High Heat-transfer Titanium Sheet-HEET®- for Heat Exchangers

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A plate-type heat exchanger (PHE) that uses seawater as a cooling/heating medium is widely employed by chemical plants, power-generating facilities and large transport ships. Titanium is a common material for these heat exchangers, particularly for their primary members, including a heat exchanging plate and piping, thanks to its excellent corrosion resistance to seawater. Improving the heat-transfer performance of PHE enables the reduction in number and size of the plate used in PHE and thus enables the entire facility to be downsized. Kobe steel have developed a high heat-transfer titanium plate-HEET®-which has a heat-transfer performance that is significantly improved by fine irregularities imparted on its surface. The surface area increased by the fine irregularities, along with the promoted nucleate boiling, has improved the heat-transfer and particularly increased the evaporative heat transfer by approximately 20% or more.

Introduction

Titanium has excellent corrosion resistance against seawater. Therefore, it is frequently applied to the primary members, such as heat-exchanging plates and piping, of plate-type heat exchangers (PHEs) that use seawater for cooling and heating. Such PHEs are commonly found in chemical plants, power-generating facilities, and large transport ships, etc.[1] **Fig. 1** shows the structure and operating principle of a PHE. A PHE is an apparatus for exchanging heat between seawater and a medium to be heated or cooled by the seawater and comprises a plurality of plates, wherein seawater is made to flow in the opposite directions on both the side of each plate. As shown in **Fig. 2**, there are three types of heat transfer that are responsible for heat exchange: namely, liquid-single-phase forced-convection heat transfer, in which hot water discharged from a factory, for example, is cooled by cold seawater; evaporation heat transfer, in which working fluid is converted into gas by warm seawater as in the case of ocean thermal energy conversion; and condensation heat transfer, in which working gas is converted into liquid. Improving the performance of each type of heat transfer improves the efficiency of heat exchangers. Also, decreasing the number and size of plates used in a PHE enables downsizing of the entire facility.

Various research and development have so far been carried out to improve the efficiency of heat exchangers. As for the methods of improving the heat transfer from the plate material, particularly in the case of evaporation heat transfer, there has been reported a method of thermally spraying stainless steel particles on a plate surface to make it porous,[2] and a method utilizing the electrodeposition of copper to form a coating film with fine asperities on the surface.[3] It has been confirmed that, in these methods, the fine asperities on a surface act as boiling nuclei to promote nucleate boiling and thus improve evaporation heat transfer. All these methods, however, suffer from problems in long-term stability, e.g., the exfoliation of

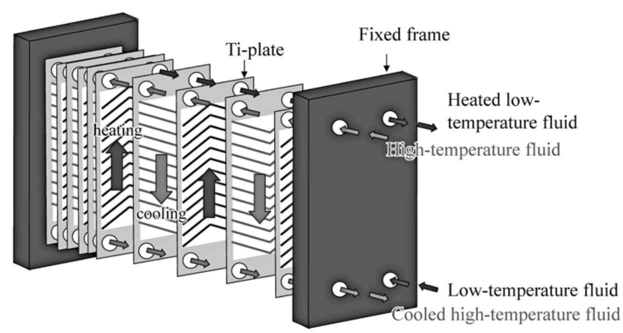

Fig. 1 Structure and principle of plate-type heat exchanger

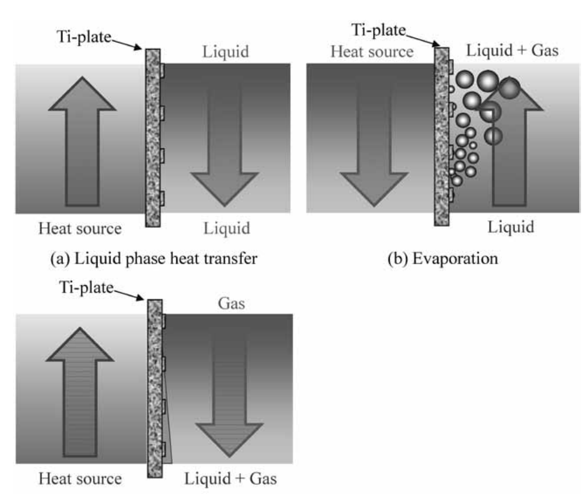

Fig. 2 Outline of heat transfer types

surface asperities, and in the processing cost and productivity.

As a way of solving these problems, Kobe Steel has proposed a method of forming fine asperities on a surface of a titanium sheet using a transfer-printing rolling technology.[4] **Fig. 3** shows the outline of this technology. Transfer-printing rolling is a technology in which a roll having fine recesses on its surface is used to roll a titanium sheet and the recesses result in asperities being formed on the surface of the sheet. A titanium sheet having fine grooves (groove width: 200 μm, mound width: 100 μm, depth: 30 μm) imparted by this technology, as shown in **Fig. 4**, has been confirmed to improve evaporation heat-transfer performance by 10% to 40% compared with commonly used smooth-surfaced sheets, when the fine grooves are arranged so as to be perpendicular to the flow.[4]

Actual PHE plates are press-formed so as to have a complex corrugated pattern, such as the herringbone pattern shown in **Fig. 5**, to improve heat-exchange efficiency and mechanical durability. The undulating shape of the plates causes the flow inside a PHE to change direction; hence it is desirable for a plate to have a shape (pattern) that allows a high heat exchange effect in all flow directions. Against this backdrop, Kobe Steel has developed a high heat-transfer titanium sheet (hereinafter referred to as "HEET®" note), having a polka-dot pattern in which cylindrical fine asperities are arranged in a staggered manner. The company has started mass production of the sheet. **Fig. 6** shows the surface morphology and cross-sectional structure of the coil of HEET obtained by transfer-printing rolling. The asperities are so arranged as to cover the entire surface of the sheet and have a uniform shape with their height being approximately 25 μm.

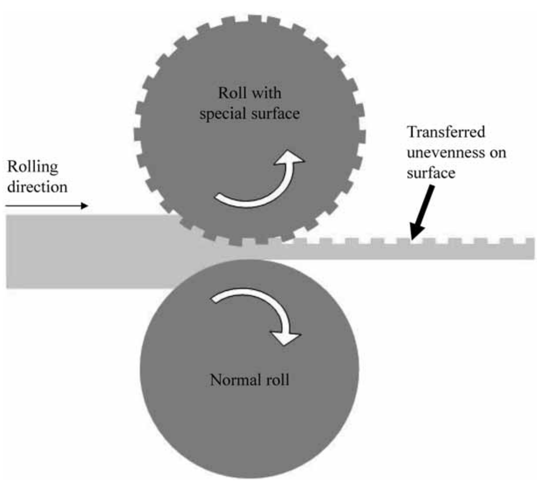

Fig. 3 Outline of transfer-printing rolling technology

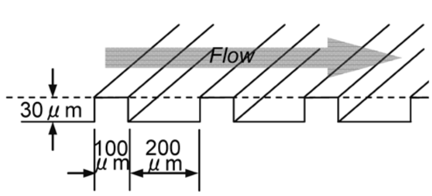

Fig. 4 Schematic of fine grooves

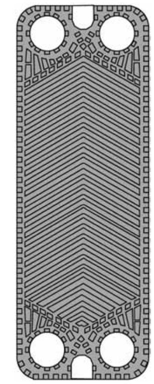
Fig. 5 Pattern diagram of typical heat exchanger plate

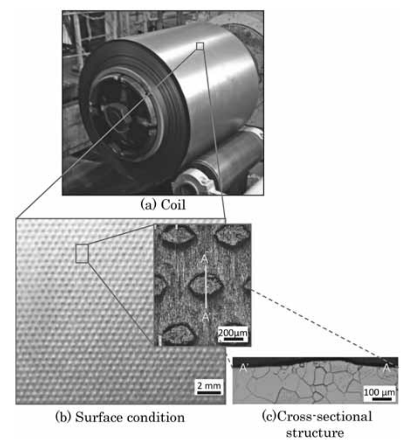

Fig. 6 Coil, surface condition and cross-sectional structure of high-heat-transfer titanium (HEET)

HEET has been adopted in the ocean thermal energy conversion (OTEC) demonstration plant on Kume Island, Okinawa, which is gaining attention as a source of renewable energy and has been in continuous operation since 2013. This paper introduces the effect of HEET in improving heat transfer performance, as well as the results of the heat-transfer performance evaluation of the PHE in the actual ocean thermal energy conversion demonstration plant.

1. Heat-transfer performance evaluation test

1.1 Sample preparation

The following explains the production method of HEET. Firstly, CP titanium (ASTM G1) material was hot- and cold-rolled into a sheet having a

note) HEET is a registered trademark (No. 85652095) of Kobe Steel.

predetermined thickness, and cylindrical fine asperities, arranged in a staggered manner as shown in Fig. 6, were transfer-printed on a surface of the sheet. The sheet, with a thickness of 0.6mm, was subjected to heat treatment and flatness correction before being cut into a plate of HEET having a width of 80mm and length of 200mm to be used for the evaluation of thermal conductivity. A conventional smooth-surfaced normal titanium plate of the same size was also prepared as a reference material.

The HEET material was also wound to form a welded cylinder with an outer diameter of 19mm, a wall thickness of 0.6mm and a length of 550mm, whose outer surface being the sheet surface with fine asperities.

1.2 Method of evaluating heat transfer performance

The plates of HEET and normal titanium plate were used for the test of evaporation heat transfer. **Fig. 7** is a schematic diagram of the heat transfer test. Heat exchanger No. 1 was used as an evaporator, to which a plate of either smooth-surfaced titanium or HEET was affixed. In the case of HEET, the working fluid, Freon R134a, was made to flow on the surface with asperities, and hot water was made to flow on the other surface such that heat exchange occurred while evaporating R134a. The evaporated R134a was cooled and liquefied by a condenser to be recirculated in the apparatus. The heat-transfer surface was 50×150mm, and temperatures were measured at the inlet and outlet of each evaporator. Using the measured temperatures, heat quantity, Q, and logarithmic average temperature difference,

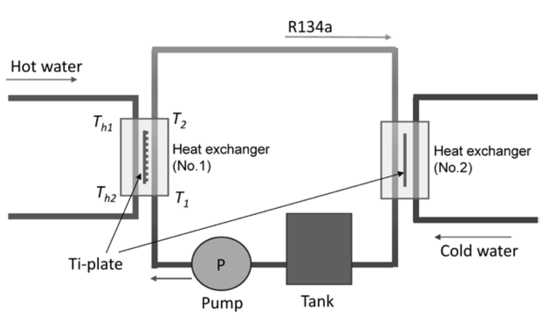

Fig. 7 Schematic diagram of heat-transfer testing apparatus

ΔT_m, were determined on the basis of Equations (1) and (2):

$$Q = l_h \rho_h c \ (T_{h1} - T_{h2}) \quad \cdots\cdots (1)$$

$$\Delta T_m = \frac{(T_{h1} - T_{h2})}{\ln \frac{(T_{h1} - T_2)}{(T_{h2} - T_1)}} \quad \cdots\cdots (2),$$

wherein T_{h1} and T_{h2} are, respectively, the input temperature and output temperature of the hot water; T_1 and T_2 are the respective input and output temperatures of R134a; l_h is the flow rate of the hot water; ρ_h is the density of the hot water; c is the specific heat of the hot water; and A is the heat-transfer area. From Q and ΔT_m thus determined, the overall evaporative heat-transfer coefficient, U, was calculated using Equation (3).

$$U = \frac{Q}{A \Delta T_m} \quad \cdots\cdots (3)$$

The effect of HEET on condensation heat transfer and liquid-single-phase forced-convection heat transfer was also investigated. In the test of condensation heat transfer, Heat Exchanger No. 2 in Fig. 7 was used as a condenser, to which a plate of either normal titanium or HEET was fixed. In the case of HEET, the working fluid, R134a, was made to flow on the surface with asperities, and cold water was made to flow on the other surface so as to perform heat exchange. Whereas, in the test of liquid-single-phase forced-convection heat-transfer, a plate of either normal titanium or HEET was fixed on Heat Exchanger No. 1 in Fig. 7 and, in the case of HEET, cold water was made to flow on the surface with asperities and hot water was made to flow on the other surface so as to perform heat exchange. In each of the tests, temperatures were measured at the inlet and outlet of respective heat exchanger, as in the case of the evaporative heat transfer test, and the overall heat-transfer coefficient, U, was determined on the basis of Equations (1) to (3). **Table 1** summarizes the conditions of these tests.

In the case of evaporation heat transfer, an attempt was made to visualize the generation of bubbles during heat exchange, using the tube of HEET with fine asperities on its outer surface. **Fig. 8** shows the schematic diagram of the test and **Table 2** summarizes the testing conditions. A part

Table 1 Heat-transfer testing conditions

	Hot water			Cold water			R134a		
	Inlet temperature (℃)	Flow volume (m^3/s)	Flow rate (m/s)	Inlet temperature (℃)	Flow volume (m^3/s)	Flow rate (m/s)	Flow volume (m^3/s)	Mass flux (kg/m^2s)	Saturation pressure (MPa)
Evaporation	35	3.0	0.6	10	5.0	0.8	0.1	23	0.5
Condensation	40	3.0	0.6	10	2.0	0.4	0.1	22	0.9
Liquid phase heat transfer	70	5.0	0.9	20	1.0	0.2			

Table 2 Visualization testing condition

Hot water		Cold water		R134a		
Inlet temperature (℃)	Flow volume (m^3/s)	Inlet temperature (℃)	Flow volume (m^3/s)	Evaporative temperature (℃)	Saturation pressure (MPa)	Heat flux (kW/m^2)
40.0	25.0	6.0〜17.0	1.0~2.0	30.0〜33.0	0.65~0.74	20.0~40.0

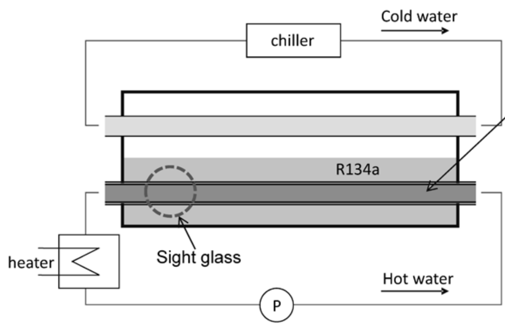

Fig. 8 Schematic diagram of visualization experiment

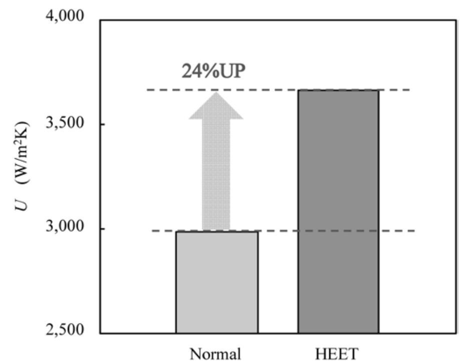

Fig. 9 Evaporation heat transfer performances of HEET and normal plate

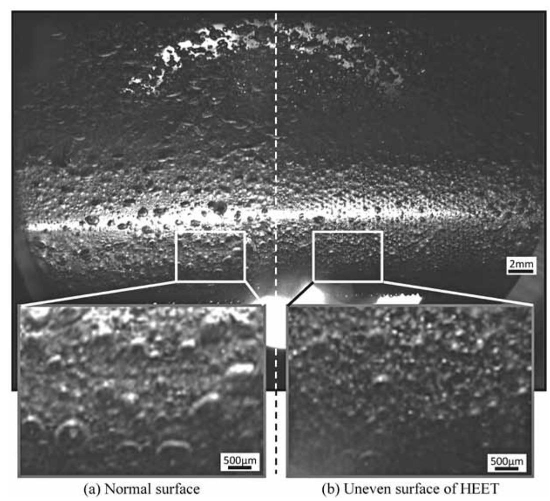

Fig.10 Boiling on surface with asperities and normal of welded tube

of the outer surface of the welded tube was polished such that the fine asperities were removed and the roughness was adjusted to be equal to that of the smooth surface. The welded tube was immersed in R134a and hot water was made to flow inside the welded tube so as to boil R134a on the outer surface of the welded tube. The testing apparatus was provided with an observation window from which the status of bubble generation from the surface with fine asperities and from the smooth surface was captured by a high-speed camera.

2. Results of heat-transfer performance evaluation

2.1 Evaporation heat transfer

Fig. 9 shows the results of evaporative heat transfer tests performed on HEET and on smooth-surfaced plate. It has been confirmed that HEET exhibits a heat-transfer performance approximately 24% higher than that of the smooth-surfaced plate. Thanks to the fine asperities, HEET has a surface area approximately 6% greater than that of the normal sheet; however, the improvement effect of heat-transfer performance is greater than this increment of surface area. **Fig.10** shows the example of an image captured by a high speed camera showing boiling on the welded tube. To the left of the broken line at the center of the photo is the surface portion where the fine asperities were removed and the roughness was adjusted to make it equal to that of the smooth surface. It can be confirmed that a greater number of finer bubbles are generated on the surface of HEET, with its fine asperities, compared with the smooth surface. In general, boiling on a sheet surface occurs from fine scratches and cavities that serve as boiling nuclei to generate bubbles. On the other hand, in the case of HEET, the fine asperities are believed to perform the work of scratches and cavities, promote nucleate boiling and, as a result, improve the heat transfer performance.

2.2 Condensation and liquid-single-phase forced-convection heat-transfer

In the test of condensation heat transfer, the U values for the smooth-surfaced titanium plate and HEET are 910 W/m^2K and 943 W/m^2K, respectively: HEET exhibits a performance improvement of approximately 6% compared with the smooth-surfaced plate. Also in the case of liquid-single-phase forced-convection heat-transfer, the U values for the smooth-surfaced titanium plate and HEET are 2,050 W/m^2K and 2,283 W/m^2K, respectively: HEET exhibits a performance improvement of approximately 11% compared with the smooth-surfaced plate.

Although estimated, the mechanism of performance improvement exhibited in the test, is believed to be attributable to the increased surface area and the generation of turbulence causing the agitation of fluid inside the heat exchanger.

3. Verification of heat exchangers

In practical operation, a plurality of plates, each press-formed to have a complex corrugated pattern as shown in Fig. 5, are assembled into a PHE. To confirm the effect, therefore, an evaluation was conducted on a PHE having a size of approximately 700 × 2,400mm, which is the size of the PHE actually used for the ocean thermal energy conversion demonstration plant. The evaporation heat transfer performance was examined on a plate press-formed into a predetermined shape and was assembled into a heat exchanger. **Fig.11** shows the results. It has been confirmed that HEET achieves a performance improvement of approximately 20% in the actual PHE. **Fig.12** shows the 100kW-class ocean

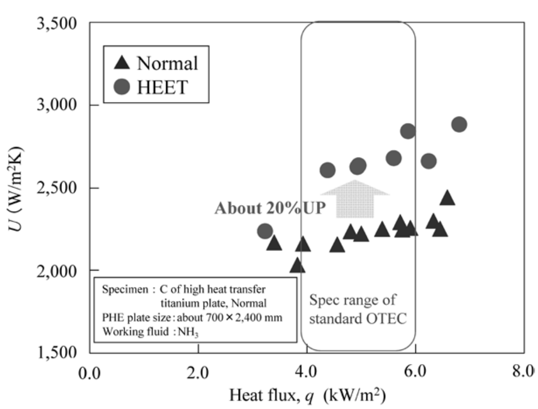

Fig.11 Relationship between overall heat transfer coefficient (U) of evaporation and heat flux (q) on PHE of OTEC

Fig.12 OTEC demonstration plant

thermal energy conversion demonstration plant built in Okinawa in 2013. It has been confirmed, also in this plant, that HEET improves the evaporation heat transfer performance by 20%, verifying its effectiveness.

Conclusions

A high heat-transfer titanium sheet (HEET) exploits rolling transfer-printing technology to form fine asperities on its surface. These fine asperities improve heat transfer performance, probably by increasing the surface area and promoting nucleate boiling, and have been confirmed to improve the performance, particularly the evaporation heat transfer performance, by approximately 20% or greater.

Generally, a liquid film generated in condensation heat transfer covers the plate surface, deteriorating heat transfer performance, whereas the fine asperities on HEET are expected to promote the discharge of such a liquid film. Future studies will focus on the optimization of the shape of fine asperities and application to various types of heat exchangers.

Some of the achievements of this development have been obtained through the work on the 2011-2014 project of the New Energy and Industrial Technology Development Organization, "Technological research and development of natural energy including wind power, etc. / Research and development of ocean energy technology / Research and development of next generation ocean energy power generation technology (ocean thermal energy conversion)." We would like to express our appreciation here.

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