Expanding Application of Micro Channel Equipment (Diffusion Bonded Compact Heat Exchanger; DCHE™)

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Abstract

The demand for microchannel heat exchangers, a type of compact heat exchanger, is expected to increase as they are used in applications requiring light weight and compactness and as apparatuses for offshore equipment. Above all, their demand has been increasing in recent years for use in the fuel supply systems of offshore equipment that uses liquefied natural gas (LNG) and small-capacity LNG vaporizers for satellite bases.
These applications require, not only pressure tightness and compactness, but also measures to be taken against the freezing of the fluid serving as the heat medium. In the case of diffusion bonded compact heat exchangers (DCHE™s), concepts having to do with the suppression of freezing have been incorporated into their design, and tests were conducted using liquid nitrogen and LNG, to establish the design guidelines for the range of vaporization performance and icing. This report introduces the effort to apply a DCHE™ to LNG vaporizer applications.

Introduction

Microchannel heat exchangers, or diffusion bonded compact heat exchangers (hereinafter referred to as the "DCHE™"),[Note 1)] have high pressure resistance and are used as compressed gas coolers for natural gas processing plants, heat exchangers for natural gas fluids, as well as for coolers and precoolers of compressed hydrogen for hydrogen refueling stations. With the requirements for improving equipment reliability and for compactness, studies are taking place to use the DCHE™ for LNG vaporizers and natural gas processing plants in the future.

This paper mainly introduces the characteristics of the DCHE™ from aspect of its design for LNG vaporizer applications.

1. Structure and characteristics of DCHE™

1.1 Structure of DCHE™

The DCHE™ is a type of compact heat exchanger and has a structure consisting of stacked plates with millimeter-sized channels. Kobe Steel has the designing and manufacturing technology of brazed aluminum plate-fin heat exchangers (hereinafter referred to as the "ALEX™"[Note 2)]), which have been delivered for more than 50 years, and the DCHE™ exploits this technology. An ALEX™ comprises a brazed core body for exchanging heat, and a header and nozzle for guiding the fluid into the core (**Fig. 1**).[1)] The DCHE™ has a stacked structure like the ALEX™, and the manufacturing know-how and design concept cultivated for the ALEX™ can be applied to the DCHE™.[2)] The greatest differences in the manufacturing process are found in the processes of etching to form channels, and diffusion bonding to join the plates all at once. Etching is a technology for melting and processing metals by utilizing the corrosive action of chemicals such as etching solutions. This technique is applied to stainless steel plates to form channels through which fluid passes. Since the DCHE™ applies diffusion bonding, it has a pressure resistance higher than those of other heat exchangers.

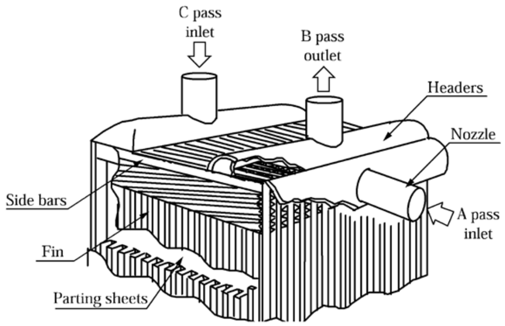

Fig. 1 Structure of ALEX™

1.2 Characteristics of DCHE™

The DCHE™ has the following basic characteristics:

(1) Performance highly resistant against pressure and heat
By selecting material and optimizing channel size, it can be used up to 100 MPa and 900℃. The applicable temperature range follows the allowable stress table stipulated by the law for each material.

[Note 1)] DCHE is a registered trademark of Kobe Steel, Ltd.

[Note 2)] ALEX is a registered trademark of Kobe Steel, Ltd.

(2) Compactness
Its large heat-transfer area ensures high heat-transfer performance, making its size approximately 1/10 of those of multi-tube (shell & tube) heat exchangers.

(3) Excellent corrosion resistance
The use of SS316L and the like enables its application to cooling water, etc.

It should be noted, however, that the ALEX™ is more economical, and the ALEX™ is proposed for applications where it is applicable, e.g., where the temperature difference between fluids is smaller than 50℃ (single phase), the application is not corrosive, and the pressure resistance requirement is 13 MPa or lower.

Kobe Steel handles both the DCHE™ and ALEX™, each being a type of compact heat exchanger, and can propose an optimum heat exchanger in accordance with the design and operating conditions. Kobe Steel also has performed numerous stress analyses on various static equipment such as heat exchangers and pressure vessels. Therefore, in the case of operations with a large temperature difference between fluids, or with a significant operating variation that causes concerns about damage during operation, it is also possible to predict the expected lifetime of heat exchangers by using the finite element method of analysis (hereinafter referred to as "FEM analysis").

1.3 Applicable use of DCHE™

As described above, the DCHE™ is a compact heat exchanger with excellent heat transfer performance. For this reason, it is used, for example, for offshore equipment with footprint limitations and coolers for hydrogen refueling stations. It is also adapted to cases where the ALEX™ cannot be used, e.g., coolers using cooling water for natural gas or hydrogen gas and LNG vaporizer applications with a large temperature difference between fluids of 50℃ or greater.

The recent increase in shale gas production in the United States has initiated several projects, not only for onshore natural gas plants, but also for offshore floating production storage and offloading (FPSO) systems for oil and gas as well as natural gas liquefaction processing facilities (Floating LNG),[3), 4)] in which the DCHE™ is often applied to heat exchangers of the natural gas fluid and after-gas coolers of compressors. Also expected as offshore applications are LNG vaporizers used in the fuel supply systems of LNG fueled ships (Fuel Gas Supply Systems: FGSSs).

In these applications, natural gas is expected to be increasingly used as an environmentally friendly fuel, with emissions of carbon dioxide, sulfur oxides and nitrogen oxides lower than those of coal and petroleum, to comply with the new limit on sulfur content stipulated by the International Maritime Organization (IMO)[5)] and to meet the 2025 regulations on CO_2 emissions.[6)] In addition, the DCHE™ is expected to be applied to offshore facilities with limitations in footprint area, requiring equipment down-sizing.

As for onshore applications, the demand for natural gas supply systems using LNG satellite terminals[Note 3)] for industrial use is on the rise.[7)] From the perspective of achieving global warming countermeasure goals, there are high expectations in Japan, the United States, Europe, and Asia for hydrogen as a means of storing increasing renewable energy in large quantities over medium-to-long terms, and the construction of hydrogen refueling stations is in progress with the prevalence of fuel cell vehicles (FCVs).[8)-10)] The DCHE™ has been applied to the aftercoolers of compressed hydrogen and precoolers for dispensers used there.

The following sections describe the details of Kobe Steel's unique design concept and the approach of the DCHE™ in the natural gas vaporizer applications used in the fuel supply systems for offshore and satellite terminals, whose demand is increasing in recent years.

2. Antifreezing structure

Besides compactness, it is important for LNG vaporizer applications to prevent hot water and glycol water used as a heat source, from being frozen in the channel inside a heat exchanger by the cold heat of LNG, so as to keep the operation running continuously. For other types of heat exchangers, such as multi-tube heat exchangers, it is recognized as one of the problems that, when freezing occurs, it is necessary to stop the operation of the LNG vaporizer until the ice is thawed. Hence, Kobe Steel has incorporated a unique concept into its design and applied a structure that is less likely to cause freezing to the LNG vaporizer applications. This section provides an overview.

2.1 Concept 1: Stacked structure[11)]

In the case of LNG vaporizer applications, the conventional concept involves two-fluid heat

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[Note 3)] A secondary receiving terminal that accepts and regassifies LNG carried from a primary receiving terminal by a lorry, or the like exchange between LNG, which is the COLD side fluid, and the HOT side fluid, and the design is conducted with the number of layers based on COLD: HOT = 1: 1. In this structure, however, if the fluid in the channel on the HOT side is plugged by freezing, it is necessary to wait until it naturally thaws. On the other hand, by applying the COLD: HOT = 1: 3 structure including two HOT1 layers and one HOT2 layer against one COLD side layer as shown in **Fig. 2**, it is possible to supply the heat of HOT2 to HOT1, even if freezing begins to occur in the layer of HOT1, which is in contact with the COLD side. Thus, it is possible to suppress the freezing of the HOT side fluid that obstructs the channel, unlike the conventional COLD: HOT = 1: 1 structure. Hereinafter, the combination of COLD: HOT = 1: 1 is referred to as the 1: 1 structure, and the combination of COLD: HOT = 1: 3 is referred to as the 1: 3 structure.

2.2 Concept 2: LNG channel pattern design

When LNG is supplied at a low pressure, there is created a region where LNG is evaporated inside a heat exchanger. Therefore, it is predicted that the temperature of the metal (the wall temperature of channels) of the heat exchanger will decrease due to the latent heat and the increase in the heat transfer coefficient on the LNG side. To mitigate this, a channel type (straight channel) with poor heat transfer is intentionally adopted in the part where the heat transfer coefficient is high in the LNG vaporization region. In addition, in order to reduce the heat-transfer area in the LNG evaporation region, a channel design with a large pitch is adopted for the LNG channels.

Meanwhile, on the heat medium side, a channel type with a high heat transfer coefficient (wavy channels) and a channel type with a small pitch are adopted so that a large heat-transfer area can be obtained for the sake of raising the temperature of the metal of/in the heat exchanger.

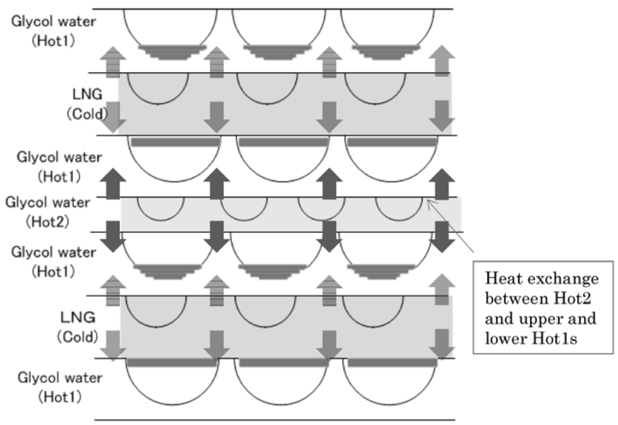


Fig. 2 Concept of antifreezing

3. Performance test using liquid nitrogen (LN_2) and LNG

The effectiveness of the antifreezing structure described in the previous section was examined by investigating the changes in the LNG outlet temperature and the pressure loss of the fluid on the HOT side, while confirming the performance of the equipment and the freezing conditions of the fluid in the channels. This section provides an overview.

3.1 Test with high pressure LN_2

3.1.1 Confirmation test of vaporization performance range

Two DCHEs™, one with the 1: 1 structure and the other with the 1: 3 structure, were prepared to confirm their operable ranges while using the parameters of LN_2 inlet temperature, LN_2 flow rate, etc. for both of the structures. The heat medium used for the test was 40 vol% propylene glycol water with a freezing temperature of -22℃. **Fig. 3** shows the results of the confirmation test performed on the range for vaporizing performance. First, a test was carried out at an inlet temperature of 60℃ and a flow rate of 32.5 m^3/h for propylene glycol water, and a flow rate of 1,500 kg/h for LN_2. The results confirmed that the LNG outlet temperature satisfies the specified temperature without freezing for both the 1: 1 structure and 1: 3 structure.

Next, the operation range in which freezing occurs was confirmed by increasing the LN_2 flow rate stepwise to 2,000 kg/h, 2,500 kg/h, and 3,000 kg/h while keeping the flow rate of propylene glycol water constant (32.5 m^3/h) and decreasing the inlet temperature stepwise from 60℃ to 50℃, 40℃ and 30℃. As a result, the 1: 1 structure used

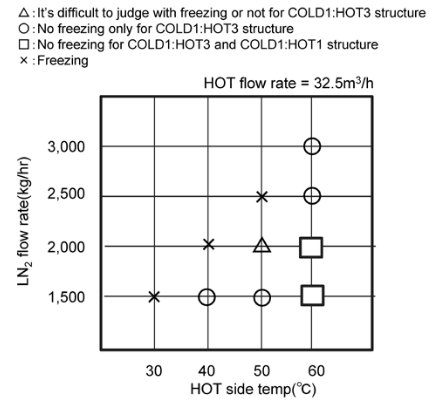


Fig. 3 Test results of range for vaporizing performance

in conventional design exhibited a decrease in heat transfer performance and an increase in pressure loss on the heat source side, which are considered to be attributable to freezing, for all the conditions at the propylene glycol water inlet temperature of 60℃, flow rate of 2,000 kg/h or higher, and inlet temperature of 50℃ or below. On the other hand, the 1: 3 structure caused no freezing in all the conditions indicated by the circles (○), confirming that it can handle a wider range of operating conditions than the 1: 1 structure can.

3.1.2 Confirmation tests on performance of recovery from freezing

After the above test, a test was carried out to confirm the performance of the recovery of the heat source fluid from freezing. The test results are graphed in **Fig. 4**, the change in flow rate is graphed in **Fig. 5**, and the change in pressure loss is graphed in **Fig. 6**. The testing conditions were as follows:

First, a test was conducted under the conditions of an LN_2 inlet temperature of 60℃ and the flow rate of 3,000 kg/h. Then, the LN_2 inlet temperature was changed to 50℃ to confirm that freezing occurred in the fluid in the HOT side channel by checking the change in the pressure loss on the basis of the HOT side inlet and outlet pressures. From here, the flow rate was decreased to confirm whether the freezing would be reversed. As described in the graph, the flow rates were set to 1,200 kg/h, 750 kg/h, and 500 kg/h. The freezing was judged to have recovered when the pressure loss based on the inlet and outlet pressures on the HOT side decreased to their pre-freezing level under the conditions reduced to 750 kg/h and 500 kg/h. In other words, it was confirmed that, in the case of the 1: 3 structure, lowering the flow rate on the COLD side is effective for performance of recovery even when the fluid in the channel on the HOT side is frozen. Alternatively, when HOT2 is managed as a separate fluid, freezing can be reversed by increasing the temperature of the HOT2 side fluid or by increasing its flow rate.

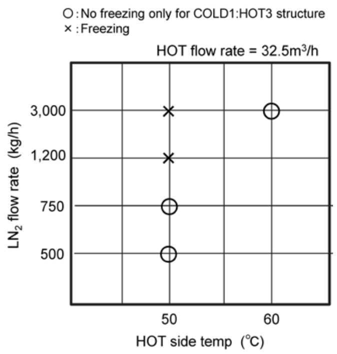


Fig. 4 Test results for performance of recovery from freezing condition

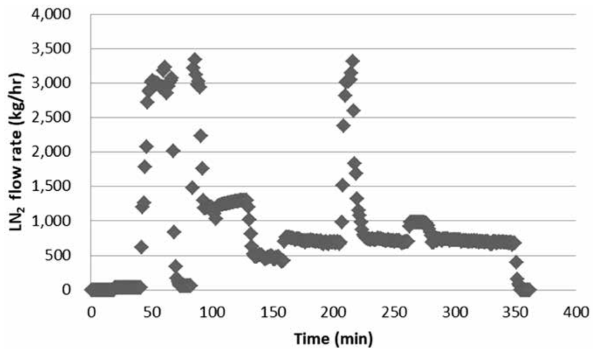


Fig. 5 Test results for performance of recovery from freezing condition (LN_2 Flow rate)

3.2 Test with low pressure LNG

3.2.1 Confirmation test on heat exchanger performance

Using low-pressure LNG, a test was conducted under conditions where an LNG vaporization region occurs inside the equipment. **Table 1** shows the test conditions. In addition to Concept 1 described in Section 2, the DCHE™ adopting the structure of Concept 2 was used, and the effectiveness of these against freezing was confirmed in test conditions ① and ② shown in Table 1. The performance evaluation of the heat exchangers was conducted by comparing the designed *UA*, in which *UA* is the product of the overall heat transfer coefficient (*U*) representing the performance of the heat exchanger

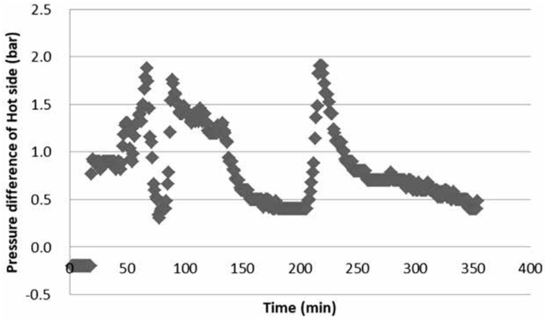


Fig. 6 Test results for performance of recovery from freezing condition (pressure difference on HOT side)

Table 1 Test condition of heat exchanger performance

	LNG side	Hot water side
Pressure	6.5 barg	2.0 barg
Flow rate	123.5 kg/h	9,753 kg/h
Inlet temperature	-125℃	①50℃ (design case) ②40℃ (critical case for freezing) ③30℃ (freezing condition)

and the heat-transfer area (A), with the *UA* of the actual device. The value *UA* is obtained by dividing Eq. (1), which expresses the heat exchange amount *Q*, by ΔT obtained from the process conditions. It is known that this is effective for evaluating heat exchangers when the flow rates of the fluids and their physical properties are close to each other.[12)]

$$Q=UA\Delta T \quad \cdots\cdots (1)$$

wherein Q: Amount of heat exchanged (kW)
U: Overall heat transfer coefficient (kW/m^2℃)
A: Heat-transfer area (m^2)
ΔT: Logarithmic mean temperature difference (℃)

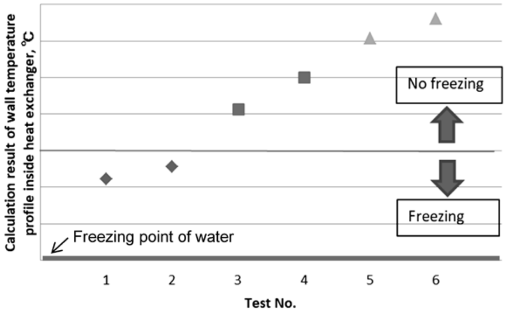
As shown in **Table 2**, conditions ① and ② both yielded results exceeding the respective values of designed conditions, confirming that there was no problem with the performance of the heat exchanger.

3.2.2 Establishment of design guidelines against freezing

Continuing from the previous section, a test was conducted under test conditions ③, shown in Table 1. The freezing conditions were confirmed by the low-pressure LNG test and were compared with the wall temperature profile, obtained by the design calculation of Kobe Steel, inside the heat exchanger. As a result, the relationship between the design-calculation wall temperature and the freezing range was determined as shown in **Fig. 7**. These results confirmed that there was a difference between the design-calculation wall temperature and the freezing point of the fluid on the HOT side. The difference is considered to be due to the changes in flow rate and temperature, which occur even in normal operation, and the design margin has been determined from these values and used as the design guideline.

Table 2 Test results for heat exchanger performance

	Design condition	Test condition ① Inlet temperature: 50℃	Test condition ② Inlet temperature: 40℃
Heat exchanged amount (kW)	26.6	19.53	20.15
Long mean temperature difference (℃)	116.8	48.1	49.7
UA (kW/℃)	0.228	0.406	0.405
Comparison between design condition and test results	100%	178%	178%



Test No.	Hot side in temp (℃)	LNG in temp (℃)
1	30	−129
2	30	−125
3	40	−129
4	40	−125
5	50	−129
6	50	−125

Fig. 7 Calculation results for wall temperature profile inside heat exchanger under each test condition

4. Verification of measures against thermal stress

LNG vaporizer applications inevitably accompany a significant temperature difference between LNG and the HOT-side fluid, which causes great thermal stress to be generated. Studies were conducted on how much thermal stress is generated, how to evaluate design life and how to reduce thermal stress.

4.1 Thermal stress evaluation by thermal stress analysis

The evaluation of thermal stress was based on confirming how many times the start and stop can be allowed under the following design conditions. The thermal stress was calculated using the FEM analysis, and the design life was derived from the design fatigue curve (**Fig. 8**) of austenitic stainless steel, as described in ASME Sec. VIII Div.2.

4.2 Evaluation of number of start/stop times in actual project

Thermal stress evaluation was carried out under the design conditions shown in **Table 3**. The resulting stress contour map is shown in **Fig. 9**. From Fig. 9, it has been found that the largest thermal stress is generated on the LNG header side of the weld between the HOT side header and core

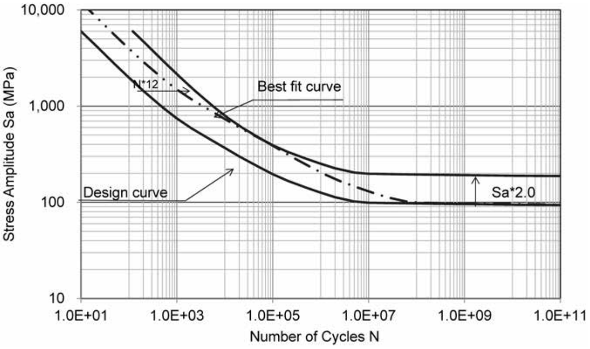


Fig. 8 S-N curve for stainless steel

Table 3 Thermal stress evaluation for design condition (three streams: LNG1, LNG2, heat medium)

	LNG side	Heat medium side
Pressure	6.0 bar	2.0 bar
Temperature	-163℃	60℃
Flow rate	LNG1:840 kg/h LNG2:680 kg/h	25,300 kg/h

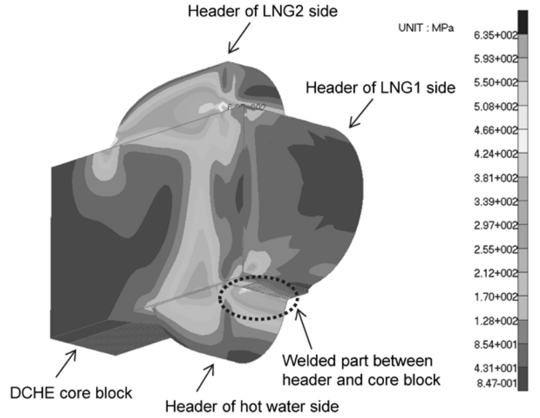


Fig. 9 Contour map of Mises stress (before improvement)

Table 4 Fatigue life evaluation for basic design and improved design

	Basic design	Improved design
Fatigue life (design)(*1)	6,900 times	40,000 times
Fatigue life (average)	75,000 times	1,000,000 times

(*1) Design fatigue life is considered safety factor by ASME rule.

body and at the weld between header and core body on the LNG side. From the maximum thermal stress amplitude at said parts and the S-N curve in Fig. 8, the design life is confirmed to be 6,900 cycles. These results confirm that the thermal stress can be reduced by properly arranging the header position to reduce the thermal stress, and at the same time, by devising the arrangement of the hot water channel. The life has been successfully improved to 40,000 cycles, which corresponds to start and stop of at least 5 times a day for over 20 years (5 times/day × 365 days/year × 20 years = 36,500 times) (**Table 4**).

5. Advantages of DCHE™ as LNG vaporizer in FGSS application

5.1 Design life (thermal stress)

The LNG vaporizers in the FGSS applications experience significant temperature differences between fluids, in which operating variation is also expected. Therefore, it is important to estimate the design life in advance, giving consideration to thermal stress.

Kobe Steel has delivered more than 200 units of the DCHE™ to hydrogen refueling stations since 2012. Thermal stress analysis has also been conducted for verification in advance for these hydrogen refueling stations. One of the advantages of the DCHE™ is that appropriate life evaluation and design improvement can be performed on the basis of experience with actual products.

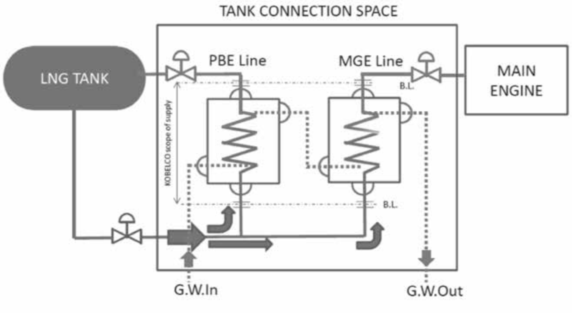
5.2 Integration of vaporizer for tank pressurization and vaporizer for main engine

A low-pressure LNG vaporizer application may require two heat exchangers, i.e., an LNG vaporizer for tank pressurization and a LNG vaporizer for the main engine. In such a case, the LNG vaporization heat exchanger for tank pressurization is activated to send out the LNG in the tank to supply it to the vaporizer for the main engine. It is an advantage for customers that an inexpensive system can be configured without using a pump. Several customers have adopted the above system. Instead of the two-units of two-fluid heat exchangers in a conventional system, the DCHE™ enables the proposal of one-unit of a three-fluid heat exchanger, comprising LNG for tank pressurization, LNG supplied to the main engine, and the fluid on the HOT side (**Fig.10**). This enables the reduction of the number of heat exchangers and effective utilization of the space. Another advantage is the ability to reduce peripheral piping and mounting. The fact that not only two fluids, but also multiple fluids can exchange heat is also considered to be an advantage of the FGSS application using the DCHE™.

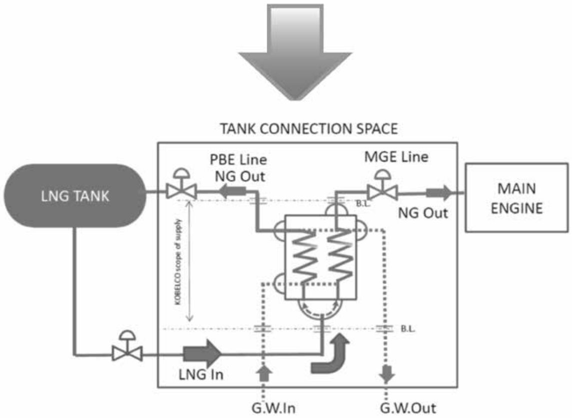
5.3 Antifreezing structure

For stable operation of LNG vaporizers, freezing of the heat medium is currently cited as the greatest concern for the customers. The DCHE™ can suppress freezing with Concept 1: stacked structure (COLD: HOT = 1: 3 structure); furthermore, as mentioned in Section 3.2.2, the design guidelines against freezing have also been established. The load of LNG fuel ship operation fluctuates and, if the operating conditions are provided by customers, it is possible to design with the focus on the risk of freezing during load fluctuations, in addition to the freezing risk evaluation, at the time of design.

Even if freezing should occur, recovering from freezing is possible while continuing operation, although it is necessary to reduce the natural gas



Layout of plate & shell type (two HX)



Layout of DCHE type (one HX)

Fig.10 System flow diagrams

flow rate, as mentioned in Section 3.1.2, which contributes to the continuous operation of natural gas processing plants.

5.4 Cost reduction by standardization

In an FGSS application, the amount of vaporization is pre-determined to some extent for each output of the main engine of the LNG fuel ship. Hence, cost reduction can be realized by standardizing equipment, preparing standard products for each vaporization amount, and manufacturing them as semi-general-purpose products.

Currently, several standard products are continuously manufactured for the DCHE™ used in hydrogen refueling stations. Here, standardization of the parts and simultaneous manufacturing have enabled cost reduction compared with the case where only one unit is manufactured. With reference to these achievements, Kobe Steel plans to promote cost reduction by standardization even for medium- and small-capacity LNG vaporizers, including those for FGSS applications.

Conclusions

This paper has introduced the characteristics of the DCHE™ in LNG applications, focusing on the design aspect. Influenced by environmental regulations, the number of LNG vaporizer applications is expected to increase in the future. Regarding the DCHE™, we would like to continue to focus on expanding sales by exploiting its compactness and the ability to integrate multiple fluids. In addition, heat exchangers used in gas treatment plants are being studied more and more as an applicable use involving natural gas.

As a manufacturer capable of proposing both the DCHE™ and ALEX™, Kobe Steel would like to contribute to the supply of equipment to the ever-increasing number of natural gas plants.

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