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Effects of Corrosion on Heat Transfer Characteristics of Double-Tube Heat Exchangers†

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This paper presents the effects of corrosion on the performance of double-tube heat exchangers using deep ocean water. Aluminum with/without coatings were possible alternative material tubes for replacing the high-price titanium tubes from the previous reported experiments. In this study, the titanium, aluminum, aluminum with electro-deposition coatings (10, 15, 20 μm) were tested under the condition of pure and corroded tubes. The temperature of sea water 70 °C and the concentration of salt 3.5 % were manufactured by corrosion manufacturing unit. The corrosion periods were 6, 12 and18 weeks, respectively. The comparison of the experimental and analytical results were performed. From these analysis, we could confirm the possibility of aluminum with electro-deposition coating 15 μm when the tubes were corroded for 6 and 12 weeks. But, when the corrosion was conducted for 18 weeks, aluminum with 20 μm coating could be considered as alternative for the replacement of titanium.

Keywords: Deep ocean water, Heat exchanger, Corrosion, Anti-corrosion coatings.

INTRODUCTION

Recently, renewable energy, such as solar, geothermal, wind and ocean energy has been paid good attention. Among them, ocean energy is available in variety of ways from tide, wave and thermal difference between surface and deep ocean water[1].

The purpose of this study is to develop a new material type heat exchangers using deep ocean water which has anti-corrosion feature and low cost compared to existing high price titanium heat exchangers. In order to attain the goal, titanium, SUS304, aluminum, copper were tested through the previous experimental studies[2]. Among them, aluminum showed the highest heat transfer performance compared to titanium but the corrosion problem of the aluminum was serious. In this study, therefore, titanium, aluminum, aluminum with electro-deposition coatings were tested for heat transfer rate under the non-corrosion and corrosion conditions.

EXPERIMENTAL

Double-tube heat exchanger

Method of design and experiment: Table-1 shows the characteristics of materials and the specification of the tubes. Table-2 shows the conditions of first and second experiments. Inner and outer flows are adjusted or fixed according to the condition of each experiment. The conditions of Table-2 were to make experimental condition of turbulent flow inner and outer flow passages.

TABLE-1
CHARACTERISTICS OF MATERIALS AND SPECIFICATION OF THE TUBES

Material	k (W/mK)	Cp (J/kgK)	ρ (kg/m^3)
Ti	22	522	4500
Al	237	903	2698

Material	Specification of the tube (mm)
Ti	12.7 D* 0.9T * 1500L
Al	12.0 D* 1.0T * 1500L
Al_ed_10	12.7 D* 1.0T * 1500L
Al_ed_15	12.0 D* 1.0T * 1500L
Al_ed_20	12.1 D* 1.0T * 1500L

For adjusting temperature difference between hot and cold water more than 5 °C, temperature of 30 °C water was supplied to inner tube, temperature of 7 °C was feed to outer tube. Test was conducted with various flow rates of water of inner and outer tubes. Fig. 1 shows the experimental apparatus.

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TABLE-2
EXPERIMENTAL PROCEDURE OF
DOUBLE TUBE HEAT EXCHANGER

	Inner flow (L/min)	Outer flow (L/min)
First experiment	1 2 3 4	10
Second experiment	2	6 8 10 12

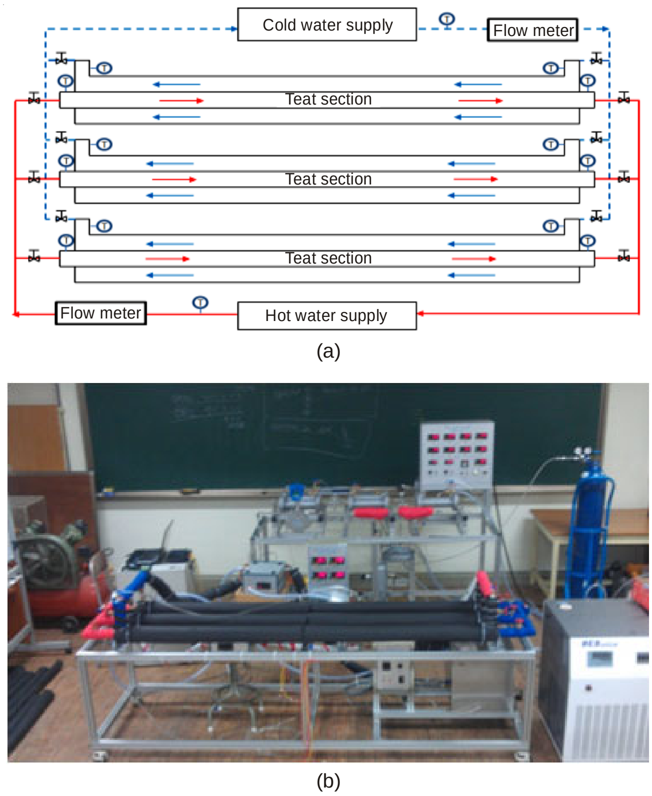

Fig. 1. (a) Schematic diagram of the experimental apparatus, (b) Experimental apparatus

Analysis method: Fig. 2 shows the flowchart of analysis procedure. Analysis was performed by using calculation process of so called ε-NTU method. Heat transfer rate and outlet temperature of water were obtained. Dittus-Boelter equation was used for heat transfer coefficients of flows of inner and outer tubes.

$$Nu = 0.023\ Re^{0.8}Pr^{0.3} \tag{1}$$

where Re is Reynolds number and Pr is Prandtl number.

Engineering equations solver (EES) program was used in this study for the calculation of heat transfer rate of each double-tube heat exchanger for various condition of flow rates and temperatures.

Manufacturing of corrosion tubes: In order to simulate the corrosion, corrosion tubes were made by using manufacturing unit as shown in Fig. 3(a).

Fig. 3(b) shows corrosion tube manufacturing unit, where distilled water with 3.5 % sodium chloride was heated at 70 °C. When the temperature is increased by 10 °C, corrosion speed is also increased by 30 %, but these conditions is limited up to 70-80 °C[3,4]. Enhanced corrosion process was performed for 6, 12 and 18 weeks, respectively, in this condition.

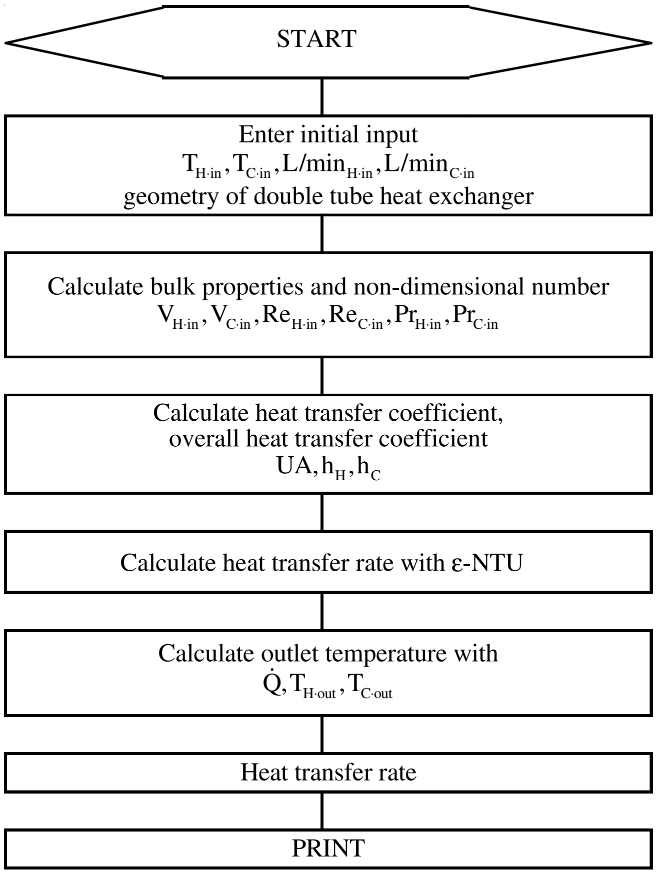

Fig. 2 Analysis algorithm of double pipe heat exchanger

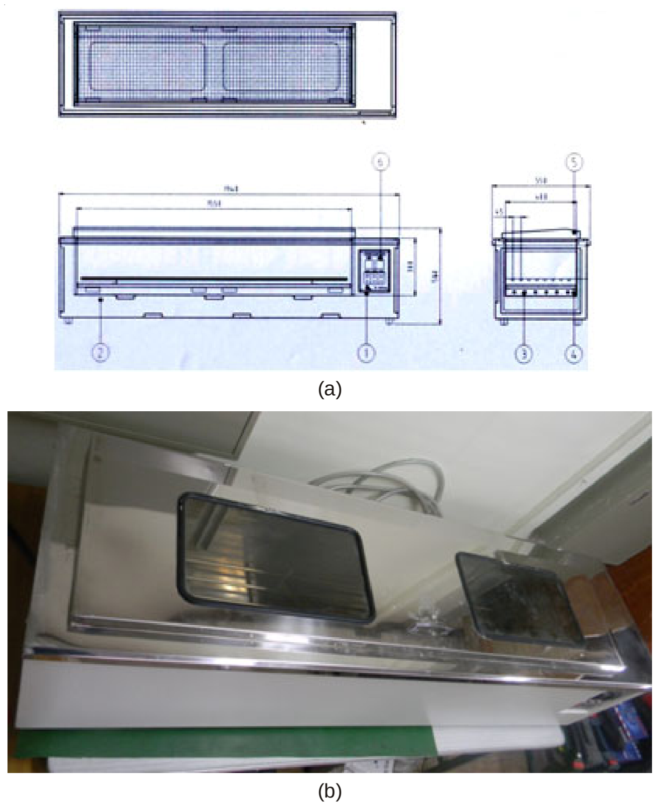

Fig. 3. (a) Design drawings of corrosion tube manufacturing unit, (b) Photograph of corrosion tube manufacturing unit

Fig. 4 shows photos of 5 tubes after exposure to 70 °C, 3.5 % salinity for 6 weeks. Aluminium generated the most corrosion, while Al with anti-corrosion coating tube showed no corrosion.

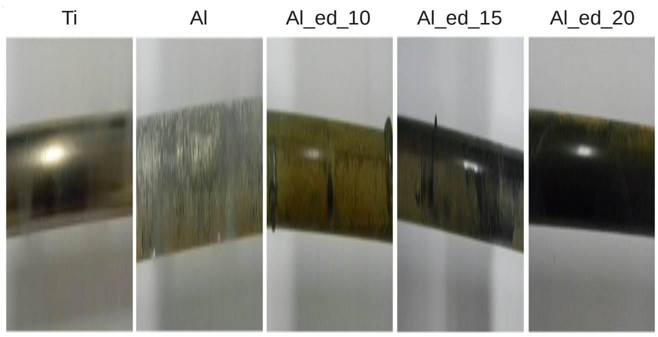

Fig. 4. Photos of tube in 6 week-enhanced corrosion

Fig. 5 shows photos of 5 corroded tubes in the same condition for 12 weeks. These photos show that blisters were generated on the surface of Al tube with electro-deposition coatings 10 and 15 μm.

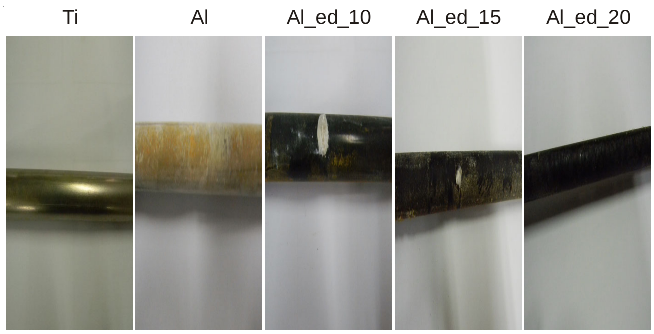

Fig. 5. Photos of tube in 12 week-enhanced corrosion

Fig. 6 shows photos of 5 corroded tubes in the same condition for 18 weeks. Aluminium was corroded more seriously and blister was also generated on the surface of Al tube with electrodeposition coating 20 μm.

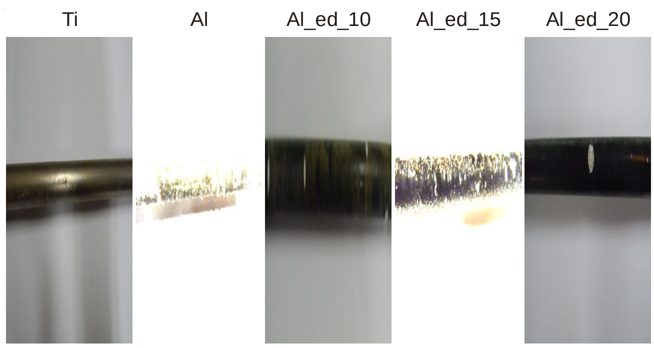

Fig. 6. Photos of tube in 18 week-enhanced corrosion

RESULTS AND DISCUSSION

Analysis results of bare tubes: Fig. 7 showed the calculated results of the heat transfer performance of the bare tubes according to the flow rates.

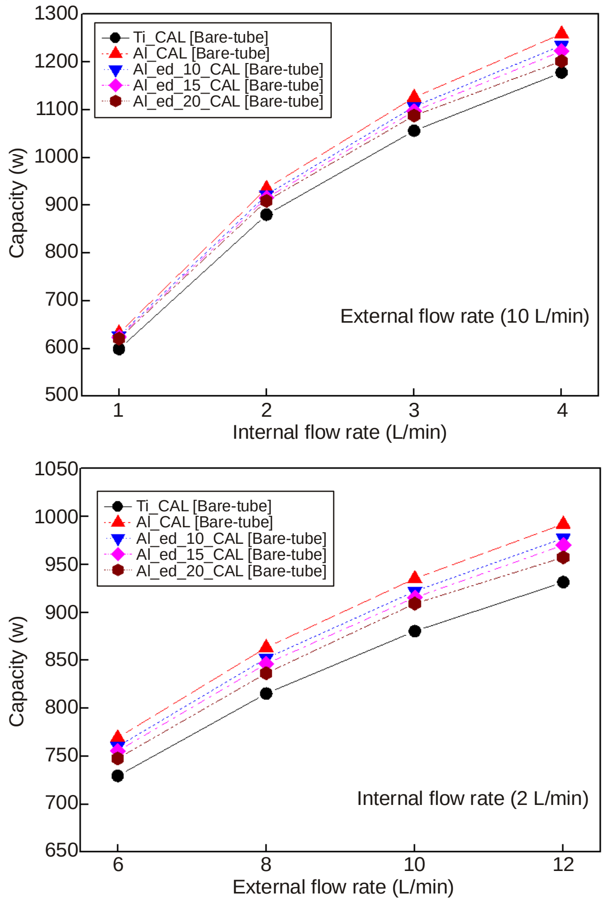

Fig. 7. Analysis value of bare tube according to flow rate change of the inner and outer tubes

Aluminium tube showed the highest heat transfer rate of 1259 W in the first experiment having the conditions of Table-2 when the inner flow rate was 4 L/min. In the second experiment, Al tube also had the highest value of 992.2 W when the outer flow rate was 12 L/min.

Figs. 8-11 show comparisons of the experimental and analytical values of heat transfer rate for various tubes according to flow rate of the inner and outer tubes.

Fig. 8 shows comparison of results of Al and Ti. Most of the results are similar when experimental and calculated values are compared. Only an experimental result of Al having inner flow rate condition 4 L/min in the first experiment has 5.8 % deviation of heat transfer rate with calculated one.

Fig. 9 shows comparison of results of Al with electro-deposition coating 10 μm and Ti. In Fig. 9, Al electro-deposition coating 10 μm has the highest heat transfer rate 1220 W when the inner flow rate was 4 L/min.

Also the results of Al with electro-deposition coatings 15, 20 μm and Ti are compared in Figs. 10 and 11. When heat transfer rate value of bare tube of Ti were set to 100 % Al; Al with electro-deposition coatings 10, 15, 20 μm had 3.01 %, 3.35 %, 1.98 %, -0.5 % deviation, respectively, in the first experiment. In the second experiment, Al, Al with electro-deposition coating 10, 15, 20 μm and Ti had 995.1 W, 991.4 W, 952.2 W, 932.4 W, 915.8 W heat transfer rate respectively. These calculated results are reliable because the deviation between experimental and calculated results is less than 5 % (1.3 %).

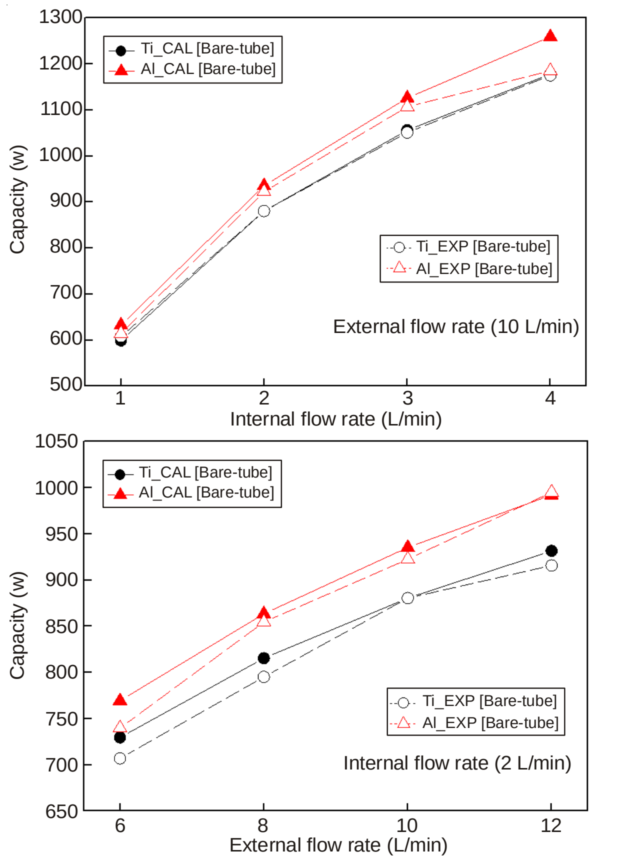

Fig. 8. Comparison of experimental and analysis results (Al, Ti) according to flow rate of the inner and outer tube

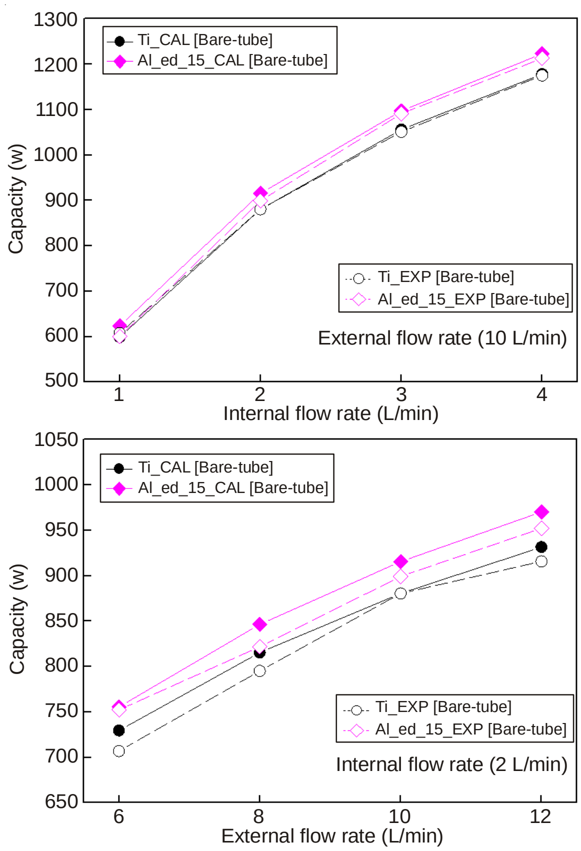

Fig. 10. Comparison of experimental and analysis results (Al with electro-deposition coating 15 μm, Ti) according to flow rate of the inner and outer tube

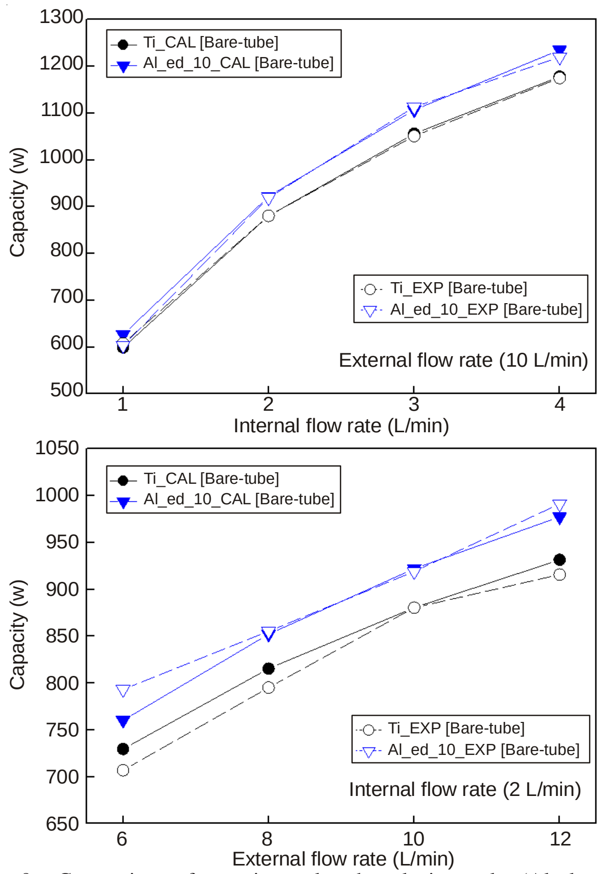

Fig. 9. Comparison of experimental and analysis results (Al electro-deposition coating 10 μm, Ti) according to flow rate of the inner and outer tube

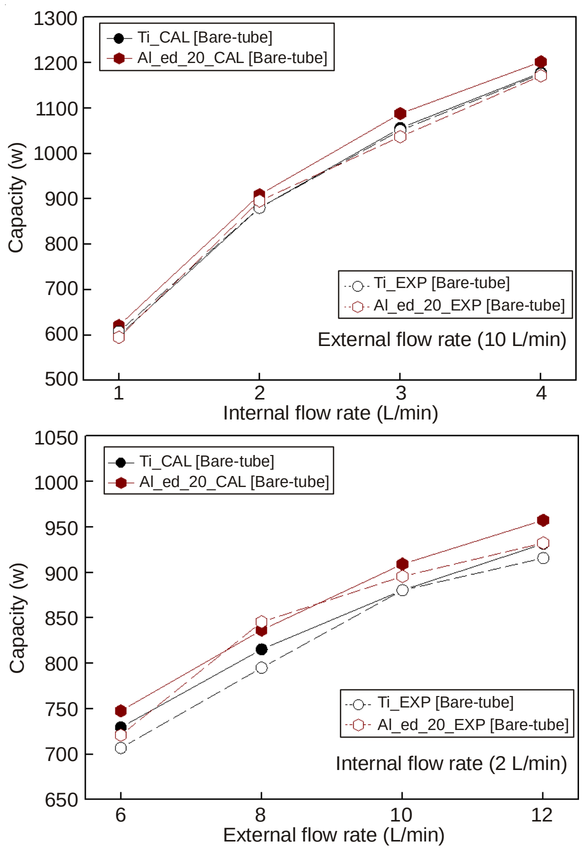

Fig. 11. Comparison of experimental and analysis results (Al electro-deposition coating 20 μm, Ti) according to flow rate of the inner and outer tube

Corrosion for 6 weeks: Fig. 12 shows the experimental results of the tubes corroded for 6 weeks. In the first experiment, Al had the highest heat transfer rate 1203 W, Al with electro-deposition coatings 10, 15, 20 μm and Ti had 1186 W, 1201 W, 1196 W, 1175 W respectively when the inner flow rate was 4 L/min. Also when the outer flow rate was 12 L/min, Al had the highest value 948.1 W and if Ti were set to 100 %, Al, Al electro-deposition coating 10, 15, 20 μm had 3.13 %, 1.3 %, 0.55 %, 0.53 % deviation, respectively, in the second experiment.

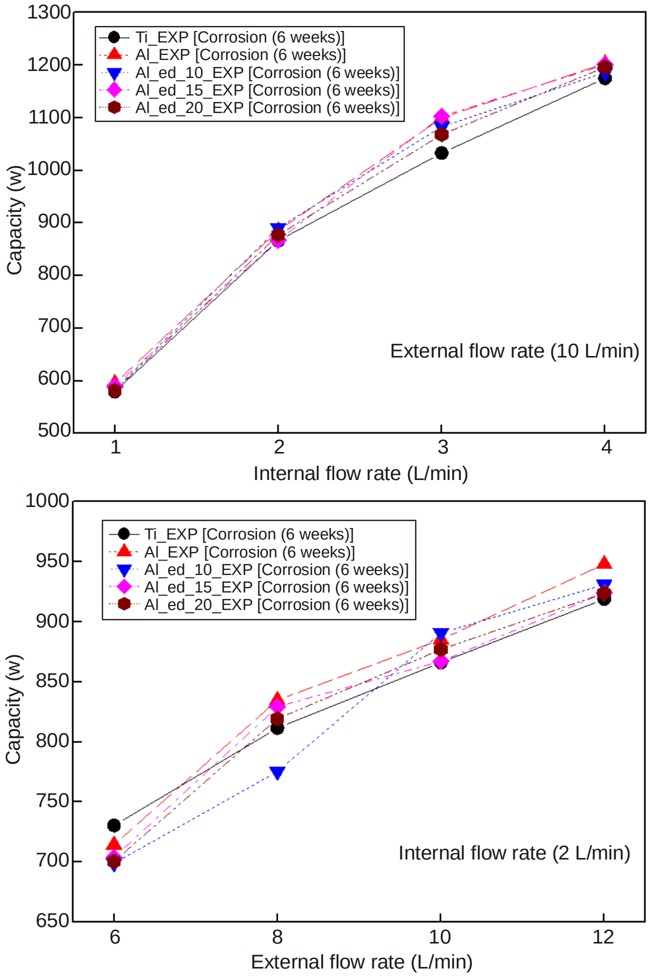

Fig. 12. Heat transfer rate of corrosion tube (6 weeks) according to flow rate of the inner and outer tube

Corrosion for 12 weeks (comparison with 6 weeks): Figs. 13-16 show the comparisons of the experimental values of heat transfer rate for various tubes corroded for 6 and 12 weeks according to flow rate of the inner and outer tubes. In the first experiment, Ti had the heat transfer rate 1148 W when the inner flow rate was 4 L/min. Al, Al with electro-deposition coating 10, 15, 20 μm had 1164 W, 1175 W, 1193 W, 1162 W respectively. When the experimental results between 6 and 12 weeks are compared, the heat transfer rate of Al corroded for 12 weeks was reduced by 3.24 % Al with electro-deposition coating 15 μm had the highest value 1194 W in the same condition. In the second experiment, the tube of Al with electro-deposition coating 15 μm corroded for 12 weeks also had the highest transfer rate 949 W.

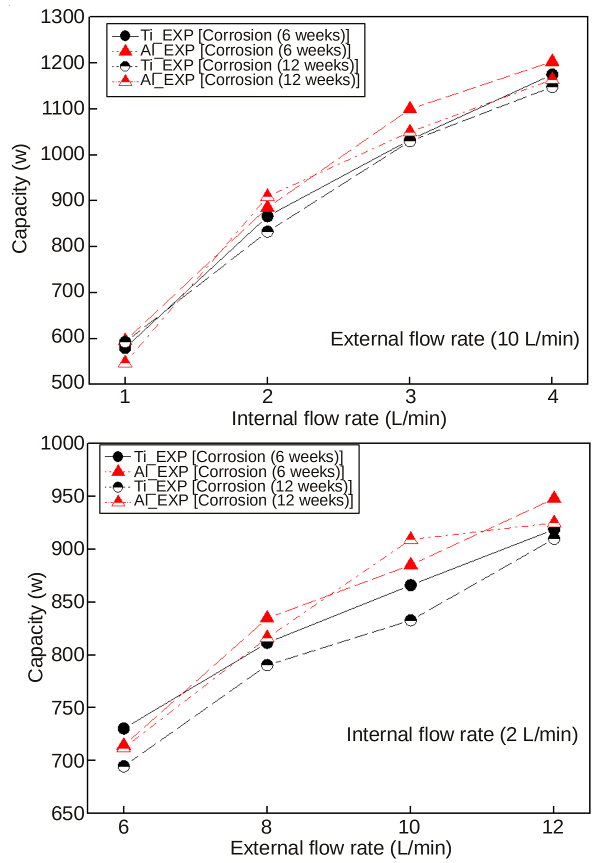

Fig. 13. Comparison of the experimental results of Al and Ti tubes (corrosion for 6 and 12 weeks) according to flow rate of the inner and outer tube

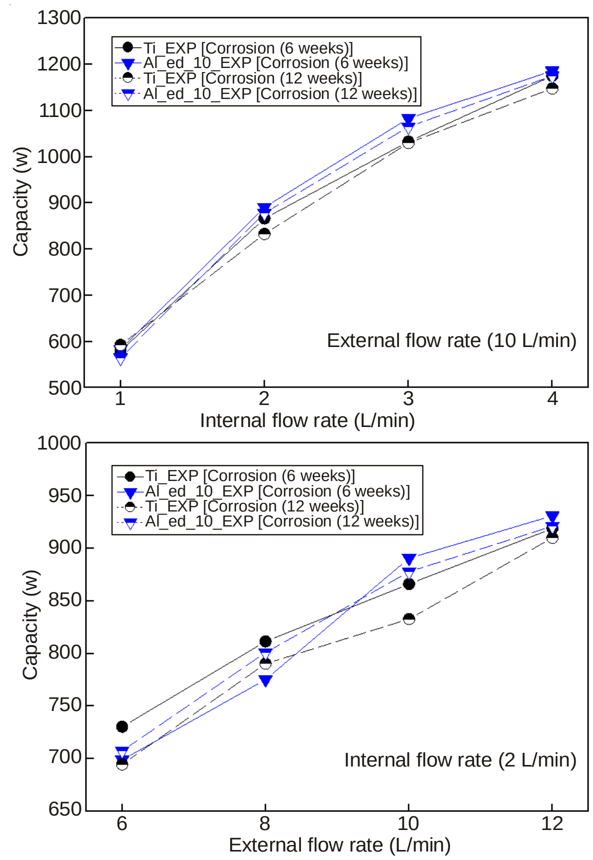

Fig. 14. Comparison of the experimental results of Al electro-deposition coating 10 μm and Ti tubes (corrosion for 6 and 12 weeks) according to flow rate of the inner and outer tube

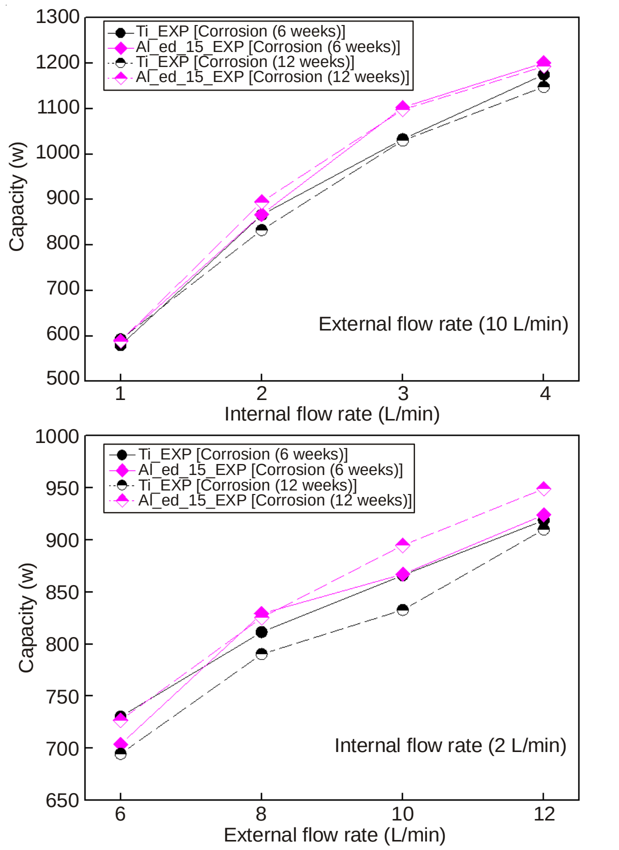

Fig. 15. Comparison of the experimental results of Al electro-deposition coating 15 µm and Ti tubes (corrosion for 6 and 12 weeks) according to flow rate of the inner and outer tube

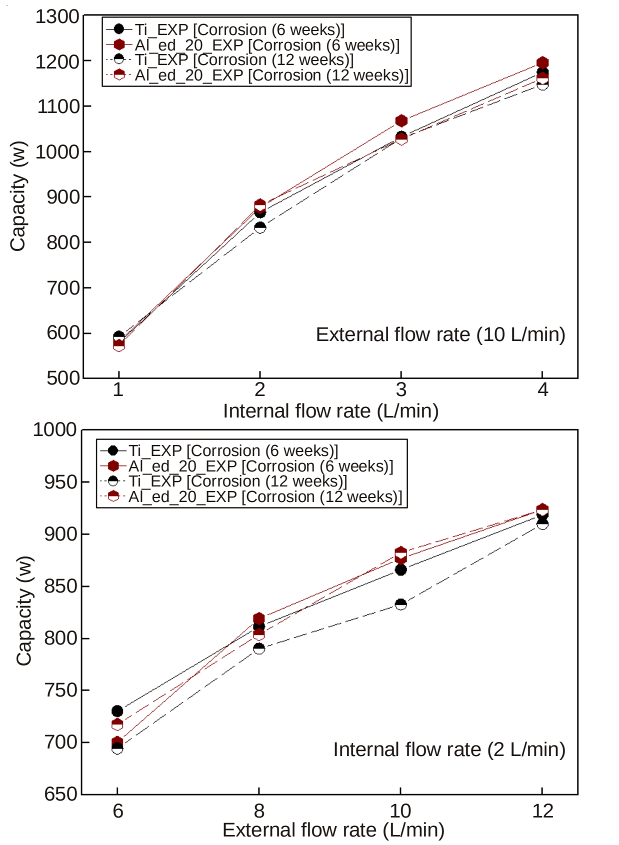

Fig. 16. Comparison of the experimental results of Al electro-deposition coating 20 µm and Ti tubes (corrosion for 6 and 12 weeks) according to flow rate of the inner and outer tube

Corrosion for 18 weeks (comparison with 6 and 12 weeks): Figs. 17-20 show the comparisons of the experimental values of heat transfer rate for various tubes corroded for 6, 12, 18 weeks according to flow rate of the inner and outer tubes. In the first experiment, Ti had the heat transfer rate 1145 W when the inner flow rate was 4 L/min. The results of Ti are nearly same in 6, 12 and 18 weeks. Al had the heat transfer rate 1090 W when the inner flow rate was 4 L/min. When the experimental results between 12 and 18 weeks are compared, the heat transfer rate of Al corroded for 18 weeks was reduced by 6.36 %. In the same comparison, the value of Al with electro-deposition coating 10 µm corroded for 18 weeks was reduced by 5.7 % (1108 W). Aluminium with electro-deposition coating 15, 20 µm had 1149 W, 1151 W heat transfer rate respectively. So, Al with electro-deposition coating 20 µm had the highest value in this condition.

In the second experiment, Al electro-deposition coating 15, 20 µm had the same results of the highest heat transfer rate 924 W when the outer flow rate was 12 L/min. From these experiments, we could confirm that Al with electro-deposition coating 20 µm had the best alternative to Ti.

Comparison of bare and corro-sion tubes: Fig. 21 shows comparison of the experimental results of bare and corrosion tubes. X-axis of the graph in Fig. 21 is corrosion period.

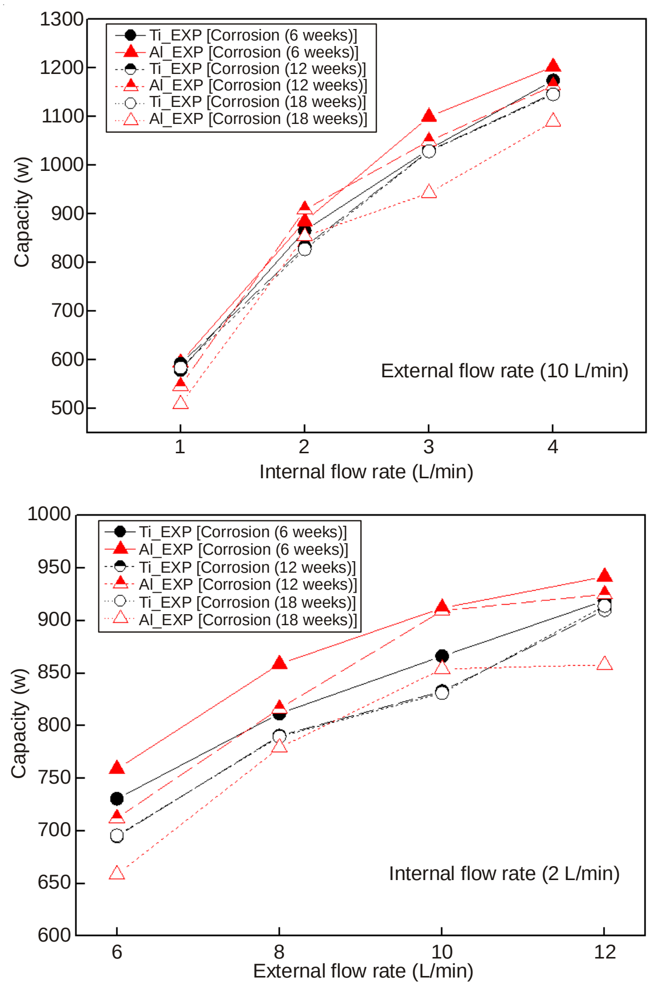

Fig. 17. Comparison of the experimental results of Al and Ti tubes (corrosion for 6, 12, 18 weeks) according to flow rate of the inner and outer tube

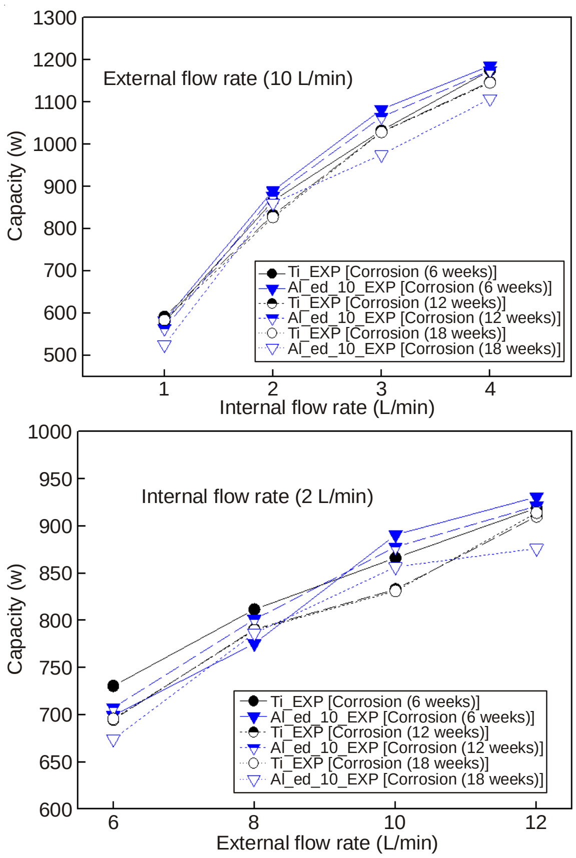

Fig. 18. Comparison of the experimental results of Al electro-deposition coating 10 μm and Ti tubes (corrosion for 6, 12, 18 weeks) according to flow rate of the inner and outer tube

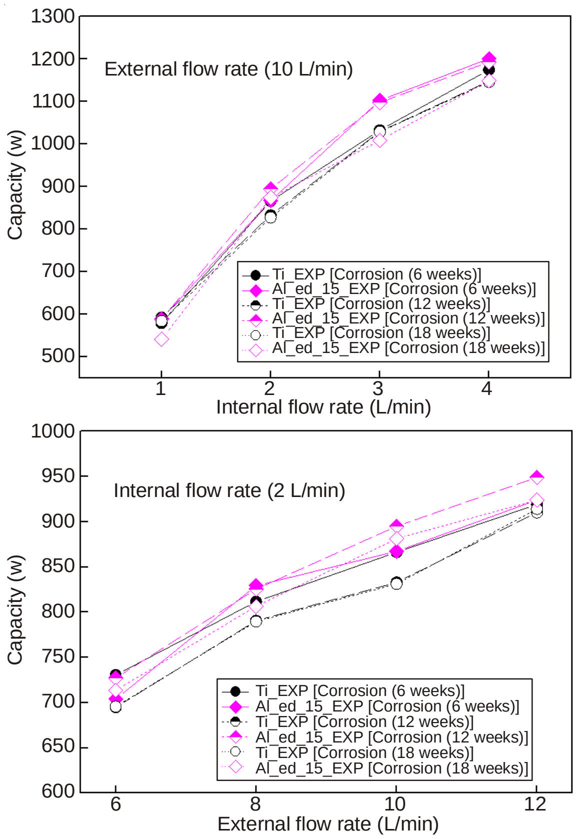

Fig. 19. Comparison of the experimental results of Al electro-deposition coating 15 μm and Ti tubes (corrosion for 6, 12, 18 weeks) according to flow rate of the inner and outer tube

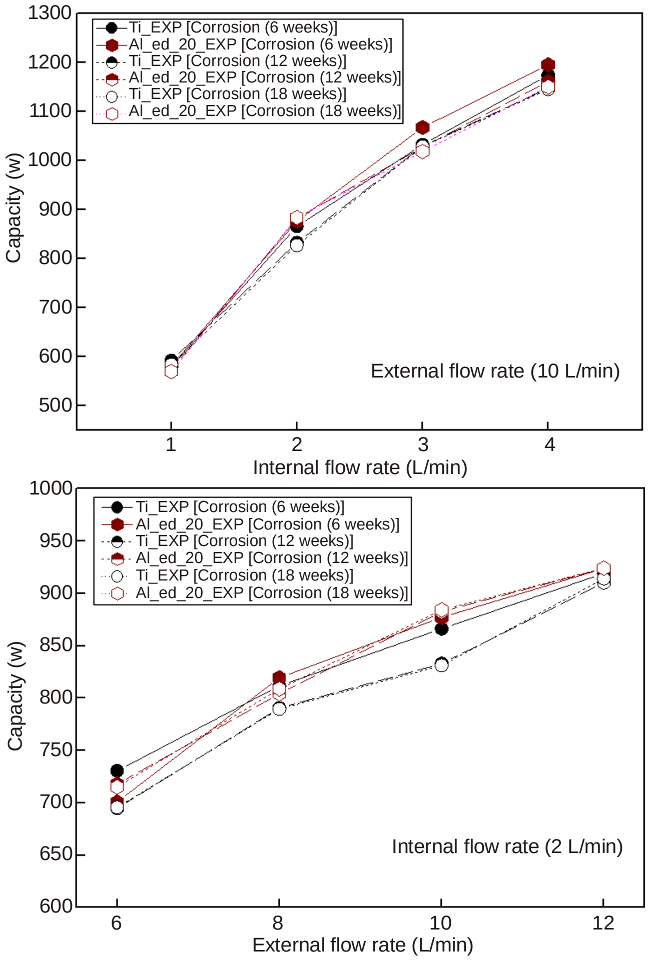

Fig. 20. Comparison of the experimental results of Al electro-deposition coating 20 μm and Ti tubes (corrosion for 6, 12, 18 weeks) according to flow rate of the inner and outer tube

The results in Fig. 21(a) are the highest heat transfer rates of each tube in the first experiment. The condition is that the inner and outer flow rates were 4 and 10 L/min, respectively. The heat transfer rate of Ti had been reduced by 2.47 % for 18 weeks corrosion period. It is not serious decrease, because Ti has anticorrosion feature. Aluminium had the highest heat transfer rate 1185 W in the experiment of bare tubes, but the value had been decreased by 8.02 % for 18 weeks corrosion period. On the other hand, Al with electro-deposition coating 20 μm had been decreased by 1.71 % and had the highest heat transfer rate 1151 W in the experimental results of the tubes corroded for 18 weeks.

The results in Fig. 21(b) are the highest heat transfer rates of each tube in the second experiment. The condition is that the inner and outer flow rates were 2 and 12 L/min respectively. The heat transfer rate of Ti had been reduced by 0.22 % for 18 weeks corrosion period. It means that the heat transfer rate of Ti tube corroded for 18 weeks is nearly same with the result of bare tube. Al also had the highest heat transfer rate 955 W in the results of bare tubes having the second experiment condition, but the value had been decreased by 13.8 % for 18 weeks corrosion period. On the other hand, Al with electro-deposition coating 15, 20 μm had been decreased by 1.39 % and 0.86 %, respectively. Aluminium with electro-deposition coating 15, 20 μm had the same results of the highest heat

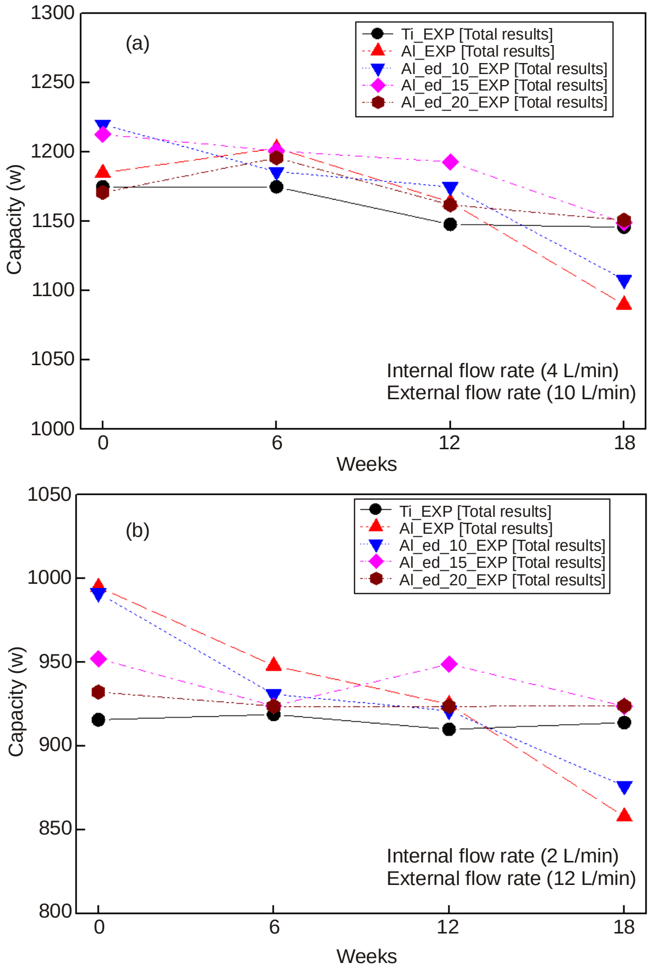

Fig. 21. Comparison of the experiment results of heat transfer rate depended on the period of corrosion

transfer rate 924 W in the condition of Fig 21(b). From these experiments, we could confirm that Al with electro-deposition coating 20 μm had the best alternative to Ti.

Conclusion

In this study, a series of experiments were performed to develop heat exchangers using deep ocean water which has anticorrosion feature and low cost compared to existing heat exchanger that consist of titanium. The experiments on aluminum were mainly performed for comparing with titanium because the alternative of aluminum was verified by former experiments. For the corrosion experiment, aluminum was coated by electro-deposition method (10, 15, 20 μm thicknesses). Corrosion periods were 6, 12, 18 weeks, respectively. From these experiments, we could confirm the possibility of the alternative of aluminum tube with electro-deposition coating 15 μm when the tubes were corroded for 6 and 12 weeks. But, when the corrosion was conducted for 18 weeks, aluminum tube with electro-deposition coating 20 μm could be considered as the best alternative for the replacement of titanium.

REFERENCES

1. J.Y. Park, S.H. Jin, S. Kim and H.J. Kim, *J. Korean Solar Energy Soc.*, **30**, 357 (2010).
2. K.Y. Kim, K.W. Lee, Y.C. Kwon, J.T. Kwon and C. Huh, Study on Metal Corrosion Under High Temperature, The Society of Air-Conditioning and Refrigerating Engineers of Korea, pp. 475-477, November (2012).
3. U.G. Lim, G.C. Jeong and S.Y. Lee, Corrosion and Protection of Mechanical Materials, Hyung Seul Pub (2006).
4. D.A. Jones, Principles and Prevention of Corrosion, Prentice Hall (2004); M.Y. Jo, Y.S. Suh and L.H. Jang, *J. Energy Eng*., **8**, 567 (1999).