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2018

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Heat Transfer Enhancement by Using Fin for MH Hydrogen Storage Tank
- Discuss on the Geometrical Optimization of Fin –

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ABSTRACT

In this study, the heat transfer enhancement which effects of several fins on metal hydride particle layer are estimated by experiment and simulation. The unsteady state heat conduction calculation of MH particle layer with and without fins was researched by the Solidworks simulation software and the experimental method including calculation parameters, fins' charging volume ratio and the fin shape such as cross fin and circular cross fin. Besides, another estimation parameter is the diameter of storage tank. One storage tank has an outer diameter of 80 mm, an inner diameter of 78 mm, the other has an outer diameter of 25 mm and an inner diameter of 23.5 mm. The number of fins was increased until the charging volume ratio of the fin reaching to 25 volume %. We estimated the heat transfer enhancement influence of the fins on the MH ally layer. According to our calculation results, the effective thermal conductivity is increased with increasing of charging volume ratio of fin, but this heat transfer enhancing effect is saturated while it exceeded the 10 volume percentage. In our simulation model of a circle cross fin, the tank was set as an outer diameter of 52 mm and an inner diameter of 50 mm. In the simulation results of using circle cross fins cases, the highest heat transfer enhancement effect was obtained when circular diameter of circular cross fin was 24 mm. Compared with cross fins (which has a heat transfer enhancing effect of 4.68 times compared with no fins' case), the volume content of circle cross fin was 1.4% higher than that of cross fin. However, the heat transfer enhancement effect of circular cross fin was 2.46 times higher than that of cross fin. Besides, it is confirmed that circle cross fin whose charging volume ratio is under 10% can achieve a high heat transfer enhancing effect and is suitable to heat transfer enhancing of MH particle layer.

1. INTRODUCTION

In recent years, there has been an increasing awareness of environmental issues. Also, with the population increase on a global scale and industrial development in various countries, energy consumption is increasing year by year. In addition to this background, there is also a depletion problem of fossil fuels, we are concerned about the future of the energy shortage. Under these situations, the use ratio of renewable energy should be increased more and more in the future. From the viewpoint of effective use of renewable energy, it is possible to store and transport surplus of heat and electric energy, development of a process to convert it to secondary energy convenient for use and to utilize it is desired. Hydrogen energy is attracting attention as a powerful secondary energy candidate.

As a typical hydrogen storage method, there are three methods of high pressure storage, liquefaction storage, Metal Hydride (Hereafter, abbreviated as MH) storage. Currently, the high pressure tank is used as a hydrogen storage tank for fuel cell vehicles. However, it needs to be compressed to a high pressure of 80 MPa, which is disadvantageous from the aspect of energy storage density. The liquid tank is the high density storage method focusing on the fact that liquid state volume is 1/800 of the volume of gas state, but it is necessary to take measures against thermal insulation methods and boil-off to keep liquid state. The MH storage method is a method of storing hydrogen using a hydriding / dehydriding reaction caused by heat absorption / release of an alloy. Since MH stores hydrogen in the molecular state, it can be stored in 1 / 1,000 or more of gas and it is safe because it can be used near ambient temperature and normal pressure. However, there is a disadvantage that hydriding and dehydriding reaction rate is restricted in the MH powder layer due to low effective thermal conductivity. In order to solve this problem, there is a method of placing fins into the powder layer, performing copper plating on the alloy surfaces, and mixing a substance having high thermal conductivity such as copper wire and carbon fiber into the alloy layer.

2. PREVIOUS RESEARCH

Since magnesium-based rare-earth alloys were developed in the 1960's by Brookhaven National Laboratory in the United States and Philips in the Netherlands, attention was focused on diverse functions such as hydrogen storage system, secondary battery, heat pump, chemical catalyst, technologies have been developed to use not only as storage but also as a new energy conversion medium. In recent years, in order to improve the dehydiridng reaction rate, research papers have been increased to enhance the effective thermal conductivity of the MH powder layer.

According to Yasuda, Tsuchiya, Okinaka and Akiyama, they improved thermal conductivity of the MH alloy layer by incorporating, 2 wt% carbon fiber with a thermal conductivity of 620 W / mK into the MH alloy layer. At this time, supposing that the heat transfer enhancer, carbon fibers are processed into a brush shape, high effect is obtained by arranging the carbonfibers in the radial direction, and a shell and tube type heat exchanger applying this has been prototyped. Similar attempts were being made in our laboratory, and improvement in reaction rate has been confirmed.

More recently, LIN and YANG reported as follows, in order to improve the low effective thermal conductivity of the MH particle layer, MH sheet and aluminum foam are inserted to promote its heat transfer the effect was compared and examined. It was confirmed that the effective thermal conductivity in case of inserting the aluminum foam was about 1.4 times higher than that in case of inserting the MH sheet.

3. RESEARCH METHOD

3.1 Simulation Method

In our simulation, analysis was carried out using Solidwork simulations. In order to know the influence of heat transfer promoting with the variation of charging volume ratio of metal fin, analysis was carried out with two MH tanks. The tank material is assumed as copper, the first one has an outer diameter of 80 mm and an inner diameter of 78 mm, and the other has an outer diameter of 25 mm and an inner diameter of 23.5 mm. In addition, the simulation model of the circular cross fins derived from the above results has an outer diameter of 52 mm and an inner diameter of 50 mm. Then, the effective thermal conductivity of the MH layer which is measured by our experiment is used as the thermal conductivity of MH alloy ingot. Namely, we assume the all area of inner part of tank except the metal fin is installed by MH ingot. The material of the circle cross fin to be inserted is aluminum 2017 alloy and the thickness is set to 1 mm. The inserted fins increased the number of fins until the volume content of the fin to the alloy layer exceeded 25 vol.%. The density, thermal conductivity and specific heat of various materials are shown in Table 1.

Table1: Materials and thermal properties of MH tank model

Part	Tube	MH	Fin
Material	Copper	LaNi5	Aluminum 2017 alloy
Density kg/m^3	8900	7571	2790
Thermal Conductivity W/m K	390	0.8(Effective Thermal Conductivity)	164
Specific Heat J/kg K (Physical Property Value)	390	400	840

When conducting the simulation, it was assumed that the heat transfer in the axial direction is small because the tank length is sufficiently long with respect to the diameter. Therefore, we ignored the heat transfer in the axial direction and analyzed with a radial direction two-dimensional model. Conditions for unsteady state thermal conduction analysis are as follows. Since we ignored the surface contact thermal resistance between the tank and the external tank surface, the tank external surface temperature was also kept at 80 ° C. In addition, the timing of calculation termination was set to be the time when the temperature inside the tank exceeds 75 ° C which is 90% of final reaching out temperature of this process. The calculation conditions are shown in the following Table 2.

Table 2: Analysis Conditions

Model	2D model
Initial Temperature of Test Section (℃)	Room Temperature (About 20)
Temperature of Thermostatic Bath (℃)	80

3.2 Experimental Method

In this experiment, the effective thermal conductivity of the MH particle layer with and without fins was measured using an unsteady state method. If the experiment using the MH alloy after the activation procedure is conducted in the hydrogen atmosphere, it could generate the heat by the reaction between MH alloy and hydrogen. Therefore, our experiment is all achieved under the helium atmosphere.

In the experiment, the measurement section (Test Section in the figure) is instantly immersed into a thermostatic bath and changing histories of the tube surface temperature and the MH alloy layer's center temperature are measured. Besides, other measurement items are the temperature of thermostatic bath and pressure of tank.

The measuring position of the thermocouple is shown in Figure 1, and the measurement condition is shown in Table 3.

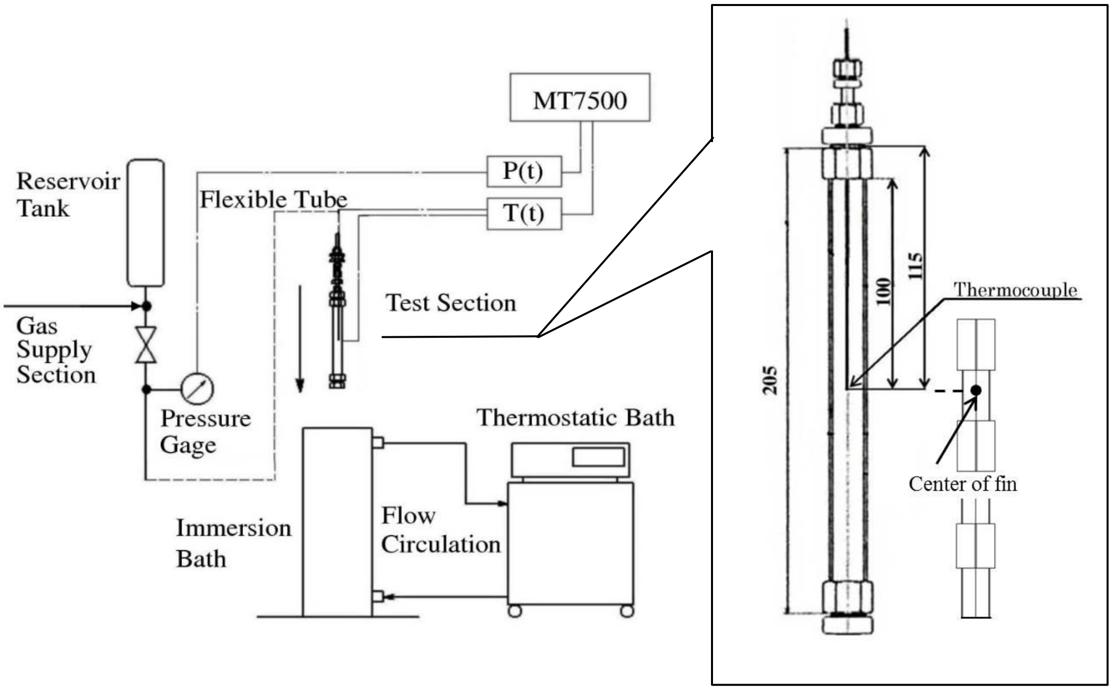

Figure 1: Simple Model Measuring Position of Thermocouple

Table 3: Experimental Condition of Effective Thermal Conductivity

Mass of MH g	100
Ambient gas	He
Pressure MPa	1.0
Initial Temperature of Test Section ℃	Room Temperature (About 20)
Temperature of Thermostatic Bath ℃	80

The effective thermal conductivity of the MH alloy layer was obtained by finite difference method. In the calculation, a cylindrical one dimensional coordinate system is adopted, and the control volume used for calculation is shown in Figure 2.

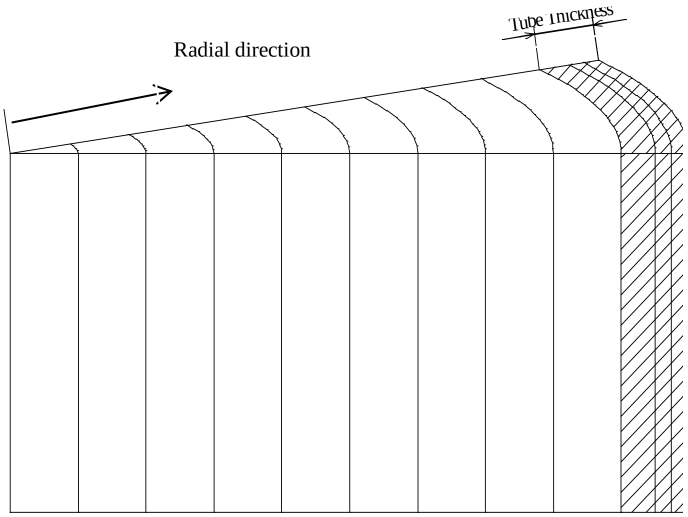

Figure 2: Control Volume of Test Section

4. RESULTS AND DISCUSSION

4.1 Relationship between Volume Content of Fins and Thermal Conductivity of MH Powder Layer

The radial fins made of A2017 are inserted into the LaNi5 powder layer in the calculation model, and the unsteady heat conduction analysis is carried out using SolidWorks Simulation. In the calculation, the tank's initial surface temperature, 20 ° C is changed to 80 ° C and, calculates the temperature change history of MH alloy layer of individual points. The timing of calculation termination was set to be the time when the temperature inside the tank exceeds 75 ° C. We considered that what is important for promoting heat transfer is not the number of fins but the volume content of fins. Therefore, we prepared two tanks of different sizes, the volume content of the fin was changed by increasing of the number of fins, and the time required for the average temperature of the powder layer and the entire radial fins to exceed 75 ° C is calculated. Calculation equation of the volume content of the radial fins is shown in Equation (1) and the analysis result is shown in Figure 3.

$$\text{Volume content of fin} = \frac{a \cdot b \cdot n + \dfrac{a^2 \cdot n}{4 \cdot \tan\left(\dfrac{\pi}{n}\right)}}{\pi \cdot r^2} \qquad (1)$$

a : Fin thickness mm
b : Fin length mm
n : Number of fins
r : Tank inner diameter mm

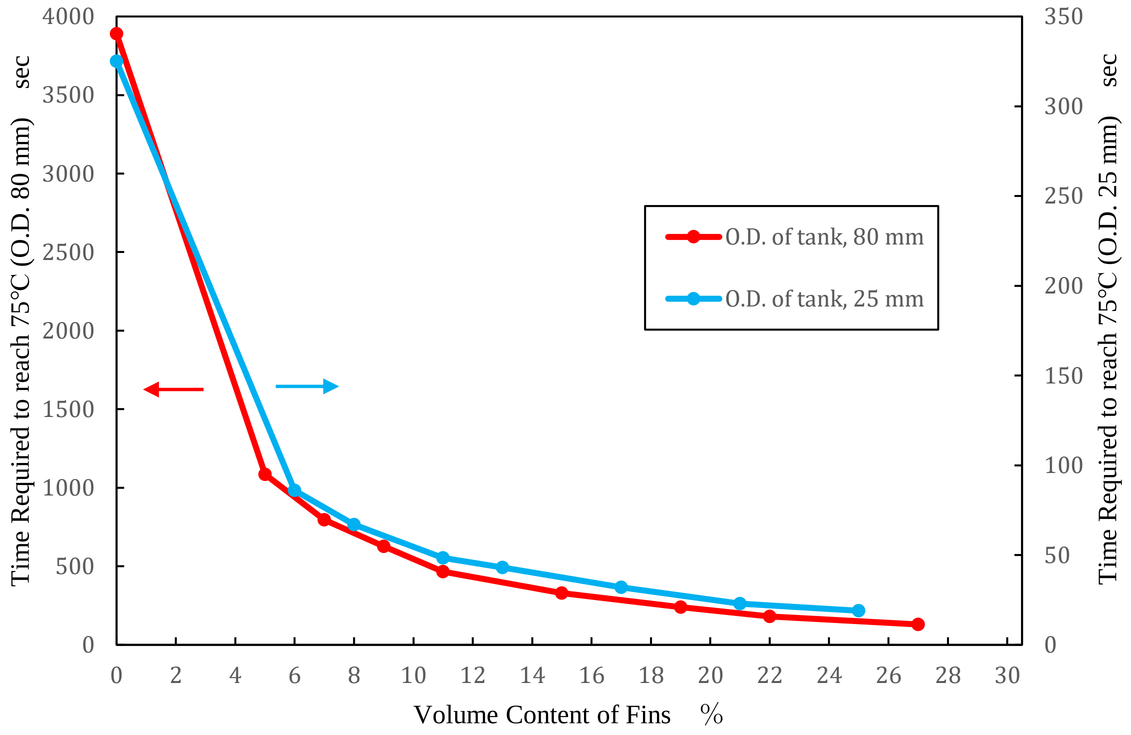

Figure 3: Time Required to Exceed 75℃ and Volume Content of FIns

As shown in Figure 3, as the content increases up to the volume content of the fin of 10%, the temperature change per second is large and the arrival time required for reaching 75 ° C sharply decreases. However, when the volume content of the fin exceeds 10%, the rate of change of temperature with time tends to become slowly. Therefore, in order to maximize the heat transfer enhancement effect of the radial fin, it is efficient to suppress the volume content of the fin to the alloy layer under 10%. From these results, in order to promote heat transfer more efficiently, we need to investigate the shape of the fin while keeping the volume content fixed.

4.2 Study of Optimum Fins Derived from Results

According to the simulation results, when the cross fin is inserted on the condition for volume content rate of the fins is about 5%, the effect of heat transfer promoting by radial fin insertion is the highest. However, the heat transfer performance on the sector shape area's center between wall and fin is not so good. In order to improve these area's heat transfer, the circle cross fin is considered and researched on this paper. As can be seen from the comparison between Figure 4 and Figure 5, the heat transfer performance on the centers of the sector area between wall and fins is higher by inserting the circle cross fins, and it can be also expected for the better heat transfer performance on entire part.

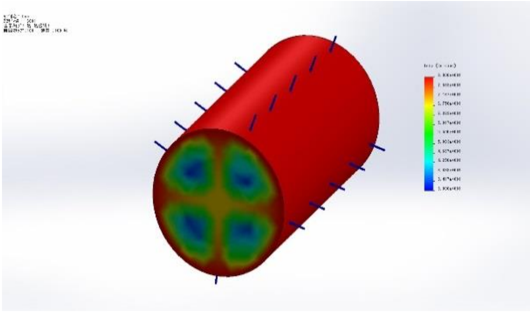

Figure 4: Temperature Distribution of Tank with Cross Fin after 100s

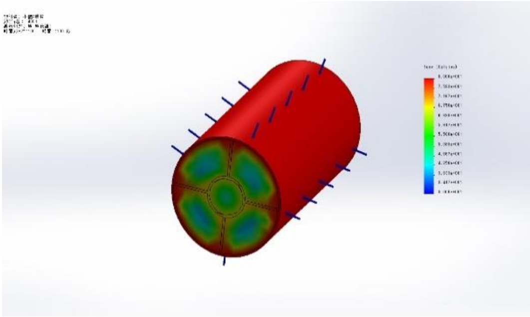

Figure 5: Temperature Distribution of Tank with Circle Cross Fin after 100s

On the research of the circle cross fin, the .internal circle diameter of the fin will be an important research parameter. In order to obtain the optimal inner circle diameter of the fin, analysis was performed using Solidworks Simulation under the same conditions as other that of analyzes. The results are shown in the Figure 6.

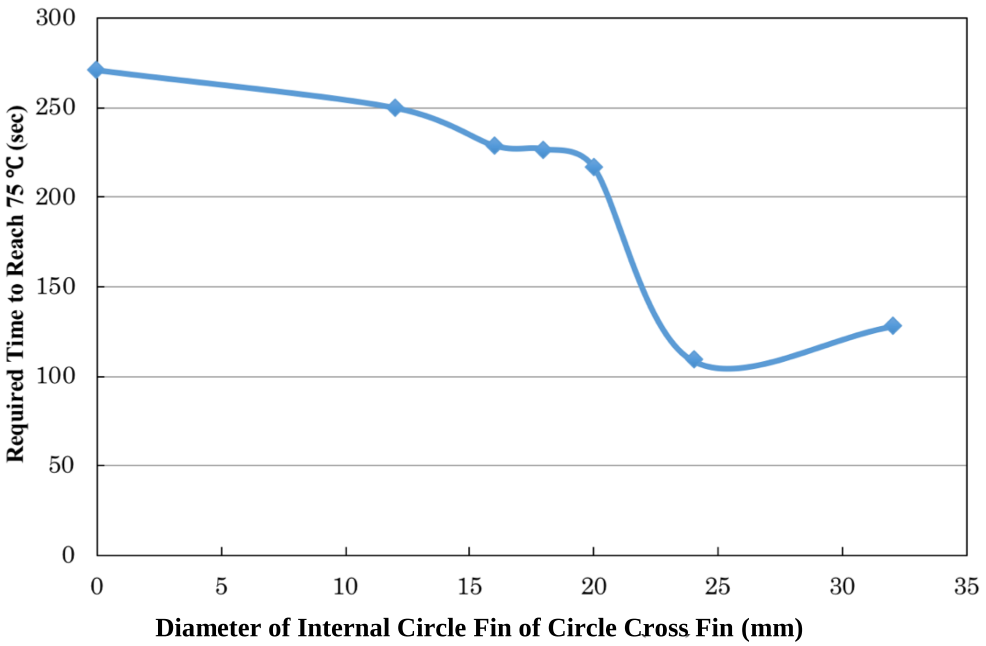

Figure 6: Required Time to Reach 75℃ vs Internal Diameter of Circle Cross Fin

As can be seen from Figure 6, when diameter of the internal circle fin of circle cross fin is 24 mm, the highest heat transfer promotion effect is exhibited. Therefore, calculation result of the circle cross fin which have diameter of internal circle fin, 24mm is compared with that of the cross fin. The simulation model is shown in Figure 7, the temperature distribution diagram of individual fin’s tank that calculation time pass the 100 second is shown in Figure 8, and the calculation result of the time is at which the lowest temperature of the MH powder layer is exceeded over 75 ° C is shown in Table 4.

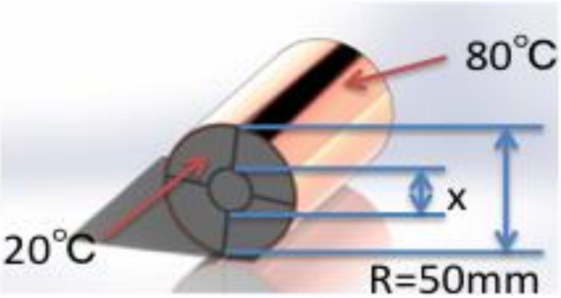

Figure 7: Simulation Model

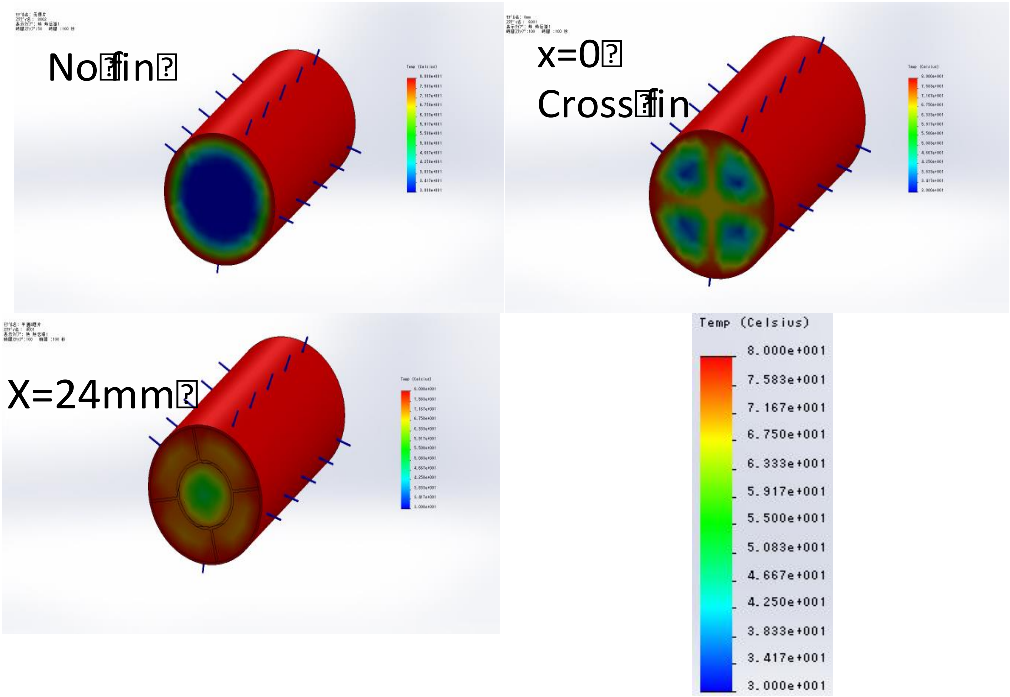

Figure 8: Temperature Distribution of Tanks with Different Fins after 100s

Table 4: Simulation results

Type	Required time to reach 75℃ (average temp. of fin and ally layer), s	Volume fraction of fin %
No fin	1270s	0
Cross fin	271s	5.04%
Cross Fin +Internal Circle Fin I.D. 24mm	109s	6.44%

Comparing the temperature changing speed between the powder layer without fin and with circle cross fins, heat transfer promotion effect of circle cross fin is 11.55 times higher than that of without fin. In addition, when comparing between circle cross fins and cross fins, although the volume content of circle cross fins is much higher about 1.4%, the heat transfer promotion effect of circle cross fins is 2.46 times higher than that of cross fin.

In order to compare the heat transfer enhancement effect of the cross fin and the circle cross fin in more detail, the temperatures at each position of MH layer after that the certain time passed are displayed. Each positions of MH layer are shown in Figure 9 as the numbers, and the temperature distribution after 50 s and 100 s are shown in Figure 10 and Figure 11.

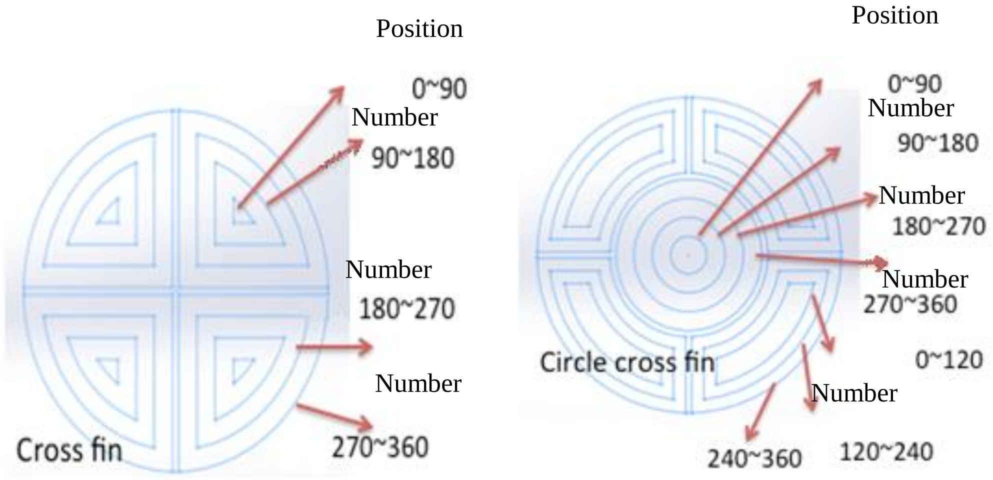

Figure 9: Location of each Number

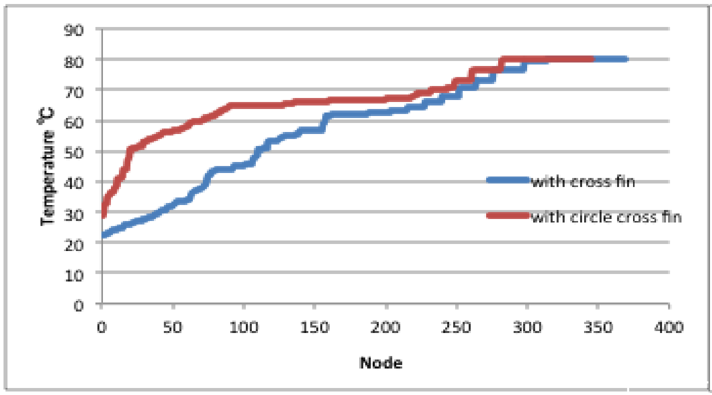

Figure 10: Temperature Distribution of Two Fin after 50s

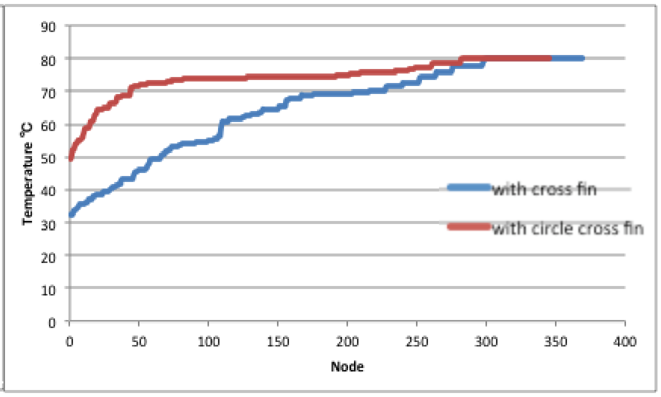

Figure 11: Temperature Distribution of Two Fin after 100s

From these figures, it can be explained that all position's temperature of a MH layer containing circle cross fins is higher than that of cross fins, and the heat transfer promotion effect of circle cross fins is much more effective than that of cross ones. Moreover, combined with the ratio of the volume content considering and the percentage of heat transfer increasing, circle cross fin is the better one for system's heat transfer enhancement.

4.3 Comparison of Analytical and Experimental Results

In order to verify these results, experiments were carried out on simple model, and the results were compared with simulation results. Since the inner diameter of the experimental copper pipe is 15 mm, simulation results were obtained by setting up a model of a tank with an inner diameter of 15 mm. Experiment was carried out by installing a cross fin or a circle cross fin with a internal circle fin diameter of 5 mm on the actual machine, and comparing with the case without fin. Comparison of the results are shown in Figure 12, Figure 13, Figure 14.

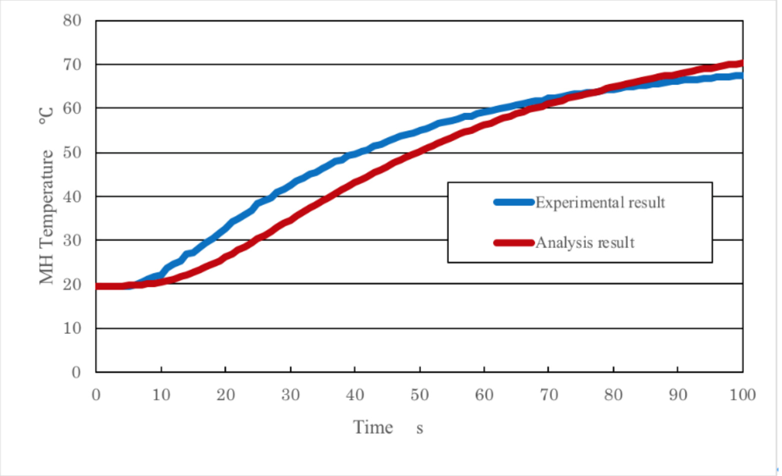

Figure 12: Temperature change of MH (MH only)

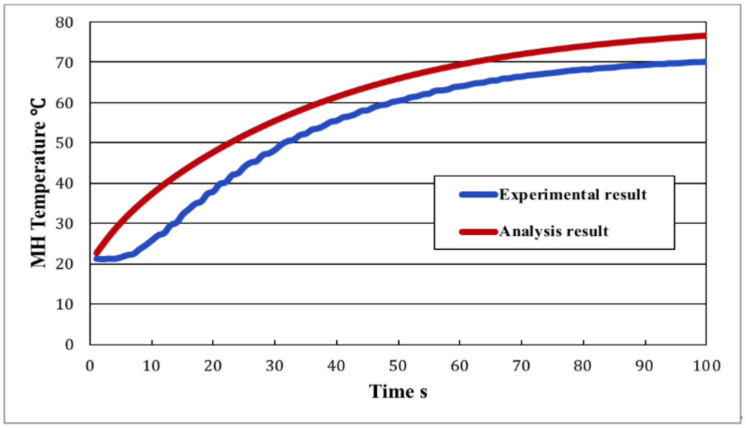

Figure 13: Temperature change of MH (cross fin)

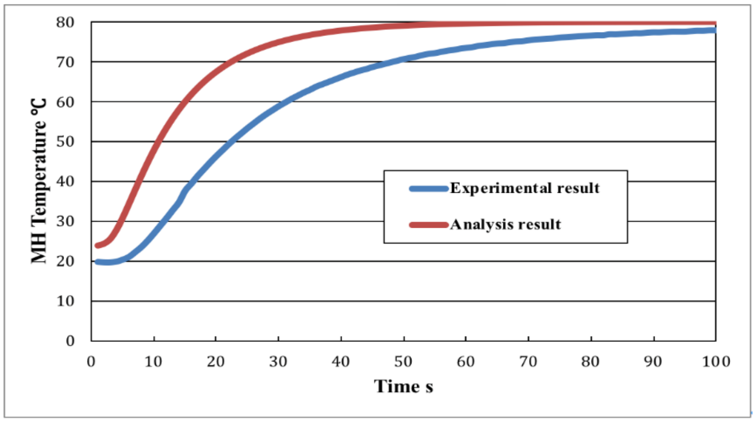

Figure 14: Temperature change of MH (circle cross fin)

As shown in these figures, it can be said that the experimental results could be estimated by the analysis results qualitatively. However, it could not be estimated well quantitatively. The one reason is that thermal resistance between the fin and the powder layer is ignored in our calculation. The other one is that there are also thermal resistances on the contacting area of assembling parts since the cross fin and the circle cross fin are made by combining aluminum.

5.CONCLUSIONS

- The installation of radial fins in the MH tank is effective and the hydrogen release rate is promoted in proportional with the increase in the volume content of fin with respect to the MH alloy layer up to about 10%, However, if it exceeds 10% or more, the promoting effect tends to be deteriorate.

- According to the simulation results, the heat transfer time of reaching 75 ° C from 20 ° C is shorten and become the shortest one when inserting the fin whose inner circle diameter is 24 mm on reactor under the outside diameter of the tank is 50mm, and the heat transfer promotion effect also achieves the highest. Compared with the MH powder layer without the fin, the heat transfer promotion effect improved 11.55 times when the circler cross fin is installed. If the comparison made to the cross fin case, the heat transfer promotion effect improved by 2.46 times. In addition, there is an optimum circle inner diameter for the outer diameter of the tank.

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