Study on optimal operational planning of an advanced co-generation system on a hotel's energy demand

M. Tomizawa[1], Y. Amano[2] & T. Hashizume[2]
[1]*Mizuho Information & Research Institute, Japan*
[2]*Waseda University, Japan*

Abstract

In order to empirically study a cogeneration system, an advanced co-generation system (ACGS) was built in Waseda University in 1999. The ACGS consists of a gas turbine system, a steam turbine system, an ammonia-water mixture turbine system, an ammonia absorption refrigerator system and an ice storage system. In the bottoming stage of ACGS, by activating an ammonia-water mixture turbine system and an ammonia absorption refrigerator system, both of which are effective for heat recovery of low temperatures, the system is made up positively using the heat cascade, which is unique compared to other systems. At present, for the introduction of the co-generation system, its practicality is not fully considered and a method has not yet been established which would lead to an operating method fitting the characteristics of the customer requirements. So it is considered very important to propose the most suitable system construction, taking an overall view of the annual earnings and cost of energy for the customers. In this paper, we cover an assumed system which changed the part of composition of ACGS and, in order to find out the initial advantages of the system, seek the most suitable composition and the most suitable operational planning of a system for cooling, electricity and heat demand of a typical hotel, and then propose an example of the system design guide.
Keywords: co-generation, lower heat, operational planning, demand.

1 Introduction

To respond to the global environmental problem, it is considered effective to utilize a technically established device such as a co-generation system as well as

WIT Transactions on Ecology and the Environment, Vol 105, © 2007 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/ESUS070331

to develop a new energy system. The cogeneration system utilizing natural refrigerant draws attention especially because it is eco-friendly.

The Advanced Co-Generation System (ACGS) which is focused on in this study can recover lower temperature heat sources, and even increase total efficiency and generate effective energy such as electricity, cool heat and heat according to the seasons. The ACGS is one of the gas turbine co-generation systems, consisting of three stages; the topping, middle and bottom stages. At the topping stage, a gas turbine is installed and the exhaust gas from it turns to steam through a heat recovery steam generator (HRSG). At the middle stage, the steam from the HRSG is forced into a back pressured steam turbine in which electricity is generated. The low-pressure steam from a back pressured steam turbine is sent into the bottom stage in which electricity, cool heat and heat is generated using the steam. The ACGS characteristically has the electricity generating and refrigerating cycles utilizing ammonia water mixture (AWM) at the bottom stage. Therefore, the lower temperature heat is utilized effectively, an ammonia absorption refrigerator (AAR) and an AWM turbine system (AWMT) which have working-fluid in common are made hybrid [1–3], the system structure enables flexible operation with changes of heat and electrical load demand according to the seasons, and an ice storage system (ISS) enables a flexible supply of cool heat for day and night.

At the moment, a method of design and producing an operational system [4–6] which is practical and fits with the characteristics of customer requirements is not yet established. So, it is important to propose the most appropriate system structure [7], examining customers' energy demands for the year. We have conducted the study of optimization of the operational planning and the system structure, focusing on the co-generation system with the ACGS [8–10], and found that the system can meet the demand for electricity and cool heat of hospitals or hotels efficiently, although the calculation related to heat demand has not been conducted.

In this study, we have examined optimization of the system structure and the optimal operational planning for a hotel, for the purpose of exploring the effect of introduction of the cogeneration system with the ACGS.

2 Mathematical programming model

The operational planning of ACGS is formulated as an optimal problem. An optimal problem consists of one objective function and multiple constraint conditions. The main conditions are energy balance and performance characteristic of each component. Since this study adopts a linear programming because it is simple, the performance characteristic should be expressed with linear equation. In fact, however, there are changes of efficiency in partial load performance and also discontinuity of performance characteristics of the components, so it is almost impossible to express in one linear equation. Therefore, we introduced a 0-1 integer variable to improve from the linear programming to the mixed integer linear programming.

Figure 1 shows the outline of the co-generation system focused on in this study. Two gas turbines are set up at the topping stage, using the city gas as the primary energy. Part of the steam recovered by the HRSG fulfils steam demands and the rest is utilized as energy source of AAR and AWMT allocated at the bottom stage. The components alone would be able to meet all demand, but we decided to take the system structure in which EHP or GHP can be used as auxiliary components.

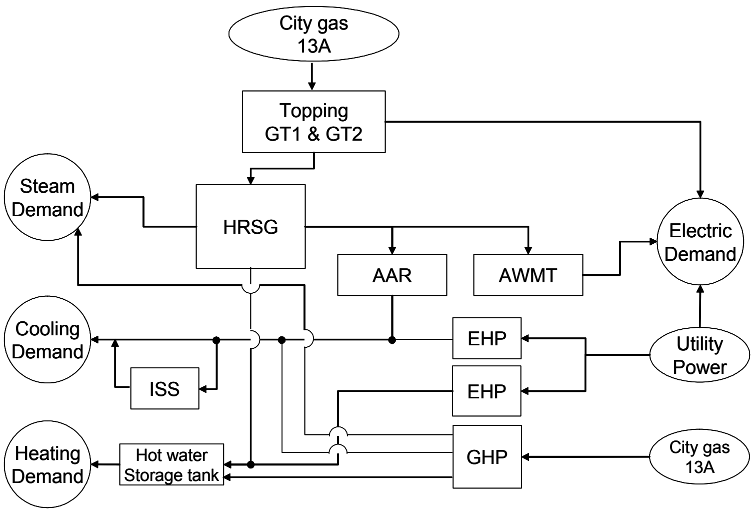

Figure 1: Assumed co-generation system.

The AAR which fulfils the cooling demand at the bottom stage of ACGS characteristically maximizes its energy efficiency at the partial load. We create a model of the relation between the amount of steam (G_{AAR} [kg/h]) allocated to the AAR and the amount of cool heat (Q_{AAR}[kW]) generated from the system. The partial load performance of AAR is shown in figure 2. In figure 2, the horizontal axis represents the steam flow rate and the vertical axis represents the AAR output power. While the rated output of AAR is 350kW, its output shows 210kW at the maximum energy efficiency (COP). Since it is difficult to express this characteristic with one linear equation, it is expressed with multiple linear equations. The model equations are as below:

$$G_{AAR}(k) = G_{AAR}^{(1)}(k) + G_{AAR}^{(2)}(k) + \cdots + G_{AAR}^{(8)}(k) \tag{1}$$

$$400 \cdot \gamma_{AAR}(k) < G_{AAR}^{(1)}(k) < 500 \cdot \gamma_{AAR}(k) \tag{2}$$

$$0 < G_{AAR}^{(2)}(k), G_{AAR}^{(3)}(k), \cdots, G_{AAR}^{(8)}(k) < 100 \cdot \gamma_{AAR}(k) \tag{3}$$

$$Q_{AAR}(k) = \eta_{AAR} \cdot G_{AAR}(k)$$

The output characteristic of GT and AWMT is nonlinear and so it is expressed with multiple linear equations as well as AAR. EHP and GHP as auxiliaries are modeled with one linear equation based on figures from a manufacturer's trade catalogue because of insufficient sample data. Meanwhile, the ice charging characteristics of ISS shows that the heat charging drops along with an increase in heat storage. The heat storage is divided into three levels, each of which is given a specific linear equation to express the ice charging characteristics. The model equations are as below:

$$R_{ISS}(k) = (1-\eta_{loss})\cdot R_{ISS}(k-1) + \left(Q_{ISS}^{in}(k) - Q_{ISS}^{out}(k)\right)\Delta t \quad (5)$$

The objective function is the minimization of running cost as follows:

$$\phi_{EL}\left(E_{buy} + E_{EHP}\right) + \phi_{Gas}\left(G_{GT} + G_{GHP}\right) \quad \rightarrow \min \quad (6)$$

The other main constraint conditions such as energy balance are shown below:

$$W_{GT} + W_{AWMT} + E_{Buy} = E_{Dem} + E_{EHP} \quad (7)$$

$$Q_{Dem}^{cool} = Q_{AAR} + Q_{EHP}^{cool} + Q_{GHP}^{cool} + Q_{ISS}^{out} \quad (8)$$

$$Q_{Dem}^{heat} = Q_{EX} + Q_{EHP}^{heat} + Q_{GHP}^{heat} + Q_{HWT}^{out} \quad (9)$$

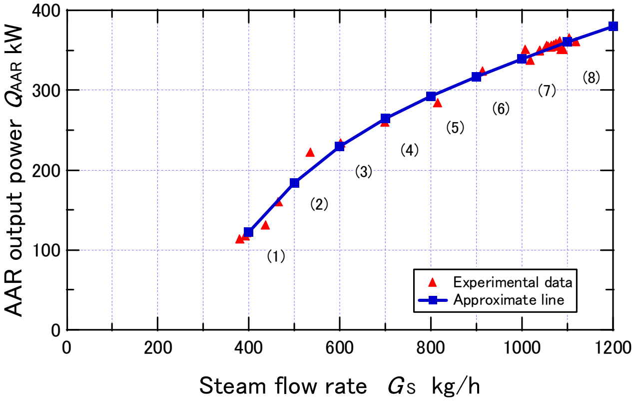

Figure 2: Output characteristics of AAR.

3 Calculation and results

3.1 Calculation procedure

Assuming the co-generation system as shown in figure 1, the operational planning to meet the demand of a hotel with minimum running costs is examined. Table 1 shows the outline of a hotel. In the parameter study taking the rated output of each component as the parameter, we extract the rated output of the component at minimum running costs. The calculation procedure is roughly divided into three steps as follows:

1) Determine a hotel to be studied and calculate the demand data of each season based on maximum temperature data,
2) Derive the optimal operational planning for the demand patterns of highest, lowest and modal temperature days for the parameters of component rated output, and
3) Select the combination of the component rated output with minimum running cost among the parameters calculated in the step 2), derive the operational planning for the total demand of the year and calculate the total cost.

The highest, lowest and modal temperature days are focused on as a typical demand day. That is because it can be said that if a certain rated output enables operation on the maximum and minimum temperature days, it also enables it to operate throughout the year. Also, the optimal rated output is focused on because the most frequent demand can result in a reduction in the annual running cost. For these reasons, we select the rated output which is sufficient to operate on the highest and lowest temperature days and also the running cost, which is the minimum on the modal demand day, and calculate the running cost of the total annual demand.

The rated output (parameter) of each component and the electricity charge menu are shown in Table 2.

Table 1: Outline of typical customer (hotel).

Type	Resort Hotel
Location	Tokyo
Gross Floor Area	67,033 square meters
Characteristics	For resort, 12 floors, lower ground floor 1

Table 2: Rated output of components and electricity charge menu.

Power purchase agreement (kW)	500-2500
Gas turbine 1, 2 (kW)	800-3200
AWMT (kW)	200-800
AAR (kW)	2000-4000
Heat pump (kW)	Cooling: 2500, Heating: 3000
ISS (kWh)	18000
Hot water storage tank (kWh)	6000
Demand charge cost (Yen/kW)	1560
Quantitative charge cost (Yen/kWh)	Peak: 13.9 (time zone (A)) Daytime(summer): 13.25 (time zone (B)) Daytime(other): 13.20 (time zone (B)) Nighttime: 6.05 (time zone (C))

3.2 Calculation results

The combination of components which minimize the annual operation cost are listed in table 3. As for the gas turbine, Turbine 1 (800kW) is used for additional start-up and Turbine 2 (2400kW) for base load. The rated output of AWMT and AAR is 600kW and 2000kW, respectively. Also, from EHP and GHP, the former is adopted as an auxiliary component. The operational procedure of these components follows.

Table 3: Calculation results of the components combination for a hotel.

Electricity purchase agreement (kW)	500
Gas turbine 1, 2 (kW)	800, 2400
AWMT (kW)	600
AAR (kW)	2000
Heat Pump (EHP or GHP)	EHP

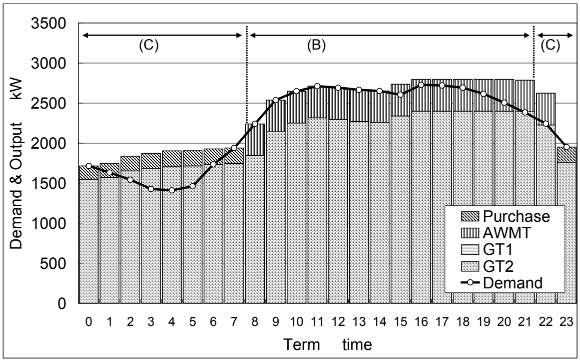

Figure 3: Electricity demand and supply (min. temp. day).

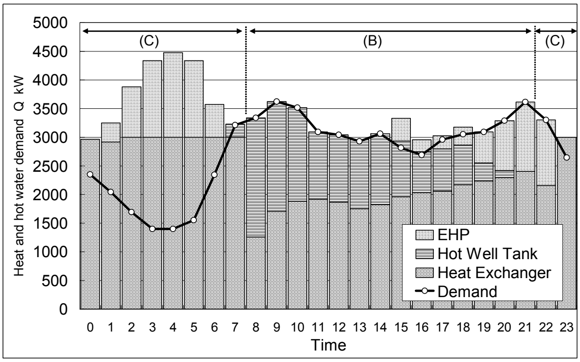

Figure 4: Heating demand and supply (min. temp. day).

3.2.1 Operational planning for minimum temperature day

Figure 3 shows the electricity demand and supply for the minimum temperature day. The gas turbine of 2400kW operates 24 hours, supplying most demand. In the time zone (C), some quantity of electricity is purchased because of low prices at night. Because there is no cooling demand in the season AWMT is operated at almost full load all of the day. Figure 4 shows the heat demand and supply. The amount of heat over the demand is charged by EHP using cheap electricity at off peak periods at night (in the time zone (C)) and the surplus is discharged at daytime to meet the demand.

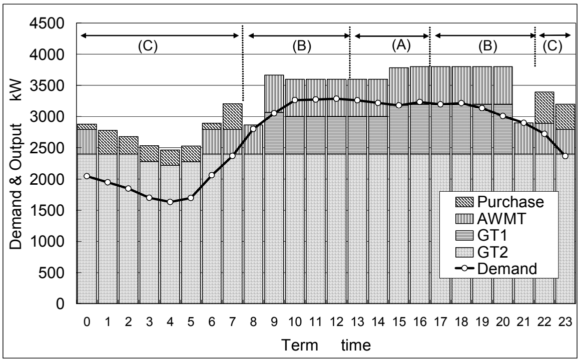

Figure 5: Electricity demand and supply (max. temp. day).

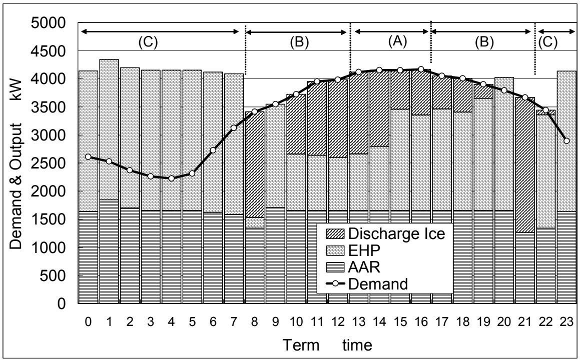

Figure 6: Cooling demand and supply (max. temp. day).

3.2.2 Operational planning for maximum temperature day

Figure 5 shows the electricity demand and supply breakdown for the maximum demand day. The gas turbine of 2400kW operates at rated output and, during the peak hour at daytime, the gas turbine of 800kW is added. Also, AWMT operates to add to the electricity supply. The surplus electricity is provided to EHP as described. Figure 6 shows the cool heat demand and supply breakdown. As seen in the figure, AAR constantly operates at 60% of the rated output because it becomes most efficient at this level, and EHP operates at night because of cheap electricity that can be stored in ISS and the cool heat is discharged from ISS in the daytime to supply the electricity demand. Figure 7 shows the heat demand and supply pattern. From 1am to 6am and from 3pm to 9pm the heat exchanger directly supplies the demand. For the rest of the time, the heat storage in the hot well tank is utilized. This is because, from 1am to 6am, 2400kW GT is operational at full load in spite of the low demand, which contributes to surplus exhaust heat, and also because the heat can be generated using EHP due to cheap electricity. Meanwhile, from 3pm to 9pm, the electricity demand is relatively high and 800kW GT is added to operate, which results in surplus exhaust heat.

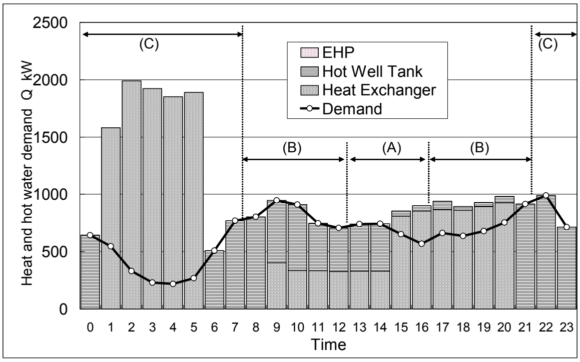

Figure 7: Heating demand and supply (max. temp. day).

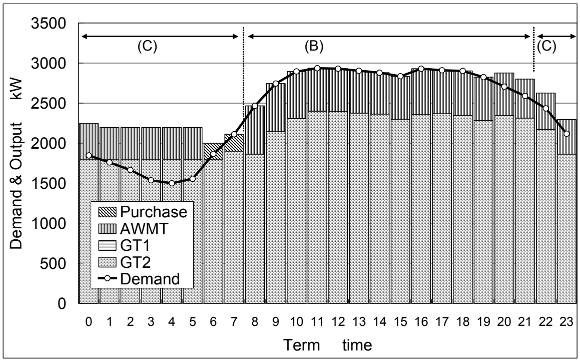

Figure 8: Electricity demand and supply (modal temp. day).

3.2.3 Operational planning for modal temperature day

Figure 8 shows the electricity demand and supply pattern for the modal temperature day. The gas turbine of 2400kW constantly operates and AWMT generates electricity to supply the demand. The excessive amount of electricity is generated beyond the demand required at night in order to cover the necessary power for operation of EHP. Figure 9 shows the cool heat demand of the supply. The cool heat is generated by EHP and AAR at night with low demand and the surplus cool heat is stored in ISS. In the daytime, the cool heat is discharged from ISS. AAR operates only for two hours and stops its behaviour for the rest of the time. This is because, as seen in Figure 8, it is a greater advantage sending the exhaust gas to AWMT and generating electricity using it. Figure 10 shows the heat demand and supply. Demand is fulfilled by direct supply by the heat exchanger. The demand of irregular movement, dropping at night and rising in the day, is adjusted to be evened out by utilizing the hot water storage tank.

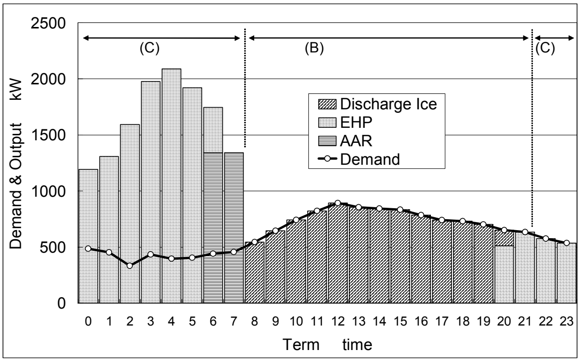

Figure 9: Cooling demand and supply (modal temp. day).

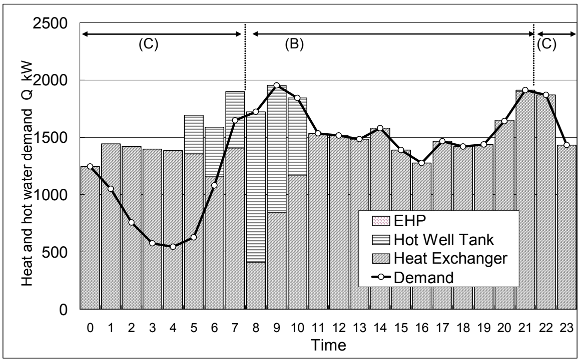

Figure 10: Heating demand and supply (modal temp. day).

4 Conclusion

We have studied the demand of a hotel on operational planning based on demands for power, cooling heat and hot heat. The following results have been obtained from this study.

1) It is possible to operate to respond to various demands throughout the year by using the co-generation system based on ACGS.
2) Exhaust heat from the gas turbines can be utilized in the wintertime for heat generation and power generation because of no cooling demand, and in the

summertime for cooling heat generation and power generation because of low demand for heat.

3) In the case of a hotel, with the combination of two gas turbine systems it is possible to operate for every representation demand day.

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