for the lower supply vent arrangement, but the supply air cannot be distributed smoothly by the auxiliary circulation fans because the shape of the air baffler is not properly designed.

Key words: *cooling system, industrial control enclosure, CFD simulation, air-flow distribution, temperature distribution*

Introduction

The machine tools (such as turning, milling or grinding machines) are normally called mother machines which are usually used to remove metal or other hard materials [1]. The industrial control enclosure of machine tool is used to prevent unfavorable environmental influences (such as dust and moisture) from damaging the electrical components [2, 3]. It can also prevent people from touching components because the door of industrial control enclosure must be closed when the machine tool is operating [4]. However, the temperature in the industrial control enclosure will rise gradually at the same time, due to the heat generation of electrical components which exist when high speed and high accurate machining is under operating in high ambient temperature environments.

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Moreover, the lifespan and efficiency of electrical components inside the industrial control enclosure will degrade because they are sensitive to temperature during operation [5, 6]. A general rule of thumb is that higher temperature in the industrial control enclosure results in a shorter lifespan of the electrical components. Furthermore, the high internal enclosure temperature will induce the equipment (*e.g.* machine tool) reliability problems significantly [7, 8]. Therefore, it will be challenging to develop high speed and high accurate machining stably without appropriate temperature management for the industrial control enclosure.

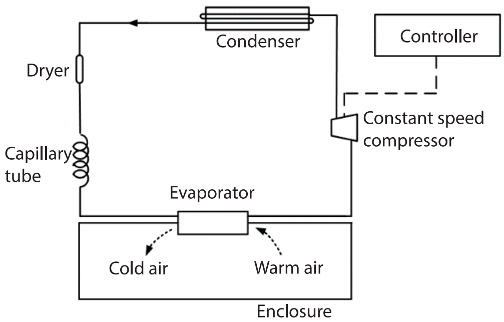

Figure 1. Schematic of typical enclosure cooling system

A variety of cooling methods have been proposed and used to cool the industrial control enclosure. These including natural-convection cooling method, forced convection cooling method, closed loop cooling method (*e.g.* commercialized enclosure cooling system). When natural-convection is not adequate, the forced convection is adopted by a fan or blower to blow the air through the enclosure that houses the electrical components [9]. In general, an enclosure cooling system is essential for managing the temperature inside the industrial control enclosure. The schematic of typical enclosure cooling system is shown in fig. 1. The figure is composed of four main components (including constant speed compressor, condenser, evaporator, and capillary tube). The evaporator will absorb heat from the air which is circulated in the enclosure. The thermal management of a sealed enclosure using different techniques such as natural-convection, heat sinks and mini-heat pipes have been explored [10].

The CFD simulation was studied by considering an aluminum electrical enclosure [11, 12]. Furthermore, CFD simulation was applied to a turbulent environment [13]. An electronic driver unit of an HVAC system operated in a dusty environment within an enclosure was analyzed by numerical method and experimental method [14]. Furthermore, the air-to-water heat exchangers operated by removing the heat from inside an enclosure using cooled water from a chiller were also investigated [15].

The applications of ANN for the field of refrigeration and air-conditioning were presented [16, 17]. It is shown that the ANN overcomes the limitations of conventional approaches (*e.g.* experimental method) based on some training data, which does not require any specific analytical equations. But, the limitations of ANN modelling should be avoided (*e.g.* the phenomenon of over-training). Moreover, the problem of natural-convection in an enclosure in heat transfer field was investigated with CFD and ANN. It has been found from the comparison between the CFD and ANN prediction that the two results have a good agreement with each other [18]. And, the ANN model was constructed and trained based on the part of database from CFD simulation. When ANN model combined with appropriate control strategy, can be used for real-time control [19].

To improve the performance of the cooling system and the air-flow distribution inside the industrial control enclosure, the CFD simulation has been conducted to analysis the air-flow distribution inside the enclosure. Because few studies discuss the heat transfer performance between upper supply vent arrangement and lower supply vent arrangement for enclosure cooling system, two types of commercialized enclosure cooling systems are implemented to assess different lay-out design of supply air vent and return air vent of the cooling system in the experiment.

Numerical simulation for improvement

As shown in fig. 2(a), the investigated enclosure cooling system is mounted to the door of an industrial control enclosure. The electrical components (*i.e.* transformer, servo amplifier) are housed inside the enclosure. The transformer is located at the bottom of the enclosure. The servo amplifier is located in the upper part of the enclosure. The dimension of the industrial control enclosure is at length of 450 mm, width of 1400 m, and height of 1610 mm, respectively. The geometry model of industrial control enclosure, cooling system, and the electrical components are shown in fig. 2(b). And, the model is established using the pre-processer (*i.e.* GAMBIT). The air inside the enclosure will be circulated by the air vents.

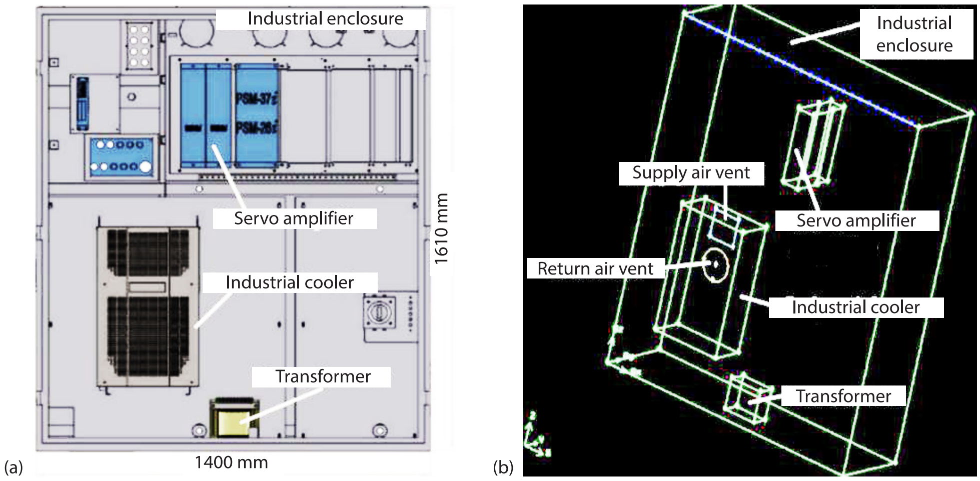

Figure 2. (a) Front view of an industrial control enclosure and (b) schematic diagram of geometry model

The grid meshes are generated also using the GAMBIT as shown in fig. 3. It can be seen that the air baffler is installed on the supply air vent of cooling system. To evaluate the application of using the air baffler for improving the air-flow distribution, a comparison between the cooling system with air baffler and the cooling system without air baffler were simulated. After the grid mesh tests, the relative error between the 325870 cells and 484833 cells is 5.06 %. The relative error between the 484833 cells and 604588 cells is 1.62%. Therefore, it revealed that 484833 cells are acceptable for obtaining accurate results at minimum computational cost.

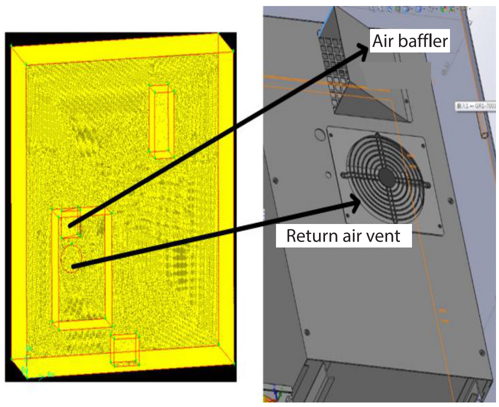

Figure 3. Grid mesh and air baffler of enclosure cooling system

Furthermore, a commercial CFD code (*i.e.* FLUENT) is used to simulate the temperature profile and velocity distribution in the enclosure. Several assumptions are made as follows to make the problem tractable:
– steady-state flow,
– flow is *considered to be* 3-D*,*

– fluid-flow is considered to be incompressible,
– thermal conductivity is constant,
– the initial temperature of the wall and air are uniform, and
– radiation is neglected.

The boundary conditions are shown in tab. 1. Moreover, the governing equations solved by FLUENT including:
– mass conservation equation,
– momentum conversation equation, and
– energy conservation equation.

Moreover, because of turbulent flow, the standard k-ε turbulent model is used to solve the flow equation.

Table 1. Boundary conditions

Interface	Type of boundary condition
Fluid	Air
Supply air	Velocity-inlet
Return air	Outflow
Shell (enclosure, servo amplifier, transformer)	Wall

The simulation conditions are shown in tab. 2.

Table 2. Simulation cases and conditions

Case	Conditions	Remark
A	Cooling system without air baffler No heat generation of electrical components in the enclosure	Velocity of supply air vent is 1.1 m/s Temperature of supply air vent is 22 °C The ambient temperature is 35 °C
B	Cooling system with air baffler No heat generation of electrical components in the enclosure	
C	Cooling system with air baffler Total heat generation of electrical component in the enclosure is 482 W (*i.e.* transformer is 77 W, servo amplifier is 405 W)	

Experimental rig

The experimental rig includes a horizontal turning lathe, an industrial control enclosure, and an enclosure cooling system. The specification of horizontal turning lathe is given in tab. 3. As shown in fig. 4(a), the cooling system is mounted to the front door of a control enclosure of the horizontal turning lathe for managing the air temperature control in the industrial control enclosure. As shown in fig. 4(b), there are components (*i.e.* servo amplifier, axial AC fan, electromagnetic contactor, and so on.) in the control enclosure. The temperature of the components will increase gradually when the machining is underway. It must be noted that the

Table 3. Specification of the horizontal turning lathe

Items	Value
Max. spindle speed	3500 rpm
Bar capacity	75 mm
$L \times W \times H$ (with chip conveyor)	4813 mm × 2100 mm × 1935 mm

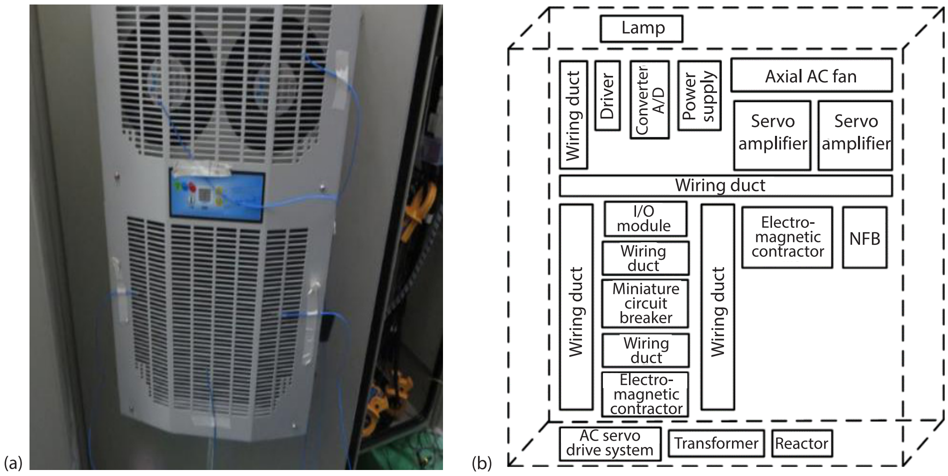

Figure 4. (a) Snapshot of the enclosure cooling system and (b) electrical components inside the industrial control enclosure

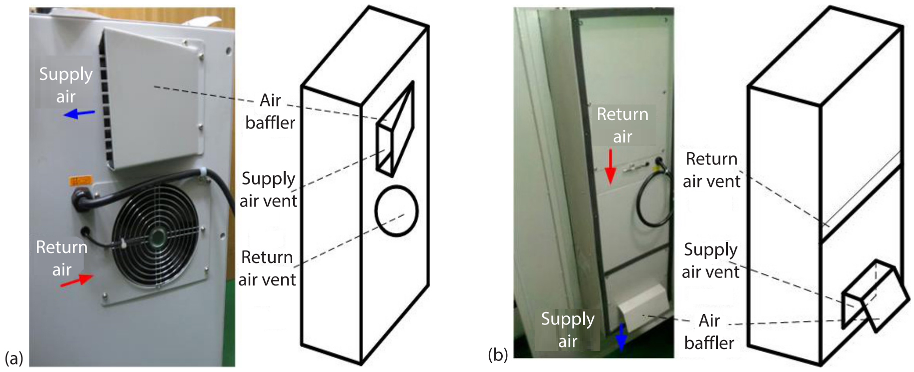

Figure 5. Snapshot and schematic representation of the cooling system; (a) A type cooler and (b) B type cooler

axial AC fan on the upper right side of the fig. 4(b), is used as the auxiliary circulation fan. Additionally, two types of cooling systems are used in the experiment.

Two commercialized enclosure cooling systems were designed at the same cooling capacity (about 900 W). Furthermore, as shown in fig. 5(a), the supply air vent of one of the cooling systems were designed above the return air vent. In other words, it is upper supply vent arrangement (hereinafter called *A type cooler*). The distance between supply air vent and return air vent is about 5 cm. On the other hand, the supply air vent of the other one is designed below the return air vent as shown in fig. 5(b), which is lower supply vent arrangement (hereinafter called *B type cooler*). It can be seen that the air baffler is installed on the supply air vent in the fig. 5. Moreover, the temperature sensors (thermocouple)

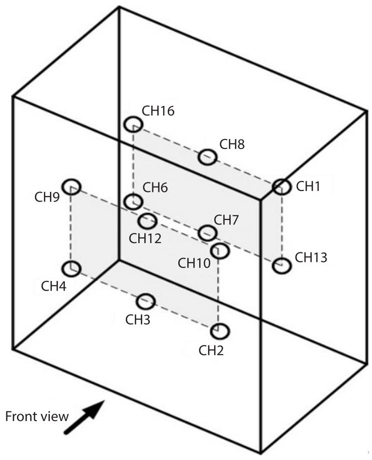

Figure 6. Temperature sensors lay-out inside the industrial control enclosure

are used to measure the air temperature at supply air vent and return air vent of the cooling system and ambient temperature. There are also temperature sensors to measure the air temperature distribution inside the control enclosure, as shown in fig. 6. Apart from this, the temperatures of electrical components were measured using a thermal imaging infrared camera after opening the door of industrial control enclosure. Table 4, depicts the summary of experimental conditions for the experimental test rig.

Table 4. Experimental conditions

Items	Value	Remark
Ambient temperature	About 29 °C	NA
Constant spindle speed	1750 rpm	NA
Set temperature of inside the industrial control enclosure	35 °C	According to the return air temperature of the cooler
Cooler start up point	36 °C (*i.e.* set temperature +1 °C)	Upper temperature for start up
Cooler stop point	34 °C (*i.e.* set temperature –1 °C)	Lower temperature for stop

Results and discussion

The simulation results of Case A are shown in fig. 7. From fig. 7(a), the short circulation of air-flow is obvious between supply air vent and return air vent of the enclosure cooling system. As shown in fig. 7(b), the temperature inside the enclosure is about 35 °C (308 K) except the air vents. Therefore, it reveals that the air-flow distribution inside the enclosure is not proper for the purpose of heat dissipation. On the other hand, the simulation results of case B are shown in fig. 8. As shown in the red circle in fig. 8(a), although minor little supply air still returns to the return air vent, but the phenomenon of short circulation of air-flow can be improved obviously because of the air baffler. However, as shown in fig. 8(b), there still exist a temperature difference (about 5 °C) between the upper and lower sides in the enclosure. The temperature of upper side is higher than the temperature of lower side. It reveals that the auxiliary circulation fan on the upper side of the enclosure is suggested to improve the air-flow distribution inside the enclosure.

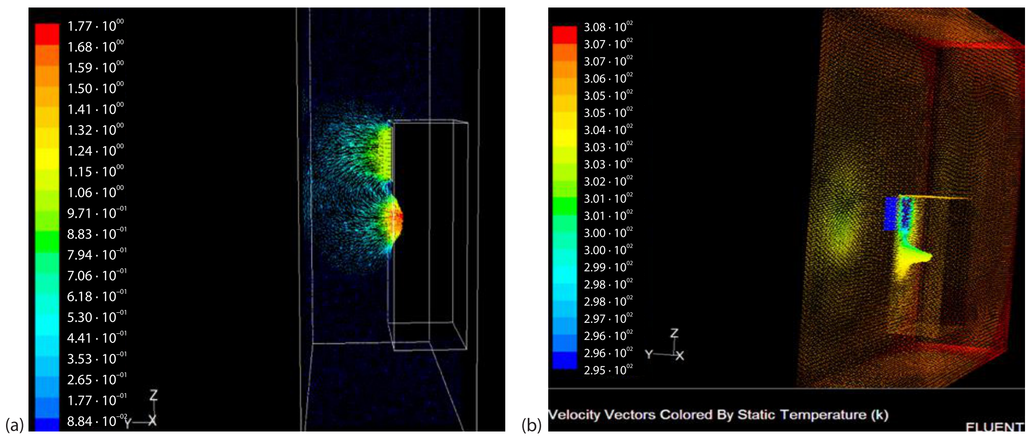

Figure 7. Velocity and temperature contour of air vents of the cooling system for Case A; (a) velocity contour and (b) temperature contour

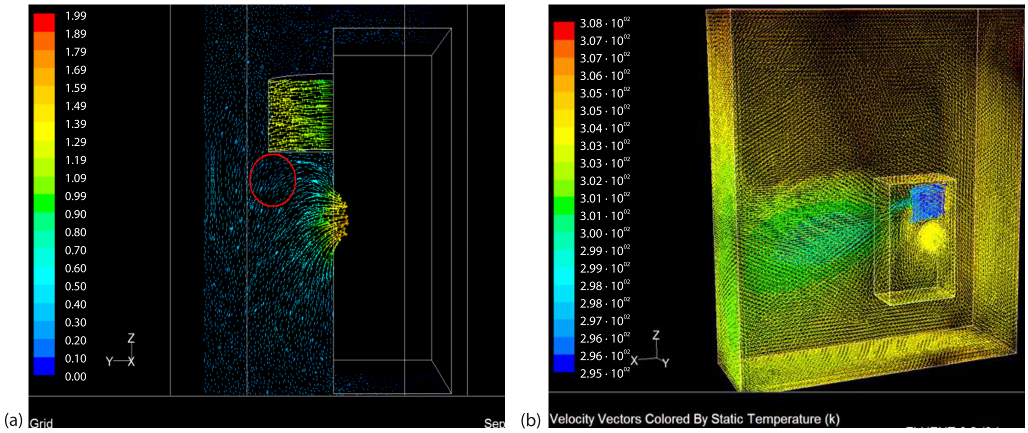

Figure 8. Velocity and temperature contour of air vents of the cooling system for Case B; (a) velocity contour and (b) temperature contour

Furthermore, the simulation results of Case C are shown in fig. 9. It demonstrates the external surface temperature of the transformer is about 92 °C, as shown in fig. 9(a), even the transformer still works normally. However, the temperature of the servo amplifier is abnormal because it is located in the upper part of the enclosure, as shown in fig. 9(b). The servo amplifier is easily damaged accordingly because of the poor heat dissipation.

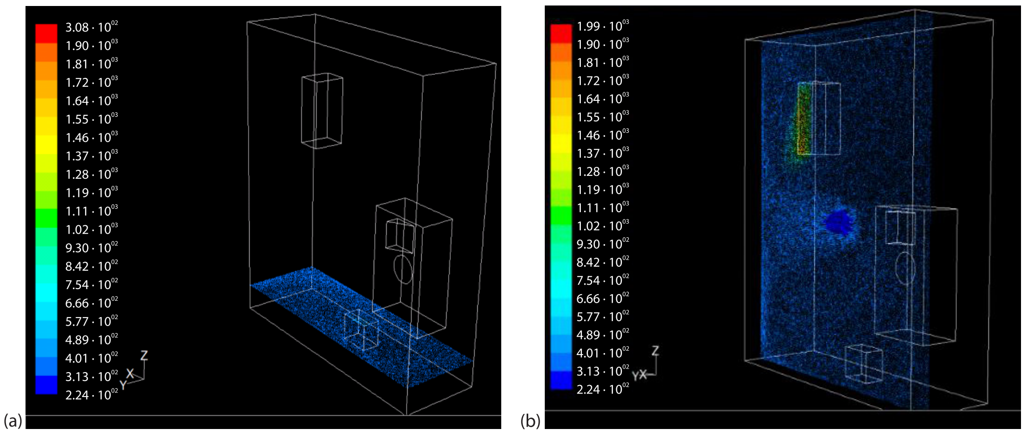

Figure 9. Temperature contour of (a) transformer and (b) servo amplifier

For the experimental results, fig. 10(a) illustrates the air temperature (such as supply air and return air) when the machine tool is operating at ambient temperature about 29 °C. Firstly, the supply air temperature and return air temperature increase gradually because the temperature of the electrical components raised. It reveals the supply air temperature decreased immediately after 36 °C because the A type cooler automatically started up until the return air temperature of the cooler reaches the set-up point. At the same time, the return air temperature also decreased gradually. However, the temperature variation trend of return air is similar to the supply air after the cooler start up. Therefore, it demonstrates that there is short circulation of air-flow slightly in the industrial control enclosure even though the air baffler is installed. It demonstrated that the results are similar to fig. 8(a). The air temperature inside the industrial control enclosure is shown in fig. 10(b). It demonstrates can be seen that the maximum air temperature difference inside the control enclosure is obvious (about 5 °C) before the cooler start up. The temperature difference has decreased to about 3 °C. Furthermore, some of supply air is sucked by auxiliary circulation fans and others downward naturally. Thus, the air temperature distribution inside the control enclosure become balanced. The heat does not accumulate in the upper part of the control enclosure. It is good for heat dissipation of electrical components.

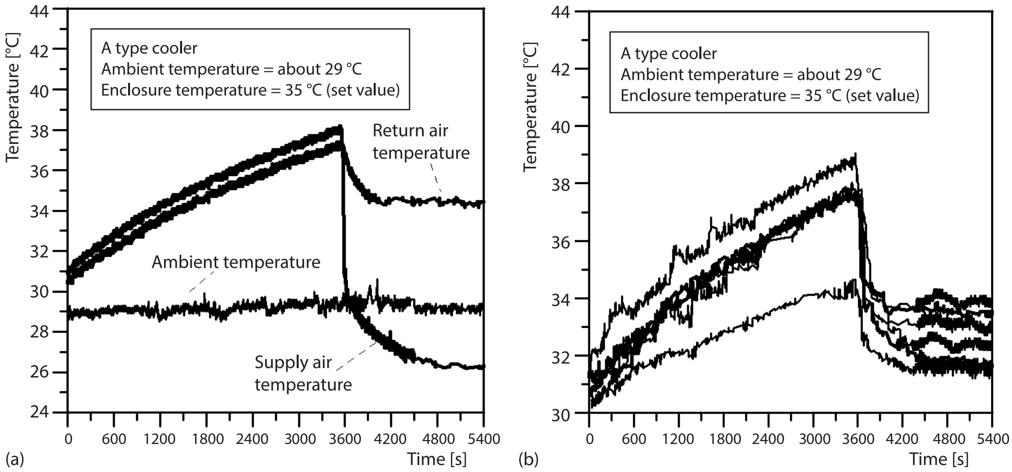

Figure 10. Air temperature when using the A type cooler; (a) temperature of supply air and return air and (b) temperature inside the industrial control enclosure

After the operation of the machine tool, the curves of the air temperature (*i.e.* supply air temperature, return air temperature and ambient temperature) when using the *B* type cooler at ambient temperature about 29 °C, as shown in fig. 11(a). It reveals that the supply air temperature also decreased immediately after 36 °C because the *B* type cooler reaches the startup set point. The return air temperature also decreased gradually. But, the temperature variation trend of return air is not similar to the supply air. There should be no short circulation of air-flow in the industrial control enclosure. The possible reason might be the position of supply air vent is below the position of return air vent, and the distance between them (*i.e.* supply air vent and return air vent) is longer than the *A* type cooler obviously. Figure 11(b) shows the air temperature inside the industrial control enclosure when the machine tool is operating. It can be seen that the maximum air temperature difference inside the industrial control enclosure is about 5 °C before the cooler start up. However, the temperature difference is increased to 10 °C (such as CH_1 and CH_3) after the cooler start up. The temperature difference value is bigger than the A type cooler. The possible reasons are that the supply air falls naturally and it cannot be sucked smoothly by the auxiliary circulation fans because of the shape of the air baffler. Therefore, the heat is accumulated in the upper part of the industrial control enclosure (such as CH_1, CH_8, and CH_{10}). It is bad for heat dissipation of electrical components which located in the upper part. On the other hand, the air temperatures of lower part of the industrial control enclosure are lower than the others (such as CH_3, CH_4, and CH_6).

Additionally, fig. 12 represents that the temperature of the electrical components after opening the door of industrial control enclosure in a few seconds by using a thermal imaging infrared camera. The maximum temperature difference about it when using the *B* type cooler is larger than that using the A type cooler, fig. 12(a) compared with fig. 12(b). The results are the same with figs. 10 and 11.

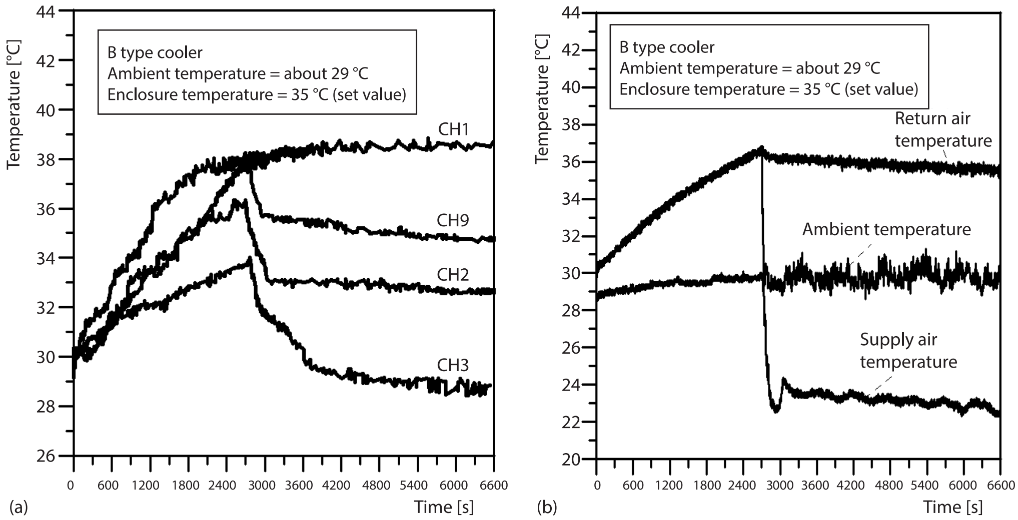

Figure 11. Temperature variable when using the *B* type cooler; (a) temperature of supply air and return air and (b) temperature inside the industrial control enclosure

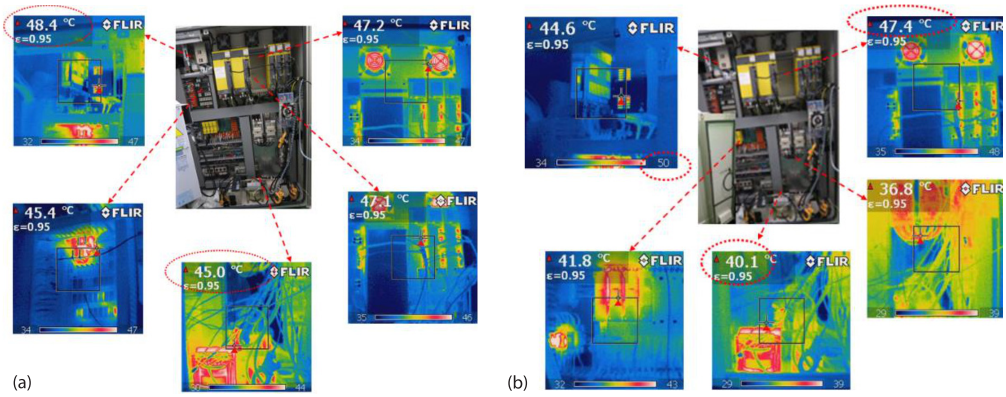

Figure 12. Variation temperature of electrical components; (a) using the *A* type cooler and (b) using the *B* type cooler

Conclusions

The enclosure cooling system is one of the excellent methods for managing the heat generated in the enclosure during machining. According to the simulation, results can be summarized as following.

- The short circulation of air-flow is obviously improved when the air baffler is installed.
- It is suggested to install the auxiliary circulation fan for the industrial control enclosure because the heat generation does not accumulate in the upper part of the enclosure.
- The auxiliary circulation fan and air baffler should be used in the experiment to improve the air-flow distribution inside the enclosure and heat transfer performance.

According to the experiments, the results can be summarized as following.

- The heat does not accumulate in the upper part of the industrial control enclosure for the upper supply vent arrangement (*i.e.* A type cooler). It is good for heat dissipation of electrical components. The air temperature distribution inside the control enclosure is well-distributed. But, the distance between the supply air vent and the return air vent is critical because the short circulation of air-flow is easy to occur.

- The lower supply vent arrangement will result in no short circulation of air-flow, but the shape design of air baffler is critical. Furthermore, the air baffler should not influence the function of auxiliary circulation fan.

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Paper submitted: December 5, 2020
Paper revised: March 15, 2021
Paper accepted: April 3, 2021

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