Development of LNG Vaporization System with Ground Source Heat Pump
Part 4 Study on optimal design method of Hybrid Ground Source Heat Pump System with the Air-Water Heat Exchangers
地中熱ヒートポンプを用いた LNG 気化システムの開発に関する研究
(第 4 報) ハイブリッド地中熱ヒートポンプシステムにおける最適設計手法の検討

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Abstract: The purpose of this paper is to clarify the optimal design method of the hybrid ground source heat pump (GSHP) system. Specifically, the representative region in Japan is selected first, assuming the introduction of the hybrid GSHP system to the LNG vaporization system, the required number of ground heat exchangers (GHEX) and air-water heat exchangers (AWHEX) are calculated by simulation tool. Next, the multiple regression analysis is carried out. The relational formula is obtained by using ridge regression regression model, and the relative error between the predicted value and the test value is about 12.1%.

1. Introduction

In the third report[1)], the authors introduced the ground temperature suppression effect of the hybrid ground source heat pump (GSHP) system with the air-water heat exchangers (AWHEX) by simulation tool[2)] which is developed in our laboratory. In addition, the purpose of this paper is to investigate the optimal design method of hybrid GSHP system with AWHEX. The way is that considering the import of the hybrid GSHP to the LNG vaporization system by selecting the representative region in Japan, and to calculate the required number of ground heat exchangers (GHEX) and AWHEX to simulate the scale of the vaporization system according to the simulation tool. The required number of GHEX and AWHEX are calculated in representative region in Japan. Then, we clarify the optimal design method of Hybrid GSHP System which is matched the size of the vaporization system and region by the multiple regression analysis.

2. Summary of calculation

In order to calculate the required number of GHEX and AWHEX, the rated output of the heat pump (50,100,200kW) and the allowable temperature of the heat pump inlet (-5℃) was set, and the calculation conditions of the vaporization system of representative cities is imported in simulation tool. Then, specific calculation conditions will be described. First of all, the weather data[3)] of representative cities in Japan (Sapporo, Sendai, Niigata, Takamatsu, Fukuoka) published by the Japan Meteorological Agency as conditions of ambient temperature in 2018 were selected. Secondly, the underground temperature of representative cities (Table 1) and condition of GSHP (Fig1) are imported. In addition, heat load of LNG vaporization in actual factory (Fig2) is also imported in simulation tool (when the heat load of vaporization exceeds the rated output of the heat pump, the heat pump processes the load up to the rated output). Finally, operating conditions of AWHEX is set. Fig 3 shows the performance characteristics of AWHEX used in the simulation. Regarding the control of AWHEX operation, it is assumed that when the ambient temperature is lower than the outlet of GHEX in the primary side and less than 5 ° C, the entire flow was bypassed without passing through the AWHEX. However, when ambient temperature was higher than the outlet of GHEX in the primary side and above 5°C, eventhough there is no heat load, AWHEX is operated to restore the underground temperature. The procedure of determining the size of GHEX and AWHEX is shown in Fig4. Fig5 shows the variation of the inlet temperature at the primary side under the condition that the number of GHEX is 36, the number of AWHEX is 20, and the rated output is 100 kW in Sapporo as an example. The minimum temperature of the inlet temperature of the primary side obtained under these conditions is -2.65 ° C and the allowable value of the primary side is -5 ° C. Therefore, it can be said that the number of GHEX 36 and the number of AWHEX 20 are the required number of GHEX and AWHEX in Sapporo.

Table 1 Typical regional underground temperature

Area	underground temperature [°C]
Sapporo	10.4
Sendai	14.0
Niigata	15.0
Takamatsu	17.8
Fukuoka	18.5

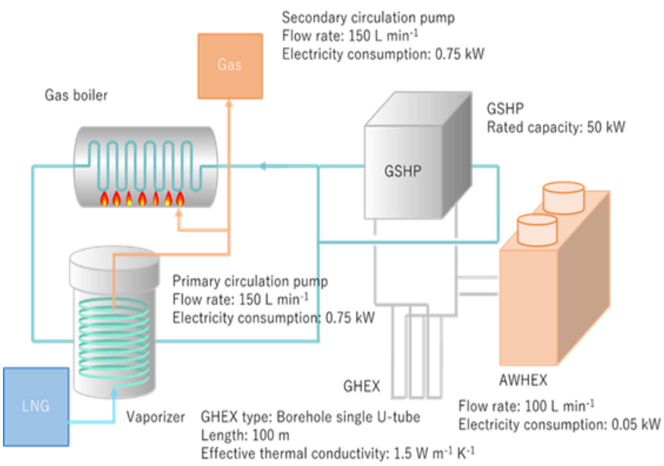

Fig1 Condition of GSHP

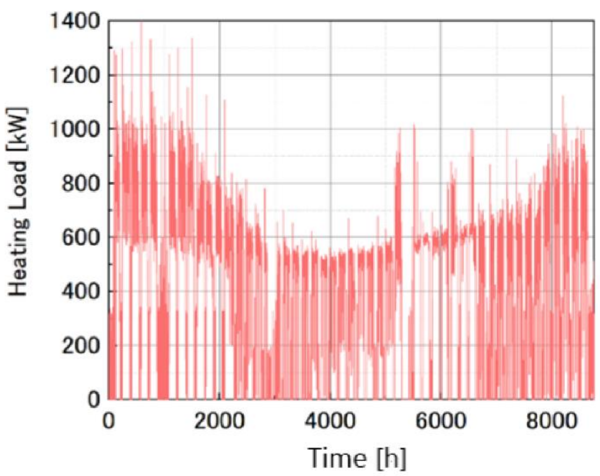

Fig2 Heat load

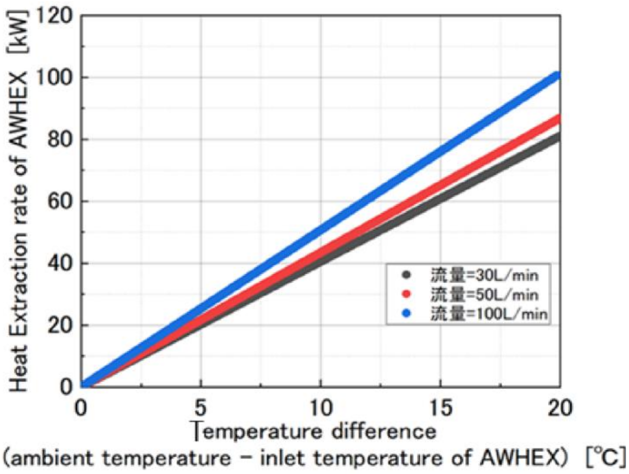

Fig3 Relationship between Heat Extraction rate of AWHEX and temperature difference

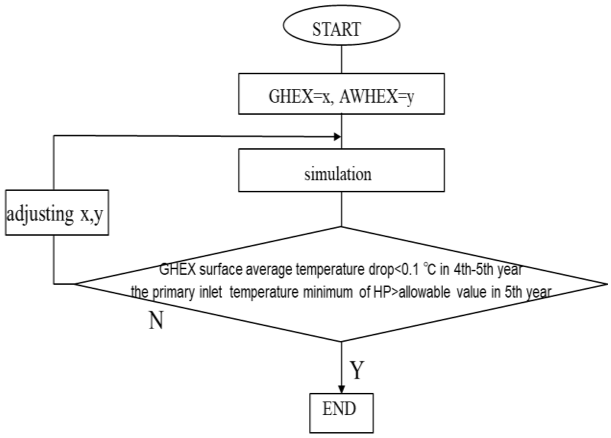

Fig4 Sizing procedure

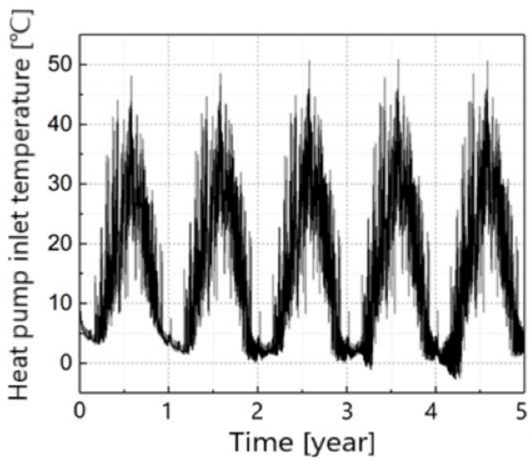

Fig5 Heat pump inlet temperature

3. Calculation of Result

The calculation results of the required number of GHEX and AWHEX for each rated heating output (50kW, 100kW, 200kW) of the heat pump and effective thermal conductivity of ground (1.5, 2.0 W/(m·K)) in each region are shown in Fig6~Fig10. The required number of GHEX or AWHEX decrease as one increases. Also, it was found that the required number of GHEX and AWHEX also increased with the increase of the rated heating output and the reducing of thermal conductivity. Moreover, the different hybrid GSHP scale characteristics are also showed . It can be said that the import of GSHP in cold regions is recommended because the required number of GHEX in Sapporo is the highest, where has the lowest ambient temperature and underground temperature. On the other hand, due to the ambient temperature in the other four regions (Sendai, Niigata, Takamatsu, Fukuoka) is higher than in Sapporo and the heat extraction of AWHEX is improved, in these regions, the required number of AWHEX increases and the required number of GHEX decreases. It can be said that the utilization of AWHEX with the rise in the ambient temperature is advantageous to the hybrid GSHP system. Therefore, it can be said that the scale of GSHP (the required number of GHEX and AWHEX) is related to the rated heating output, effective thermal conductivity of ground, ambient temperature, and underground temperature.

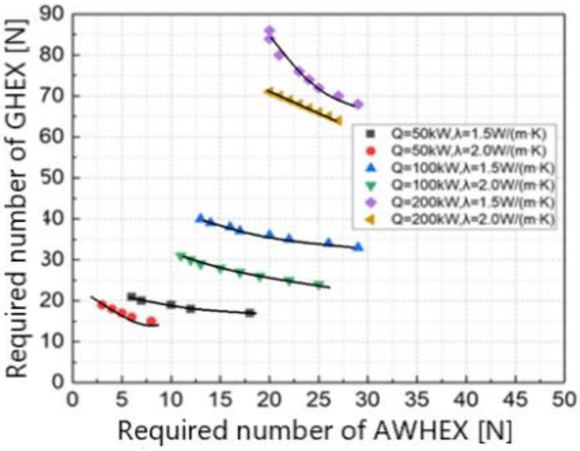

Fig.6 Relationship between required number of GHEX and required number of AWHEX（Sapporo）

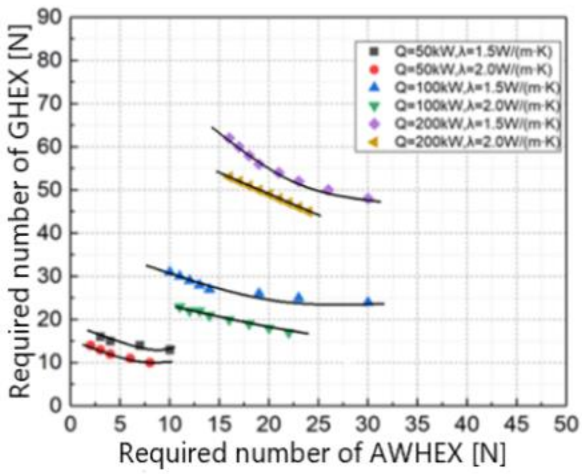

Fig.7 Relationship between required number of GHEX and required number of AWHEX（Sendai）

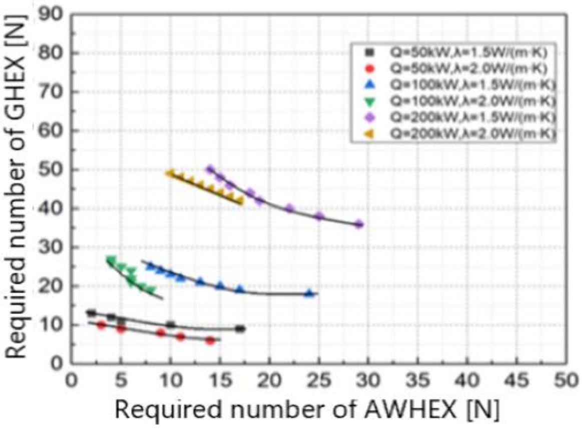

Fig.8 relationship between required number of GHEX and required number of AWHEX（Niigata）

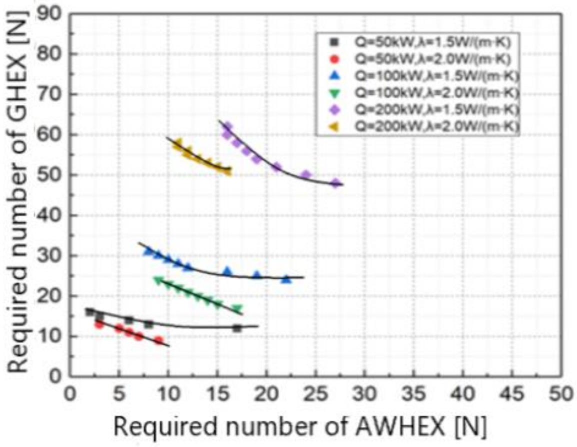

Fig.9 Relationship between required number of GHEX and required number of AWHEX（Takamatsu）

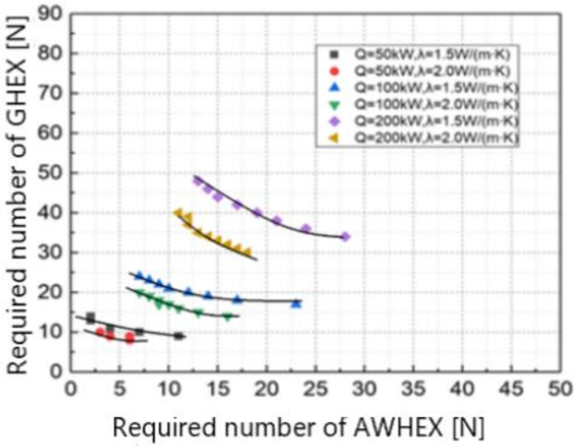

Fig.10 Relationship between required number of GHEX and required number of AWHEX（Fukuoka）

4. Multiple regression analysis

In order to clarify the required number of GHEX and AWHEX according to the scale of the vaporization system and the region, multiple regression analysis was performed by using the data shown in Fig6 ~ 10. In this multivariate linear regression, feature is the rated heating output (50, 100, 200kW), the average ambient temperature, the maximum ambient temperature, the minimum ambient temperature in one year, the underground temperature (10.4, 14, 15, 17.8, 18.7℃), the effective thermal conductivity of the soil (1.5, 2.0W/(m・K)), and required number of AWHEX in different regions. The label is required number of GHEX. However, considering that there may be multicollinearity among average ambient temperature, maximum ambient temperature, minimum ambient temperature, and underground temperature, we performed a collinearity test on average ambient temperature, maximum ambient temperature, minimum ambient temperature, and ground temperature at first. The relationship between average ambient temperature and minimum ambient temperature is shown in Fig 11. The correlation coefficient between the average outside temperature and the minimum outside temperature is 0.99, so the collinearity is the strongest. Therefore, in order to solve the problem of multicollinearity in multivariate linear regression, we used the ridge regression method to eliminate the multicollinearity among the features and achieve multilinear regression. Specifically, we imported the data sets of Fig6~Fig10 into Python, and divided the data into training data, verification data, and test data at a ratio of 5: 3: 2. Then, use the training set data to train the ridge regression model and get the weight of each feature, and the following relational formula is obtained.

$N_g = 0.30Q + 1.46T_{aa} - 0.80T_{amax} + 0.47T_{amin} - 3.74T_{s0} - 10.90\lambda - 0.53N_a + 85.24$

In order to test the nature of the model, the test set data was brought into the model and the required number of GHEX was predicted. The relative error between the predicted value and the test value is about 11.8%, and the relationship is shown in Fig 12. It should be explained that when the test values are 19, 27, and 29, these value are non-linear at the head or the tail of the trend line shown in Fig6 ~Fig10. So the relative error with the predicted values are also large.

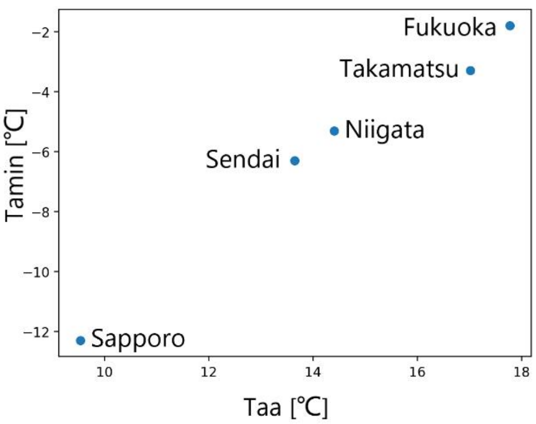

Fig.11 Relationship between average ambient temperature and minimum ambient temperature

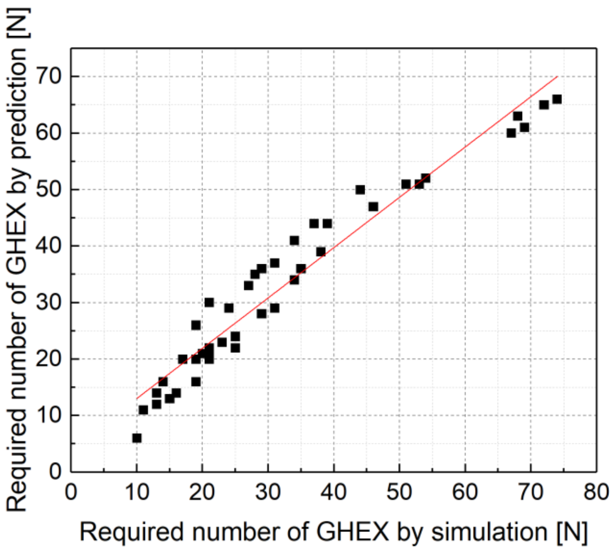

Fig.12 Relationship between required number of GHEX by simulation and prediction

5. Conclusion

1) The required number of GHEX and AWHEX were calculated according to the scale and region of the vaporization system by simulation tool.

2) The multiple regression analysis is carried out, and the relative error between the predicted value and the test value is about 11.8%. Therefore, the optimal design method of the GSHP system is clarified.

References

1) Yutaka SHOJI. Development of LNG Vaporization System with Ground Source Heat Pump (Part 3) Recovery Effect of Ground Temperature by use of Air-Water Heat Exchanger

2) 葛 隆生 ほか. 土壌熱源ヒートポンプシステム設計・性能予測ツールに関する研究：第 1-3 報 空気調和・衛生工学会 論文集. 2008;33:1-10.

3) 気象庁. 気象庁|過去の気象データ・ダウンロード.https://www.data.jma.go.jp/gmd/risk/obsdl/index.php

Subscript

Q: rated output [kW]
T_{aa}: average annual ambient temperature [° C]
T_{amax}：maximum annual ambient temperature [° C]
T_{amin}：minimum annual ambient temperature [° C]
T_{s0}：underground temperature [° C]
λ：effective thermal conductivity [W/(m·K)]
N_a：required number of GHEX [N]
N_g：required number of AWHEX [N]