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Feasibility study on tri-hybrid desalination system

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ABSTRACT

In the present study, the feasibility of a tri-hybrid desalination system for the production of electricity, energy for heating and cooling and water was studied. The tri-hybrid desalination system is a combination of a cogeneration and a desalination system. The system is composed of a generator driven by a gas engine, a gas boiler, a turbo-refrigerator, an absorption refrigerator for cogeneration, and an RO and an MED for the desalination system. The excess heat was calculated based on the electrical, heating and cooling load data and assumed that would be used for the production of water. The quantitative analysis of the product water and the energy consumption rate was compared on a month-by-month basis, and the feasibility of the tri-hybrid desalination system is explained.

Keywords: Cogeneration; Tri-hybrid desalination system

1. Introduction

The supply of drinking water and industrial water is getting shorter and shorter, and it is not distributed uniformly. In developing countries, which hold about 50% of the world's population, the demand for fresh water for industrial use is increasing, and the overall water supply is insufficient [1]. In these countries, the water supply is inadequate not only in industrial complexes, but also in daily life. Furthermore, the poor quality of the water available in developing countries has become a cause of numerous diseases, even death in some cases. In countries that experience a dry season, or limited rainfall, the central or local governments typically restrict the use of water at certain times of the year. This water shortage also applies to underground water [2]. Many countries are concerned about the reduction in fresh water due to the invasion of sea water into aquifers. In this situation, some industrialized and developing countries are trying to achieve water reclamation by recycling wastewater. The water discharged in urban areas is purified before it is flown into the river or the agricultural channel.

China is experiencing a water shortage due to the uneven distribution of water. In the southern region around the Yangtse River, water is quite plentiful. However, in the northern region around the Yellow River, the water is lacking. In 2002, China planned the South-North water transfer project, through 3 channels from the Yangtse River to the Yellow River. In this project, the total distance of the channel is longer than 1,000 km, and the total water amount is about 40 billion m^3 or more. This not only requires a huge initial investment, but also entails large running costs to transport the water to Peking. The available water in the Yangtse River is insufficient, and

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the impact on the ecosystem is unpredictable. On the other hand, the length of China's coast is about 18,000 km, and the ocean area is about 3,000,000 km^2. As seawater is plentiful, the desalination of sea water is being considered as an alternative method of producing fresh water, and related studies are currently in progress [3].

In the US and other countries, the demand for fresh water and city water is exceeding the supply. It has been reported that to solve the water shortage problem, the US coordinated a global research team that eventually drew up a 'Desalination and Water Purification Road Map' to classify US water-supply problems into short-term tasks (to be achieved by 2020) and mid/long-term tasks, and to arrange the application targets technologically. The team made case studies and comprehended the technological conditions to determine the demands, and to quantify the goal and the target amount for each demand. They also designated the technological departments and the research areas. They reported that the water shortage problem could be eventually solved [4].

Known desalination methods include multi-stage flash desalination (MSF) and multi-effect distillation (MED), which use the vacuum distillation technique, and the reverse osmosis method (RO method), which uses the membrane technique. There also is the electrodialysis (ED) method, which is currently being studied in the laboratory. MSF is a well-known method, and has been used for more than 40 years. About 80% of the desalination in the Middle East is performed using this method. The desalination plant is simple relative to the capacity, and operation and maintenance are relatively easy. A more technologically-advanced method of MED is now being used in large-scale desalination plant. As it produces a large amount of water with relatively low energy consumption, MED is excellent from an energy-saving point.

More recently, a hybrid method combining the MSF and RO methods has been used to produce fresh water and electricity. Fig. 1 shows the variations of energy consumption per ton of product water according to the change of power load, respectively for dual-purpose power system with MSF and hybrid power with MSF and RO. When the hybrid method is used, the energy efficiency is very excellent in comparison with methods in which the fresh water and the electricity are produced separately. In particular, when MSF and RO are used to produce the water, the energy consumed to produce 1 ton of water is almost half that when the fresh water is produced by MSF and RO [5]. The hybrid desalination system can also reduce the water production cost by complementing the advantages and disadvantages of the RO and MSF systems.

The hybrid desalination method is conceptually the same as the cogeneration method used in buildings. In the cogeneration, the fuel is burned to generate the power in a system composed of a gas turbine, HRSG

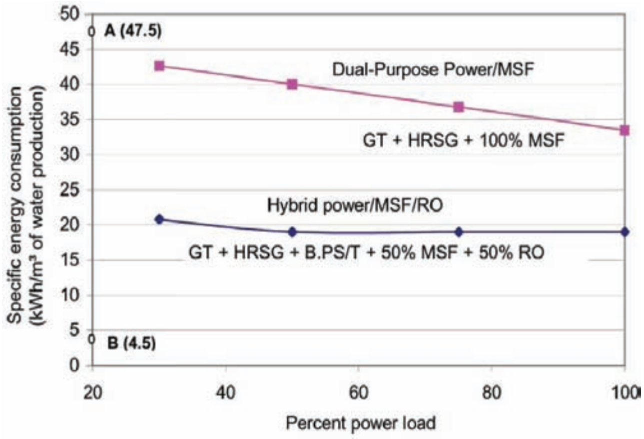

Fig. 1. Energy consumption of a hybrid desalination system [5].

(heat recovery steam generator) and steam turbine, and the heat recovered from the exhaust gas are used for the heating and cooling. The only difference is that in the hybrid desalination, the electricity is produced and that the excess heat is used for desalination through the MSF method, and that the RO is operated to desalinate the sea water using the electricity.

In this study, the desalination of sea water was investigated by combining the cogeneration and desalination systems, and using the excess heat. It was assumed that the electricity generated by the gas engine would be supplied to the building facilities, and that the heat recovered from the gas engine would be used for the heating and cooling energy. Using the electrical, heating and cooling load data, the excess heat by the seasonal discrepancy between the demand and supply of heat was calculated. With the excess heat, the sea water was desalinated through the MED method, and the fresh water amount and the energy efficiency were calculated and the results were compared.

2. Tri-hybrid desalination system

2.1. Composition of tri-hybrid desalination system

The tri-hybrid desalination system proposed in this paper is one combining MED and RO with a conventional cogeneration that produces electricity, heating and cooling energy. In the conventional hybrid desalination system, the main components are gas turbine, steam turbine, heat recovery steam generator (HRSG), MSF and RO. The power is produced in the gas and the steam turbines, and heat is recovered from the exhaust gas of the gas turbine by HRSG to generate the driving steam for the steam turbine. The exhaust heat of the steam turbine is used to operate the MSF. The temperature and the heat amount of the exhaust gas are sufficient to desalinate the sea water. In a conventional hybrid desalination system, as HRSG

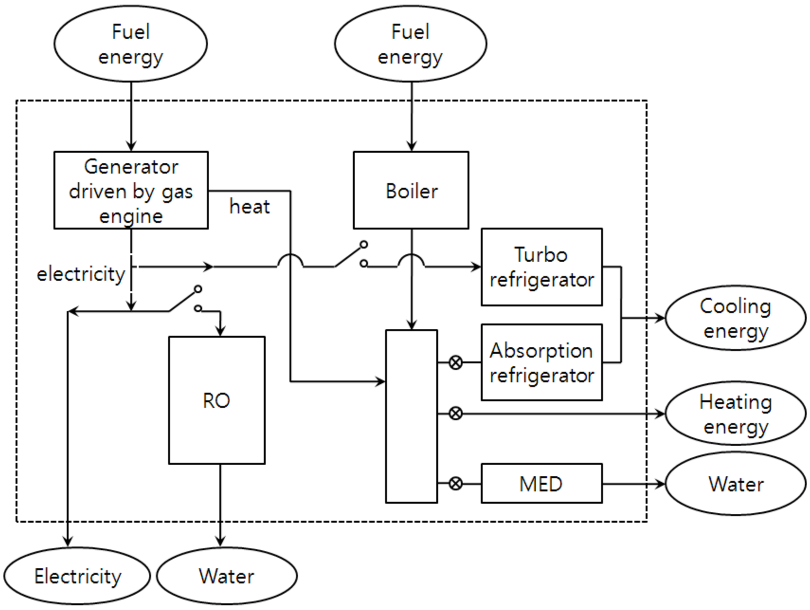

Fig. 2. Schematic diagram of a tri-hybrid desalination system and energy flow.

performs heat exchange between the exhaust gas and the water, a large heat exchange area is required, making the size of the system bigger than the other components and appropriate only for large plants.

The system proposed in the present study which produces the electricity, the heating, cooling energy and water is so simple that it can be installed within a building, and uses excess heat enough to desalinate the sea water. Fig. 2 shows a schematic diagram of the system. The most essential components of this study are the gas boiler and the generator driven by the gas engine. The generator driven by the gas engine can easily perform to the change in electric demand by controlling the speed and the step, even if the partial load is below 50%. In addition, it can recover the heat from cooling water around 90°C. The heat recovered from the gas engine is used for the heating and insufficient heat is supplied by the gas boiler. To make cooling energy during the summer, the use of a turbo refrigerator, an absorption refrigerator and the combination of turbo and absorption refrigerators were considered. A turbo refrigerator has a higher coefficient of performance than an absorption refrigerator. In Korea, absorption refrigerators are used during the summer, because large amount of the natural gas is available. When using the absorption refrigerator, we have applied both the single effect and the double effect. The double-effect absorption refrigerator needs a higher temperature of the heat source than the single-effect absorption refrigerator. In this study, it was assumed that the heat recovered from the relatively hot exhaust gas would be used to operate the double-effect absorption refrigerator.

2.2. *Electrical, heating and cooling load*

The electrical, heating and cooling load for the building in the present study was obtained from H. Heavy Industry Laboratory. The load data was for 24 h on typical days of each month, and was composed of 12 sets in total by month [6]. The building was a modern one, and the city water for the building was calculated using the heating/cooling area. As a result, it was calculated that the daily water requirement was about 1,300 tons [7].

Fig. 3 shows the typical monthly variations electrical, heating and cooling loads. In the winter, the heating load is dominant; in the summer, the cooling load is dominant. However, the electrical demand is almost constant throughout the year. The sum of the loads in each month varies significantly. This is a typical feature of heating and cooling load in areas with four distinct seasons.

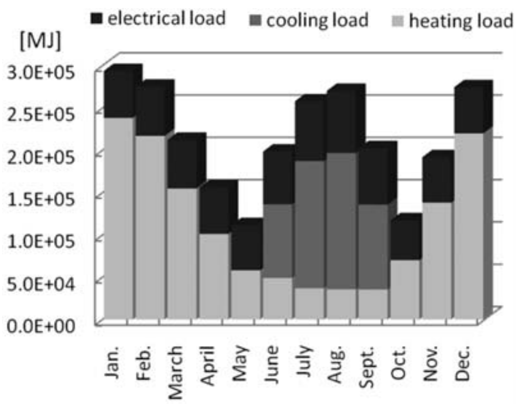

Fig. 3. Typical monthly trends of electrical, heating and cooling loads of a modern building in Korea.

3. Results and discussion

Energy sought of typical day was calculated by summating hourly load data for electricity, cooling, heating energy and water. Monthly energy sought was calculated by multiplying daily energy sought by the number of days at each month. Hourly fuel energy consumption was calculated by dividing energy sought by the efficiencies of the boiler and the generator. Daily fuel energy consumption was the sum of the hourly fuel energy consumptions. Monthly energy consumption was calculated by the same step as energy sought.

The energy efficiency was defined by dividing the monthly energy sought by the monthly fuel energy consumption for each month along with the electrical demand for RO and the heat amount for MED, if the desalination is performed. During the time of excess heat enough to make water, MED was applied. For the cooling energy, we used the turbo refrigerator, the double effect absorption refrigerator and single effect absorption refrigerator. The performances of each component are shown in Table 1.

3.1. Conventional cogeneration system

When the cogeneration system was applied alone, without the desalinating RO and MED, the monthly trend of the energy sought and fuel energy used is shown in Fig. 4. The bar graph representing the fuel energy consumption in Fig. 4 means to the fuel energy used by the gas engine and the boiler. The energy sought for electricity, cooling and heating is the same as the electrical, heating and cooling loads in Fig 3. During winter (December–February) and summer (June–September), fuel energy consumption is most because of the demand of heating and cooling energy. As shown in Fig. 4, the energy sought and the energy consumption are at a minimum in May, and are very low in October, a month of seasonal change. This is because, during the season-changing period between the winter and the summer, there is little cooling and heating load and the cooling can be achieved by ventilating the relatively cold outside airs. And both electricity and hot water are supplied.

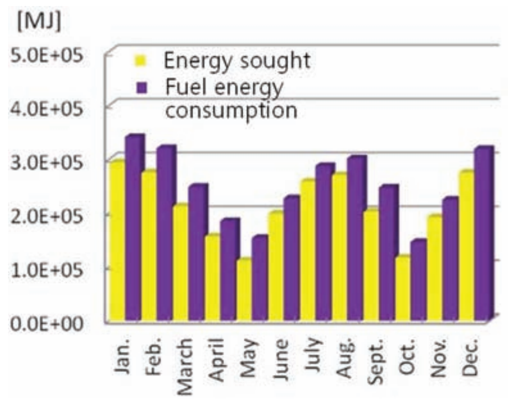

Fig. 4. Typical monthly trends of energy sought and fuel energy consumption.

Table 1
Performances of components

Electric consumption of RO, kWh/m^3		4
Number of effect of MED		8
Efficiency of generator driven by gas engine		0.35
Heat recovery ratio of cooling water		0.3
Heat recovery ratio of exhaust gas		0.15
Efficiency of boiler		0.88
COP of turbo refrigerator		5.0
COP of absorption refrigerator	Single effect	0.7
	Double effect	1.2

During winter (January–March and November–December), the energy efficiency was about 0.85–0.86. This explains the merit of cogeneration, in that both the electricity and the heat energy recovered from the generator can be utilized. During the months of seasonal change (April, May and October), the energy efficiency decreases slightly, to 0.73–0.84. This is because the heat demand is smaller than the heat recovered from the generator, and the rest of the heat is disposed. From June to September, as the cooling energy is required, the energy efficiency goes up to 0.82–0.9. The reason why the energy efficiency increases during the summer despite of the fact that heat is exhausted, is that the COP (coefficient of performance) of turbo refrigerator is 5, which is far higher than 1. The definition of energy efficiency is the same as the efficiency of the generator and the boiler, and the COP of the turbo refrigerator. If the turbo refrigerator takes over the cooling energy during the cooling-demanded period, the energy sought becomes COP times electricity used for the turbo refrigerator (5 times of the electricity in this study). Therefore, even though the efficiencies of the generator and the boiler are 0.8 and 0.88 respectively, energy efficiency could become more than those values.

3.2. Tri-hybrid desalination system with only MED

During the summer, the heating load decreases, and the cooling load increases rapidly. In the tri-hybrid system with MED, a significant amount of excess heat is available to produce water. Fig. 5 shows the monthly energy sought for electricity, heating and cooling energy and water. Fig. 6 shows the typical monthly energy sought and fuel energy consumption. In the tri-hybrid desalination system with MED, the heat sought to produce water by using MED becomes the energy that is utilized. In this case, the annual mean energy efficiency increases by about 0.12, from 0.85 to 0.97. The increase is concentrated during the period of cooling demand (June–September). The monthly energy efficiency during June–September is

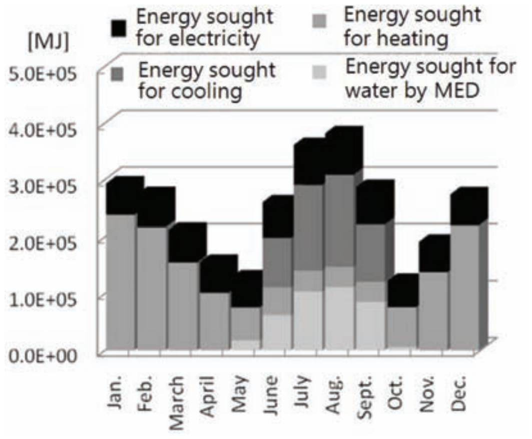

Fig. 5. Typical monthly trends of energy sought for electricity, cooling/heating energy and water by MED.

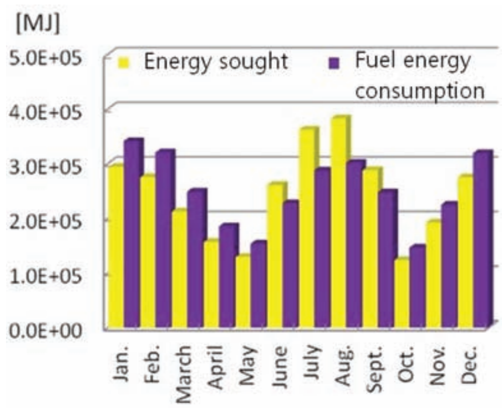

Fig. 6. Typical monthly trends of energy sought and fuel energy consumption.

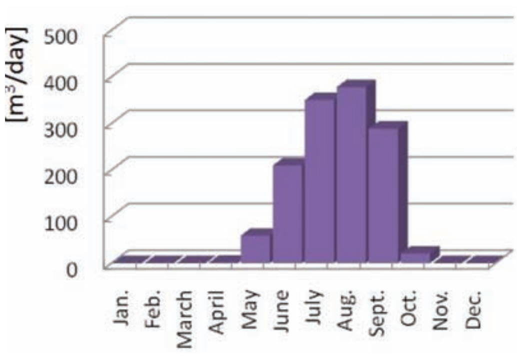

Fig. 7. Typical monthly trends of product water by MED.

1.21, which is 0.36 higher than 0.85, the energy efficiency of the conventional cogeneration.

Fig. 7 shows the amount of product water by the 8 effect MED. According to the figure, 200–350 tons of water can be produced per day. This amount is equal to 1/6–1/4 of the required quantity. When the seawater is desalinated with the 8 effect MED using the excess heat, 296 MJ of heat is necessary to produce 1 ton of fresh water.

3.3. *Tri-hybrid desalination system with RO and MED*

At the present technology level, desalination with RO is known to be the most economical. Considering all production expenses, including operation cost, initial investment, maintenance cost and labor cost, about $1 or more is necessary to produce 1 ton of water. When desalinating the sea water with RO, about 14 MJ of energy is necessary to produce 1 ton of fresh water except running cost of the pre and post processes.

When MED is used to make water during the summer, 1/6–1/4 of water requirement can be supplied. RO must be applied throughout the year to supply the water requirement. In the case of the tri-hybrid desalination system with RO and MED for water, monthly energy sought for electricity, heating/cooling and water is shown in Fig. 8. The monthly trend of this case is almost the same as the tri-hybrid desalination system with MED. The significant advantage is the reduction of the boiler capacity. When compared with the conventional cogeneration method, it was calculated that boiler capacity would be reduced by about 20%. This is because the amount of heat recovered increases by the proportionality of the total electricity and is utilized for heating energy when RO is applied. The monthly trend of energy sought and fuel energy consumption appears in Fig. 9, showing a little increment due to the adoption of RO comparing the tri-hybrid desalination system with MED. The annual energy efficiency is reduced by 0.02, to 0.95 due to the increment of both energy sought and fuel energy consumption.

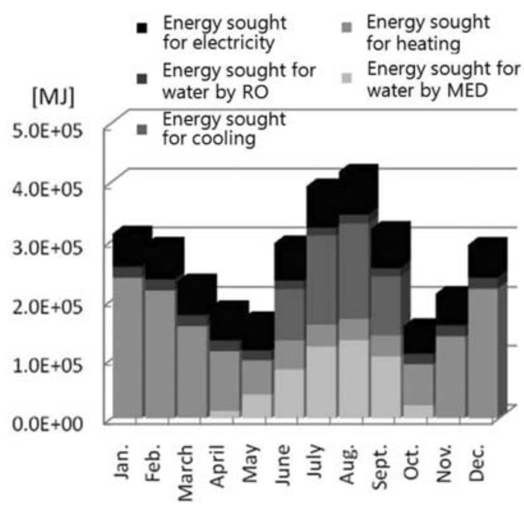

Fig. 8. Typical monthly trend of energy sought for electricity, cooling/heating energy and water.

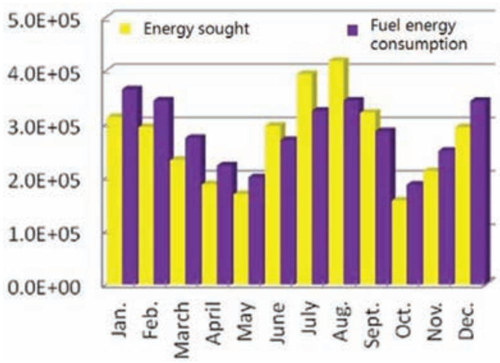

Fig. 9. Typical monthly trend of energy sought and fuel energy consumption.

According to Fig. 8, the electricity used for RO is about 1/3 of the electricity supplied to the building. During the summer, as the sea water can be desalinated with MED, the cost for the production of water can be reduced to that extent. Total electric power is compared between the standard cogeneration system and tri-hybrid desalination system with RO and MED on the typical day of August in Fig. 10. The standard cogeneration system shows two peak hours for electrical demand (2 and 8 PM) due to the cooling load. Additionally if RO applies early in the morning (0–10 o'clock), the electricity peak value of tri-hybrid desalination system does not exceed that of the conventional cogeneration system. This means that tri-hybrid desalination system does not require the additional increment of the generator, if RO is operated according to optimized schedule. Also, Fig. 10 shows that the tri-hybrid desalination system is easier to control the generator than the conventional cogeneration system.

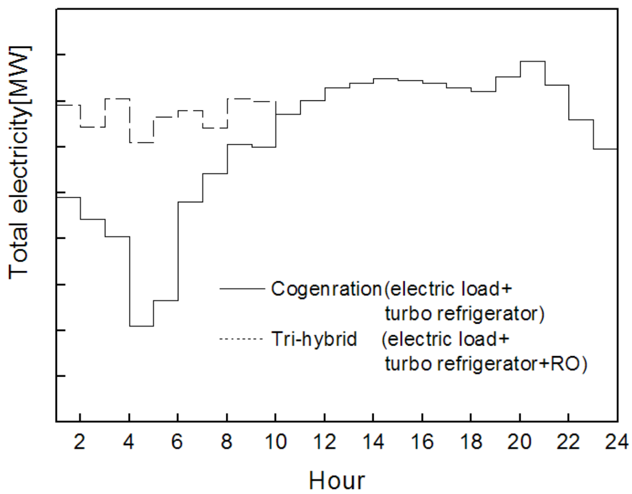

Fig. 10. Comparison of electric demand between cogeneration and tri-hybrid desalination system at the representative day of August.

3.4. Using the absorption refrigerator

The calculation was carried out based on the scenario in which the single-effect absorption refrigerator was used instead of the turbo refrigerator. The single-effect absorption refrigerator requires a medium heat source of about 95°C. It was assumed the single-effect absorption refrigerator is operated by using heat recovered from both cooling water and exhaust gas of the gas engine. The COP of the single effect absorption refrigerator is about 0.7. This means that it requires more heat energy sought than the cooling load. The calculation results reveals that amount of heat that recovered from the gas engine generator is less than the heat required for the single-effect absorption refrigerator and that more heat should be supplied from the boiler. This case consumed more fuel energy than other cases during a year and the annual energy efficiency was about 0.82, which was lower than using the turbo refrigerator during the summer, and was the lowest among all other scenarios. As it had a similar tendency to the double-effect absorption refrigerator, discussions on the single-effect absorption refrigerator was omitted.

When the double-effect absorption refrigerator was adopted, it required heat medium around 120°C. Heat recovery from the exhaust gas is enough hot to operate the double-effect desalination system. The COP of the double-effect absorption refrigerator was about 1.2. In the preliminary calculation, the cooling demand could not be met by the double-effect absorption refrigerator and the remainder should be complemented by the turbo refrigerator. Also preliminary calculation showed that this tri-hybrid system could not make enough heat to produce water. So RO desalination system was applied to produce water during the summer.

Fig. 11 shows the monthly energy sought for electricity, cooling/heating energy and water in the scenario that the double-effect absorption refrigerator and the turbo refrigerator were applied together. The overall tendency was similar to the conventional cogeneration system which produces only the electricity, cooling and heating energy. And this case was a little efficient than the conventional cogeneration system. The only difference was that, during the months where cooling was needed, the excess heat was not sufficient for desalination, compared with the case using a turbo refrigerator. On the other hand, during seasonal change periods (April–June, October) it was shown to be able to desalinate by MED.

MED for water and absorption refrigerator for cooling are not complementary but are in conflict with each other, because two systems use the heat. The monthly trend of energy sought and fuel energy consumption is shown in Fig. 12. Also the overall trend is the same as the conventional cogeneration system. The annual energy efficiency was 0.87, far lower than the tri-hybrid desalination system with a turbo-refrigerator. It can desalinate the seawater

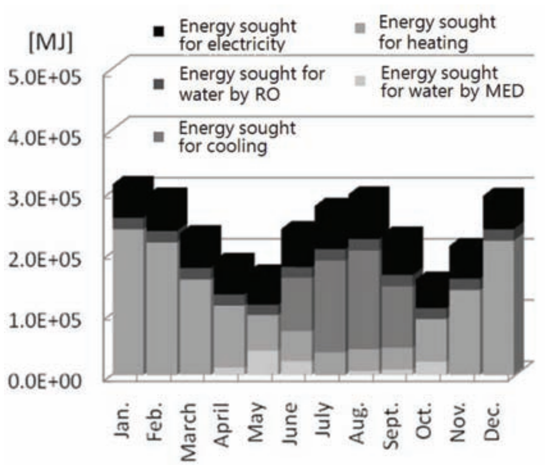

Fig. 11. Typical monthly trends of energy sought for electricity, cooling/heating energy and water.

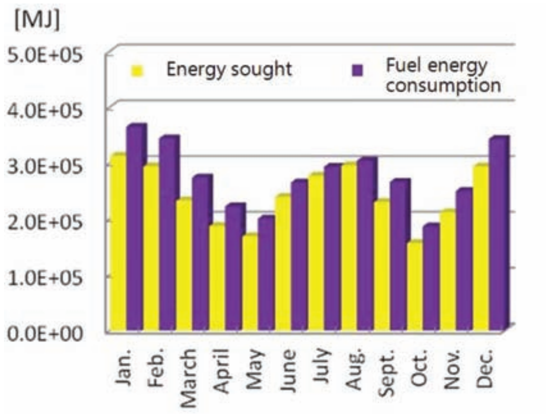

Fig. 12. Typical monthly trends of energy sought and fuel energy consumption.

during changing periods in season, but the amount was no more than 100 tons a day. The annual fuel energy consumptions of this study were compared in Table 2. The difference in annual energy consumptions among the cases was about ±3%.

Table 2
Comparison of annual energy consumption

Cooling equipment	Desalination	Annual energy consumption [MJ]
Turbo refrigerator	—	9.093×10^7
	Only MED	9.093×10^7
	RO+MED	10.32×10^7
Absorption refrigerator		
Single effect	RO+MED	10.76×10^7
Double effect	RO+MED	10.03×10^7

4. Conclusions

In this study, we have designed a method to supply electricity, heating/cooling energy and water by applying desalination with RO and MED to the conventional co-generation system. To achieve this, the electrical, heating and cooling load data of a building was used in Korea, and it was taken as a premise that the electricity was supplied by the gas-engine-driven generator conforming to the electricity. The heat recovered from the gas engine was used for heating and cooling, and the excess heat was used for desalination. By applying the method, calculations were done, and we arrived at the following conclusions:

(1) Tri-hybrid desalination system does not require the additional generator capacity comparing the conventional cogeneration system, if RO applies according to the optimized schedule.
(2) With the use of RO, the necessary capacity of the boiler could be reduced by 20% or more.
(3) When the cooling was performed with the turbo refrigerator, the annual energy efficiency could be increased by 12%. During the summer, it can supply up to 1/4–1/3 of the necessary water using the excess heat.
(4) When the absorption refrigerator using the heat for cooling and the MED using the heat for water production were adopted together, they were in conflict with each other. Even if they could produce the water during the changes in season, the amount was small.

This study has targeted a gas-engine-driven generator with good conformity to the electrical demand, and with the generation efficiency of 35%. In this case, the amount of available heat is relatively small. Of the MED desalination methods using heat, it seems advantageous to adopt the one that has a higher GOR (gain of rate) and that uses the steam directly. In this paper, the fuel energy consumption of pre and post process of the desalination system including the auxiliary equipments was not accounted for. In the future, we are going to calculate the feasibility of a tri-hybrid desalination system that produces heating/cooling energy by adopting a method in which the electricity is produced with the gas and steam turbine. The HRSG can obtain more heat even if its generation rate may be lower, and desalination is performed with the heat obtained by extracting the expanding steam from the lower-pressure end of the steam turbine.

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