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Study on Heat Transfer Characteristics of One Side Heated Vertical Channel Applied as Vessel Cooling System

Shinji Kuriyama, Tetsuaki Takeda and Shumpei Funatani
University of Yamanashi
4-3-11 Takeda, Kofu-shi Yamanashi 400-8511 Japan.
phone: +81-55-2208324, g14mm015@yamanashi.ac.jp

Abstract – *The inherent properties of the Very-High-Temperature Reactor facilitate the design of the VHTR with high degree of passive safe performances, compared to other type of reactors. However, it is still not clear if the VHTR can maintain a passive safe function during the severe accident, or what would be a design criterion to guarantee the VHTR with the high degree of passive safe performances during the accidents. In the Very High Temperature Reactor (VHTR) which is a next generation nuclear reactor system, ceramics and graphite are used as a fuel coating material and a core structural material, respectively. Even if the depressurization accident occurs and the reactor power goes up instantly, the temperature of the core will change slowly. This is because the thermal capacity of the core is so large. Therefore, the VHTR system can passively remove the decay heat of the core by natural convection and radiation from the surface of the reactor pressure vessel (RPV). This study is to develop the passive cooling system for the VHTR using the vertical channel inserting porous materials. The objective of this study is to investigate heat transfer characteristics of natural convection of a one-side heated vertical channel inserting the porous materials with high porosity. In order to obtain the heat transfer and fluid flow characteristics of a vertical channel inserting porous material, we have also carried out a numerical analysis using the commercial CFD code. From the analytical results obtained in the natural convection cooling, an amount of removed heat enhanced inserting the copper wire. It was found that an amount of removed heat inserting the copper wire (porosity = 0.9972) was about 10% higher than that without the copper wire. This paper describes a thermal performance of the one-side heated vertical channel inserting copper wire with high porosity.*

I. INTRODUCTION

The inherent properties of the Very-High-Temperature Reactor facilitate the design of the VHTR with high degree of passive safety performances, compared to other type of reactors. However, it is still not clear if the VHTR can maintain a passive safety function during the severe accident, or what would be a design criterion to guarantee the VHTR with the high degree of passive safe performances during the accidents. Japan Atomic Energy Agency (JAEA) is advancing the technology development of the VHTR using the HTTR and is now pursuing design and development of commercial systems such as the 300MWe gas turbine high temperature reactor GTHTR300C(Gas Turbine High Temperature Reactor 300 for Cogeneration)[1].

From the view point of the safety characteristic, the passive cooling system should be designed for the VHTR as the best way of the reactor and vessel cooling systems (VCS). So, the gas cooling system by natural convection is one of candidate systems for the VCS of the VHTR. Figure 1 shows a schematic drawing of the passive cooling system. This study is to develop the passive cooling system for the VHTR using the vertical rectangular channel in which the porous materials were inserted.

In general, when cooling high temperature circular or rectangular channel by forced convection, there are several methods for enhancement of heat transfer such as attaching radial or spiral fins on the channel surface or inserting twisted tape in the channel. However, it has to take into consideration the deterioration of the structure strength by attaching the fins on the heat transfer surface with the design of the cooling channel. The best design exists to increase the heat transfer and to reduce the flow resistance of the channel. On the other hand, there are lots of experimental studies regarding the effective thermal conductivity of the packed bed and the radiation heat transfer characteristic of the fibrous packed bed. These studies have been done mainly focusing on development of insulator material using the nonmetallic material. The experiment and the analysis were conducted to obtain the heat and mass transfer coefficients, flow resistance, and so on. The experimental and analytical studies on radiation heat transfer of porous material have already been performed in the case of porosity < 0.8 [2-5]. As for the studies on the fibrous packed bed when the porosity was high (porosity, $\varepsilon > 0.98$), there were some researches on the heat transfer of the fibrous packed bed using the high thermal conductivity material [6, 7].

The purpose of this study is to investigate the heat transfer characteristics not only by forced convection [8, 9] but also by natural convection in the vertical rectangular channel inserting the porous materials with high porosity. This paper describes the heat transfer coefficient and the amount of the removed heat in the proposed channel.

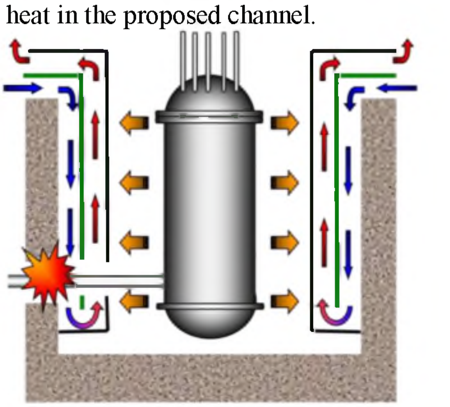

Fig.1 Schematic drawing of passive cooling system

II. EXPERIMENTAL APPARATUS

Figure 2(a), 2(b), 3(a) and 3(b) shows a schematic drawing of the experimental apparatus. The experimental apparatus was a vertical rectangular channel having one copper plate and the other stainless steel plates. The thickness of the copper plate and stainless steel plate were 4mm and 5mm respectively. A sheathed heater was attached to the surface of the copper plate. The outside of the heater was covered with an insulator to prevent the loss of heat by thermal convection and radiation. Though there was the loss of heat from the top and bottom flanges, we evaluated the loss of heat by measuring the temperature distribution. The cross section of the channel was a square having the width of 100mm. The height of the channel was 1200mm. The gas temperatures of the inlet, outlet, and inside of the channel, and the wall temperatures of the channel were measured with a K-type thermocouple. The thermocouple which measured the gas temperature was traversed from the heated surface to the counter surface. The gas temperature was measured at the positions of 3, 6, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 85, 90, and 95mm. The porous material of the fiber packed bed was made of copper. The diameters of the copper wires were 1mm and 0.5mm. The porosity of the rectangular channel was set to be 0.99 or higher. The fiber packed bed is shown in Fig.4.

The heater was controlled to the constant power. Therefore, the thermal condition of the heated surface assumes the constant heat flux condition. At first, we carried out the experiment using the channel without the copper wire under the condition of laminar flow forced convection cooling. Air flowed into the channel from the bottom to the top by the blower while the one side surface of the channel was heated. When all the temperature reached the constant temperature for 30 minutes or more, we assumed that the steady state was established. Then, the various parts of the temperature were measured. The gas temperatures were measured by traversing the thermocouple during the steady state. Next, the copper wire was inserted into the channel, and the similar experiment was done. The measurement error of the temperature was within ± 0.1 K. The flow rate and average velocity of air were calculated from the laminar flow meter. The laminar flow meter is made by Yamada Manufacture Company. Measurement range of volumetric flow rate was 0.83 to 12.8 L/s. The average velocity and Reynolds number were 0.183m/s and 1160, respectively. The reproducibility of the laminar flow meter was ±0.35%F.S. The measurement accuracy of the manometer was ±0.15%F.S. The error margin of the amount of the removed heat using the experimental data was less than 15%.

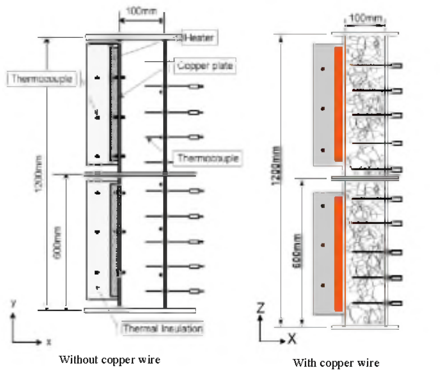

Fig.2 Experimental apparatus ((a) without copper wire, (b) with copper wire)

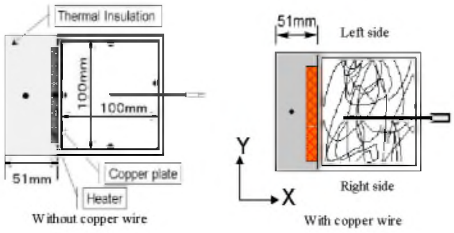

Fig.3 Cross section ((a) without copper wire, (b) with copper wire)

Fig.4 Fiber packed bed (copper wire of Φ0.5mm)

III. EXPERIMENTAL RESULTS OF FORCED CONVECTION COOLING CASE

In order to obtain the influence of changing the porosity and the influence of increasing the heat input onto the enhancement of heat transfer, we have performed the experiments of heat transfer and flow resistance. Experimental condition is shown in Table 1. Porosity was calculated as follows. Volume of the vertical channel is calculated by $100 \times 100 \times 1200 = 1.2 \times 10^7$ (mm^3). Volume of the copper wire is obtained by $\pi d^2/4 \times L$ (mm^3). Thus, porosity, ε, can be obtained by the following equation.

$$\varepsilon = 1 - \pi d^2 L/(4.8 \times 10^7).$$

Table1 Experimental condition of forced convection cooling

Type	Porosity	Surface Area of Wire [m²]	Wire Diameter [mm]	Wire Length [m]	Heat Input [W]
W1	0.9964	0.173	1	55	357,486,614
W2	0.9964	0.346	0.5	220	357～829
W3	0.9973	0.259	0.5	165	357～829
W4	0.9982	0.173	0.5	110	418～829
N/A	1	—	—	—	357～829

Figures 5, 6 and 7 show the temperature distributions of air along the channel width. The horizontal axis shows the dimensionless distance from the heated surface. The vertical axis indicates the temperature difference from the air temperature at the inlet position. In the case when the copper wire was inserted into the channel, the gas temperature near the heated surface was higher than that in the case without the copper wire. This is because the copper wire was heated by thermal radiation from the heated surface. As the heat transferred to the gas from the copper wire, therefore the gas temperature at the outlet increased. On the other hand, the gas temperature near the counter surface was lower than that in the case without the copper wire. The reason why increasing the temperature of the counter surface was the radiation heat transfer from the heated surface and the heat conduction from the side walls. Also, the side and counter surface temperature of the case without copper wire was higher than the case with copper wire. The amount of copper wire in 'W2' case was larger than in 'W4'. However, the temperature difference between the cases with/without copper wires was larger in Fig. 7 than that in Fig.5 because the heated surface temperature in the case of W2 was lower than in the case of W4 (Table 2). The amount of the heat transferred from the heated surface by thermal radiation increased with increasing the temperature of the heated surface. However, we could not evaluate the amount of the heat transferred by thermal radiation and by thermal conduction in this experiment. It will be necessary to discuss in detail the heat transferred from the heated surfaces in the future.

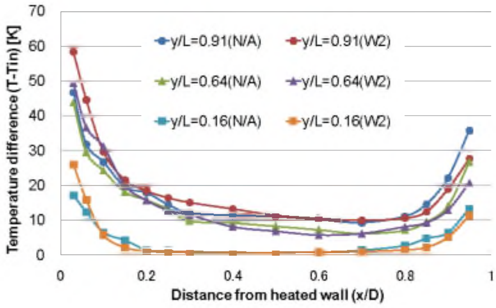

Fig.5 Distribution of gas temperature along the channel width (736W, W2&N/A)

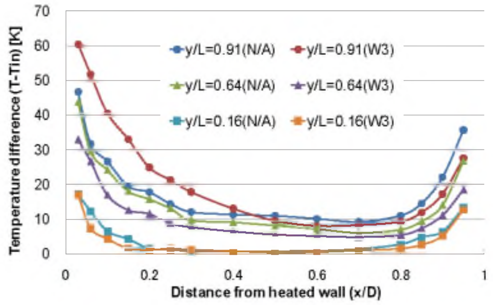

Fig.6 Distribution of gas temperature along the channel width (736W, W3&N/A)

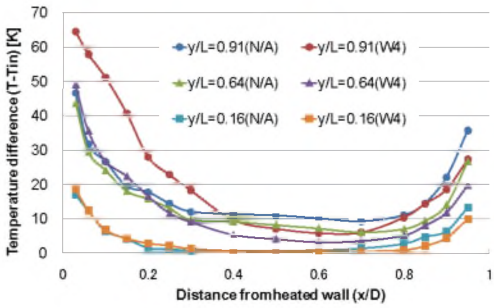

Fig.7 Distribution of gas temperature along the channel width (736W, W4&N/A)

Figs.8 and 9 show the temperature distribution of walls along the flow direction. The horizontal axis indicates the dimensionless distance from the inlet of the channel. The vertical axis indicates the temperature difference between the wall temperature and the gas temperature at the inlet of the channel. The wall temperature in the case of the smooth channel was higher than that in the case of the smooth channel inserting the copper wire. This is because the large amount of heat was transferred from the wall to the air in the case of the smooth channel inserting the copper wire. The distribution of wall temperature of W2 and W3 cases are almost same.

The experimental condition and results are shown in Table2. Here, the amount of the removed heat by air was obtained as follows. The integrated average temperature was obtained from the gas temperature at 15 positions of the channel width. The temperature difference between the outlet (y/L=0.91) and inlet (y/L=0.07) of the channel was obtained. The thermal properties of gas were evaluated from the arithmetic average temperature between the inlet and outlet of the channel.

The ratio of the removed heat is shown in Fig.10. The horizontal axis shows the heat input of the channel. The vertical axis shows the ratio of the removed heat. Here, Qs was the amount of the removed heat by the smooth channel. Qw was the amount of the removed heat by the smooth channel inserting the copper wire. The ratio of the amount of the removed heat was obtained from Qs and Qw. Qs and Qw are obtained by the following method. In the forced cooling case, the flow rate can be measured by the laminar flow meter. The temperature difference between the inlet and outlet air temperature can be also measured by the thermocouple. Thus, we evaluated the cooling performance in terms of the amount of heat removed by air flow. On the other hand, the heat loss from the channel wall can be calculated by using the heat transfer coefficient at the vertical heated surface by natural convection. In this apparatus, heat loss from the stainless steel wall can be obtained by using the reported heat transfer coefficient. Therefore, we controlled the room temperature at around 20°C. The heat loss from the stainless steel will depend on the wall temperature. If the wall temperature distribution is almost same, the heat loss is almost same. Thus, the influence of the heat loss on the heat transfer performance of the channel will be small.

The amount of the removed heat increased with increasing the heat input. This is because the copper wire is heated by thermal radiation with increasing of the wall temperature. The heat transfer coefficient and thermal conductivity will not increase even if the wall temperature increased. Thus, it is possible to enhance the heat transfer by thermal radiation. The surface area of the copper wire in the case of W2 is larger than that in the cases of W3 and W4. To increase the surface area is the one of method for enhancing the heat transfer. However, the amount of the removed heat is not increased. The amount of the removed heat may decrease with increasing of the flow resistance.

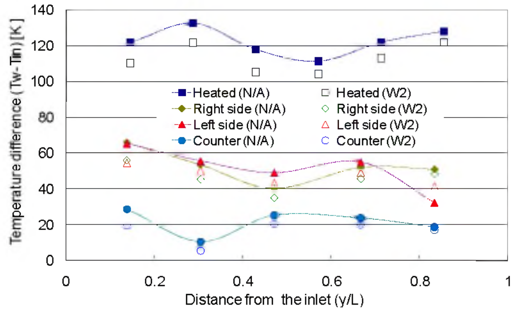

Fig.8 Distribution of wall temperature along the flow direction (736W, W2&N/A)

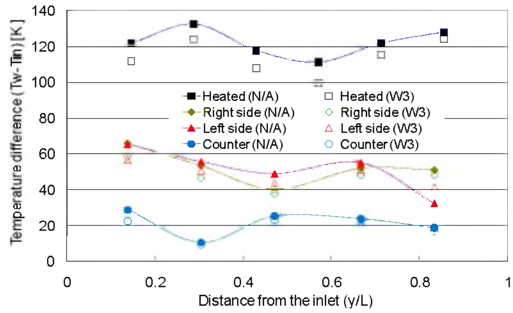

Fig.9 Distribution of wall temperature along the flow direction (736W, W3&N/A)

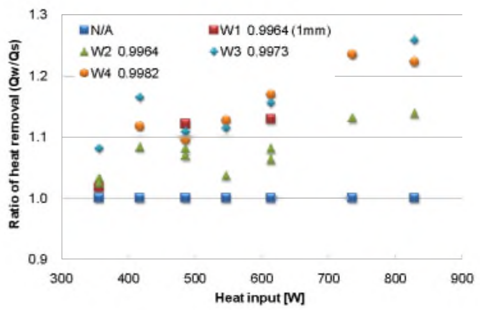

Fig.10 Thermal performance of rectangular channel inserting porous material

Table 2 Experimental results of forced convection cooling

Heat Input [W]	Wire Type	Heated Surface [°C]	Inlet Gas [°C]	Temperature Difference [K]	Porosity	Surface Area [m²]	Ratio of Heat Removal
486	N/A	105.8	19.4	86.4	1.0000	–	1.000
	W1	111.5	25.7	85.8	0.9964	0.173	1.122
	W2	99.9	17.8	82.1	0.9964	0.346	1.080
	W3	93.7	14.2	79.5	0.9973	0.259	1.108
	W4	117.3	31.5	85.8	0.9982	0.173	1.095
547	N/A	120.7	22.3	98.5	1.0000	–	1.000
	W2	107.7	17.7	90.0	0.9964	0.346	1.037
	W3	100.1	11.4	88.7	0.9973	0.259	1.115
	W4	120.0	23.2	96.7	0.9982	0.173	1.127
614	N/A	127.6	20.3	107.3	1.0000	–	1.000
	W1	129.5	25.2	104.3	0.9964	0.173	1.129
	W2	120.9	19.8	101.1	0.9964	0.346	1.081
	W3	111.0	10.9	100.1	0.9973	0.259	1.156
	W4	134.4	28.6	105.7	0.9982	0.173	1.169
736	N/A	148.9	22.0	126.9	1.0000	–	1.000
	W2	135.7	18.2	117.6	0.9964	0.346	1.131
	W3	128.7	11.0	117.7	0.9973	0.259	1.235
	W4	141.6	19.5	122.1	0.9982	0.173	1.236
829	N/A	160.9	20.0	140.9	1.0000	–	1.000
	W2	149.1	18.4	130.8	0.9964	0.346	1.138
	W3	141.1	10.8	130.3	0.9973	0.259	1.259
	W4	158.1	21.8	136.4	0.9982	0.173	1.223

IV. ANALYTICAL RESULTS OF FORCED CONVECTION COOLING CASE

The temperature distribution of air in the vertical rectangular channel was obtained using a commercially available analysis code PHOENICS. This analysis took into consideration the thermal radiation between the heated surface and cooled surface. Figure 11 shows an analytical model of the vertical rectangular channel. The outside of the channel wall was not modeled, and it assumed a natural convection heat transfer boundary. The analysis took the buoyancy into consideration. The physical properties of the solid took the temperature dependence into consideration. The physical properties of the fluid took the temperature and pressure dependence into consideration for the analysis. The number of the calculation cells of the analytical model was about 0.85 million. Though the PHOENICS could use the k-ε (KECHEN) turbulence model, we did not use the model in the analysis. This was because the analysis condition was in the laminar flow region. Thus, we also did not do the grid sensitivity study. This was because the numerical results will not be affected by the turbulence model and grid size in the present flow region. Table 3 shows the analysis condition.

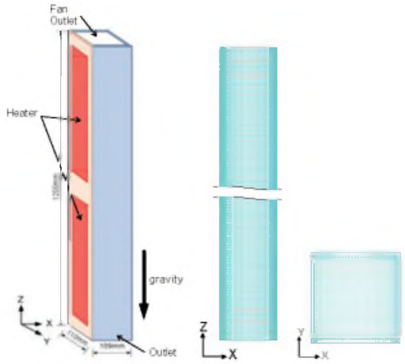

Fig.11 Analytical model of the vertical rectangular channel

Table 3 Analysis condition

Analysis Condition	
Softwear	Phoenics(Chan Co. Ltd.)
Dimenstion	X, Y, Z = 109, 110, 1200 mm
Thickness	Copper, Stainless = 4, 5 mm
Number of cell	(X, Y, Z) = (59, 60, 240)
Total number of cell	849000 cells
Fluid	Air
Ref. Temperature	20℃
Ref. Pressure	101300 Pa
Buoyancy effect	Boussinesq approximation
Turbulence model	KECHAN
Radiation model	IMMERSOL
Boundary Condition	
Heat flux	4.7239 kW/m^2 (346.5W)
Inlet velocity	0.583 m/s
Heat transfer coefficient at outer wall	6W/m^{2}K
Emissivity	Copper, Stainless = 0.3, 0.5

The boundary condition at the inlet of the rectangular channel was assumed to be the inflow condition. The inlet velocity set to 0.583 m/s according to the experimental results. The boundary condition at the outlet of the channel assumed the outflow condition. The outer surface of the channel was assumed to be the natural convection heat transfer boundary condition.

Figure 12 shows an example of the numerical results of the temperature distribution of air in the rectangular channel at various vertical positions. Left figure shows the temperature distribution in the outlet of the channel. Right figure shows the temperature distribution in the inlet of the channel. Figure 13 shows the numerical result of the temperature distribution of air in the channel. The numerical results were in agreement with the experimental ones quantitatively. However, the gas temperature in the vicinity of the heated wall was higher than the experimental data. This was because the loss of heat from the heated wall to the outer side of the channel could not be evaluated accurately in the analysis. Therefore, the loss of heat from the heated wall in the experiment was larger than that in the analysis.

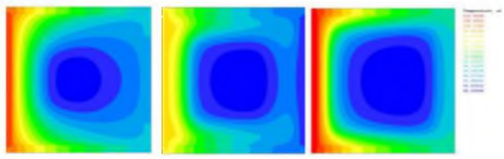

Fig.12 Temperature distribution of air (Left: outlet, Center: center, Right: inlet)

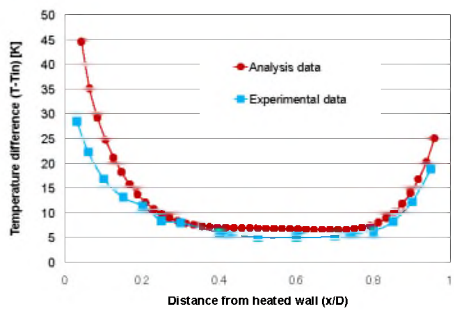

Fig.13 Temperature distribution of air along the channel width

V. EXPERIMENTAL RESULTS OF NATURAL CONVECTION COOLING CASE

Table 4 shows the experimental conditions of the natural convection cooling. Figure 14 shows the temperature distribution of the channel walls along the flow direction. The temperature distribution of air in the channel between heated and cooled surfaces is shown in Fig.15. The thermal power was 529W.

The gas temperature at the outlet increased when the copper wire was inserted into the channel. It seemed that the copper wire will be heated by thermal radiation from the wall. Thus, air was heated not only by the wall but also by the copper wire. However, the temperature of the heated wall increases if the heat transfers coefficient decrease. In Fig. 14, the wall temperature without the copper wire was lower than wall temperature with the copper wire. This differs from the case of the forced convection. Therefore, the temperature distribution of Fig. 15 is different from the tendency of the forced convection. The flow rate of natural convection decreases because the flow resistance increases by inserting the copper wire. Therefore, it is necessary to measure the flow velocity of natural convection by the experiment in the future.

In the experiment of the natural convection cooling case, we did not measure the flow velocity. This was because we did not want to add the flow resistance by measuring the flow velocity. Therefore, we could not draw the figure of the relationship between the heat input and the ratio of the removed heat as in Fig.10 of the forced cooling case. However, it will be possible to enhance the heat transfer even if natural convection is used for cooling.

Table 4 Experimental condition of natural convection cooling

	imput [W]	Poro. [-]	Area [m²]	Dia. [mm]	Len. [m]	Temp. [°C]
E1	529.0	1.0000	0.48	-	-	24.3
E2	529.0	0.9967	0.64	1	50	24.6
E3	529.0	0.9967	0.64	1	50	22.7

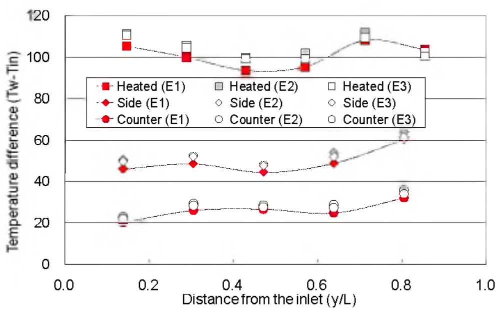

Fig.14 Temperature distribution of wall along the flow direction (E1&E2&E3)

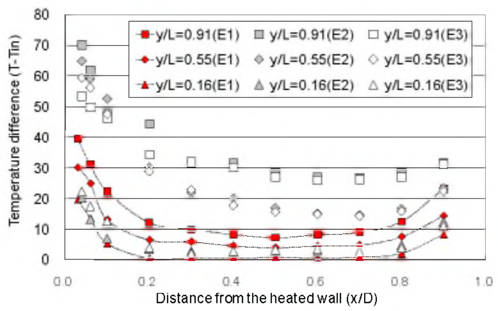

Fig.15 Temperature distribution of air along the channel width (E1&E2&E3)

VI. ANALYTICAL RESULTS OF NATURAL CONVECTION COOLING CASE

Figure 16 shows an analytical model of the vertical rectangular channel inserting the copper wire. The analysis condition and the boundary condition are indicated in Table 5.

In order to estimate the amount of removed heat by thermal radiation, we assumed the 9 straight longitudinal wires as the porous material. Figure 17 shows the temperature distribution of air in the vertical rectangular channel. The left hand side of the figure shows the temperature distribution in the case of no wire. The right hand side of the figure shows the temperature distribution in the case of inserting 9 wires. Figure 18 shows the distribution of flow velocity in the channel. It is found that the air temperature of the center part at the outlet of the channel with the copper wires is higher than that without the copper wire.

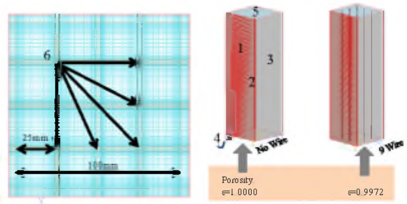

Fig.16 Analytical model of the vertical rectangular channel inserting the copper wire

Table 5 Analysis condition and boundary condition for natural convection

Analysis Condition	
Softwear	Phoenics(Chan Co. Ltd.)
Dimenstion	X, Y, Z = 109, 110, 1200 mm
Thickness	Copper, Stainless = 4, 5 mm
Number of cell	(X, Y, Z) = (109, 110, 120)
Total number of cell	1438800 cells
Fluid	Air
Ref. Temperature	20℃
Ref. Pressure	101300 Pa
Buoyancy effect	Considerration of property change
Turbulence model	KECHAN
Radiation model	IMMERSOL
Wire type (porosity)	W1(ε=1.0000), W2(0.9984), W3(0.9972)
Number of wires	(W1, W2, W3) = (0, 5, 9)
Boundary Condition	
1. Heater	529W, 1000W, 2000W, 3000W
2. Back wall	20W/m²K
3. side wall	6W/m²K
4,5. Free inlet/outlet of the duct	
6. Wire diameter, Emissivity	2mm, Copper, Stainless = 0.3, 0.5

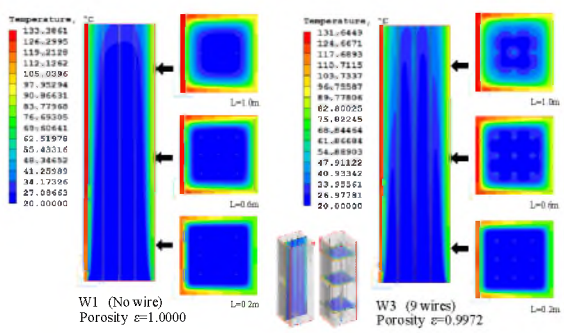

Fig.17 Temperature distribution of air (Left: no wire, Right: 9 wires)

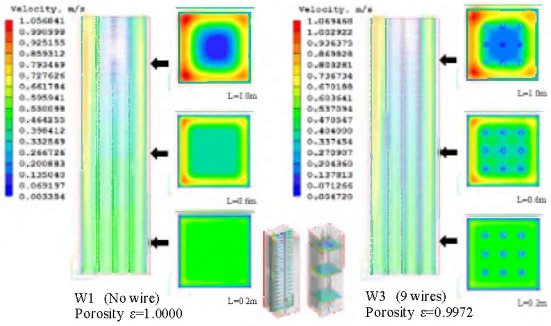

Fig.18 Flow velocity of air (Left: no wire, Right: 9 wires)

VII. ANALYSIS RESULTS OF INSERTING COPPER WIRE MODEL

Figure 19 shows inserting copper wire model. Figure 20 and 21 shows the temperature distribution of air at Y-plane and Z-plane. Heat input is 529W. As shown in fig. 21, the gas temperature increases with increasing the porosity. Figure 22 shows the temperature distribution along the channel width. The monitor point is z/L = 0.91.

The gas temperature near the copper wire of the analytical result is higher than that of the experimental one. This is because we cannot measure the temperature near the copper wire by the thermocouples. The numerical gas temperature between the copper wires is almost same as the experimental one.

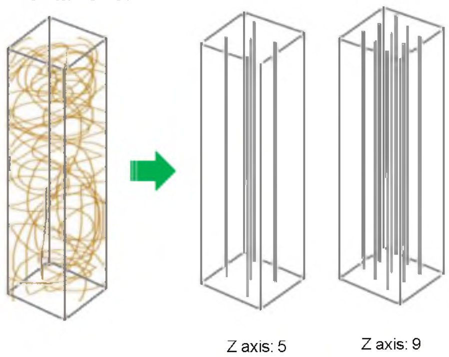

Fig.19 Modified model

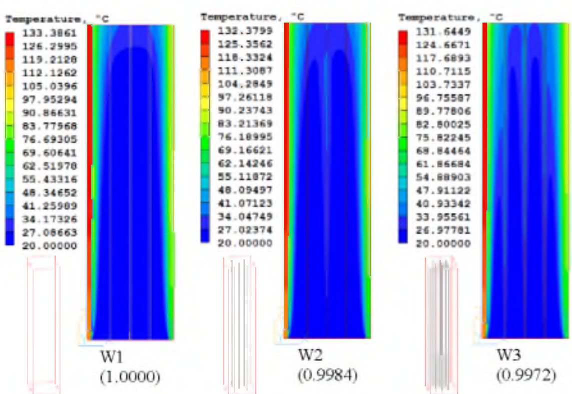

Fig.20 Temperature distribution of air at Y-plane (529W)

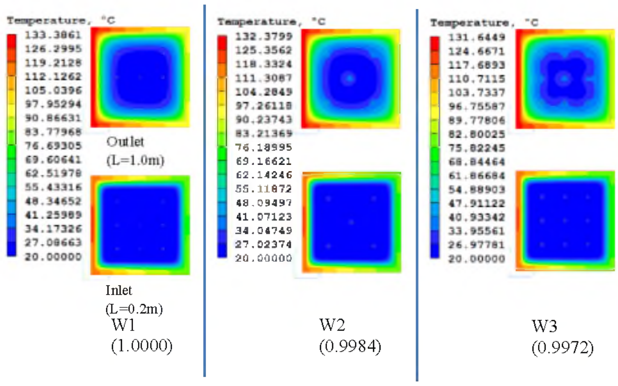

Fig.21 Temperature distribution of air at Z-plane (529W)

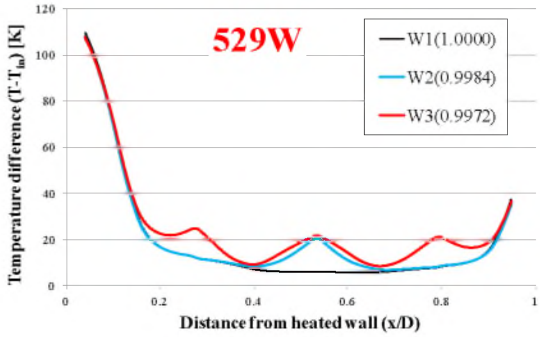

Fig.22 Temperature distribution of air along the channel width

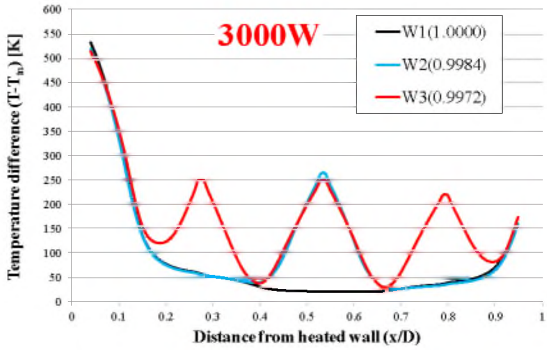

Fig.23 Temperature distribution of air along the channel width

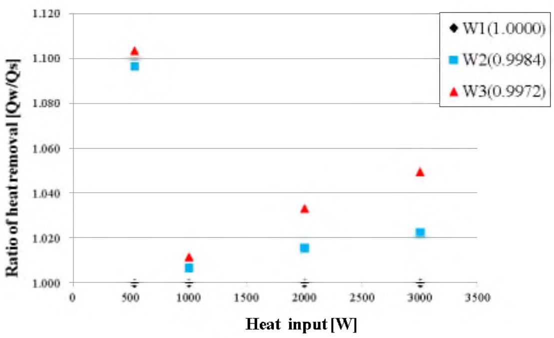

Fig. 24 Thermal performance of rectangular channel inserting porous material

Table 6 Analytical results

Heat input	Porosity	Heated wall temperature [℃]	Temperature difference[K]	Flow velocity [m/s]	Volume flow rate [m^3/s]	Heat removed [W]	Ratio of heat removal
529W	1.000	131.234	31.324	0.441	4.410E-03	149.624	1.000
	0.9984	130.169	35.221	0.427	4.266E-03	164.118	1.097
	0.9972	129.404	36.389	0.417	4.172E-03	165.142	1.104
1000W	1.000	220.282	58.359	0.585	5.847E-03	352.394	1.000
	0.9984	217.880	60.788	0.569	5.689E-03	354.830	1.007
	0.9972	216.276	62.528	0.559	5.589E-03	356.523	1.012
2000W	1.000	399.007	111.051	0.812	8.121E-03	840.912	1.000
	0.9984	392.664	115.572	0.804	8.036E-03	854.220	1.016
	0.9972	388.481	119.295	0.803	8.028E-03	868.981	1.033
3000W	1.000	566.646	165.099	0.995	9.950E-03	1408.285	1.000
	0.9984	553.123	173.180	0.996	9.957E-03	1440.153	1.023
	0.9972	544.709	180.830	1.006	1.006E-02	1478.367	1.050

Fig. 23 shows the temperature distribution of air along the channel width in the case of 3000W of heat input. The maximum temperature difference is about 250 K. It is possible to remove more heat by inserting the copper wire case than by the plane wall case. Figure 24 shows the ratio of the removed heat. The amount of the removed heat increased with increasing the heat input. This was because the copper wire was heated by thermal radiation with increasing of the wall temperature as same as the force convection case. Thus, it was possible to enhance the heat transfer by thermal radiation. It is possible to increase the amount of transported heat from the reactor pressure vessel by applying this method. In Table 6, flow velocity is decreased by inserting the copper wire. This is because the flow resistance in the channel is increased by inserting copper wire.

CONCLUSIONS

The heat transfer experiment analysis has been carried out using the vertical rectangular channel inserting the porous materials. The results obtained from the experiments are as follows.

The amount of the removed heat increases with increasing the heat input. This is because the copper wire is heated by thermal radiation with increasing of the wall temperature. Thus, it is possible to enhance the heat transfer by thermal radiation. It was found that this method will be possible to enhance the heat transfer at the higher temperature condition.

It is possible to enhance the heat transfer even if natural convection is used for cooling. However, the flow rate of natural convection decreases. This is because the flow resistance is increased by inserting the copper wire. We need to consider methods that reduce the flow resistance.

From the analytical results obtained in the case of natural convection cooling, it was found that an amount of removed heat inserting the copper wire (porosity = 0.9972) was about 10% higher than that without the copper wire.

If the amount of the copper wire is large, the gas temperature in a channel will increase. However, if the amount of the copper wire is too large, the flow rate is reduced. It is not possible to improve the heat removal necessarily. There may be an optimal amount of the copper wire.

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