Integrated Energy Simulation for Building and MEP Systems Including Thermal Cascading in Consideration of the Characteristics of Thermal Energy Media

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SUMMARY

This research focuses on the evaluation of thermal energy efficiency in a building including thermal cascading systems such as cogeneration, solar-thermal, and PV systems, combined with final energy consumption for space heating and cooling, a dehumidifier, and a water heater. The thermal energy efficiency of the whole system varies depending on not only calorific balances but also on the temperature of heat conveying media and its flow-rate to each consumption unit. Based on the concept of the simulation tools, the major development work involves the modeling of cogeneration units.

As the first development phase, a sample system consisting of one unit of each form of equipment has been completed adopting the “forward method.” This paper describes the overview of the development of the method by showing some results for a sample case study.

1. INTRODUCTION

Carbon emissions reduction in the commercial and residential sectors is an urgent requirement, and there is a particular need for action on the demand side to make more efficient use of energy in the building sector, where energy consumption is rising markedly. In order to exploit the potential of supplied energy to the full, multistage use through onsite conversion to heat and electric power ought to be pursued. As a concrete method to realize this goal, cogeneration systems are expected to promote and expand.

Cogeneration systems are, along with solar power generation, designated “efficiency improving” technologies under the Japanese Energy Conservation Standards for Buildings.[1] They work by simultaneously generating electricity onsite to power machinery, lighting, and so on. They use the heat generated in the process for purposes such as air conditioning and water heating, thus raising the efficiency of primary energy use. Unlike most high-efficiency equipment, the performance of cogeneration systems is affected by the balance of electricity demand and heating/cooling demand, as well as by the timing of such demand. Assessing the effects quantitatively necessitates coupled calculation with all heat and electricity demand, including buildings, air conditioning, electrical equipment, and sanitation facilities.

One simulation program that enables such calculations to be made is the “BEST” building energy simulation tool now under development in Japan, with the initiative of Ministry of Land, Infrastructure, Transport and Tourism, which handles housings and facilities in an integrated manner in order to assess the energy performance of buildings as a whole.[2]

In view of the above background, the purpose of this study is to present a simulation logic for cogeneration systems that makes possible coupled calculation with each category of demand (building/air conditioning, electricity, and sanitation).

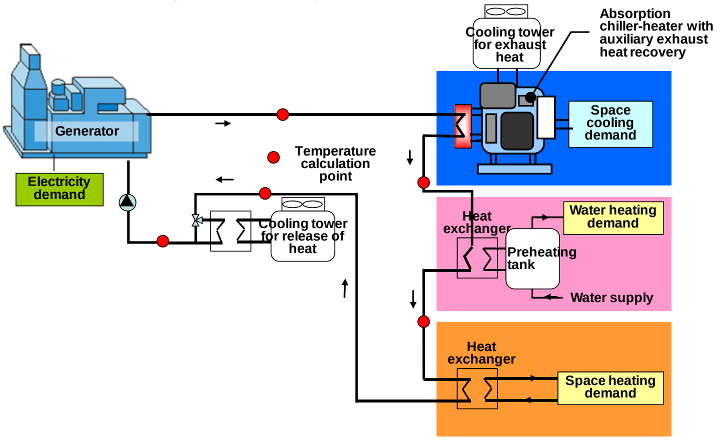


Figure 1 Example of cogeneration system configuration

2. Existing simulation algorithms

To serve as a point of reference before proceeding with this study, below we describe the algorithms used by existing simulation programs “CASCADE III”.

This is a cogeneration system design and assessment program published by SHASE in 1995. Equipment load is derived from the electricity and heat energy balance in order to calculate annual energy consumption.

As the purpose of this study is to develop a simulation logic for incorporation into BEST, as described above, a departure must be made from the CASCADE III approach in that the heat balance must be expressed based on the flow rate and temperature difference of the heat medium (water), and calculations must be performable at rapid intervals of around five minutes. Table 1 shows a comparison of the principal specifications of each approach.

The basic approach adopted for this study is, as Figure 2 shows, to perform calculations using the inlet temperature at the previous time for equipment with heat capacity (pipes and the preheating tank), and the outlet temperature of upstream equipment at the current time in the case of equipment for which heat capacity is disregarded (all equipment apart from pipes and the preheating tank).

Table 1 Comparison of the specifications between CASADEIII and BEST

Item	Current CASCADE III specifications	Required specifications for BEST (suggested)
Calculation time interval	1 hour	Variable between 1 hour and 1 minute
Exhaust heat output	･Calculation of the balance of the amount of heat ･No distinctions between heated water, steam, and exhaust gas	Calculated from temperature difference of heat medium and balance of flow rates
Exhaust heat temperature	Fixed	Load following
Preheating tank/pipe temperature	No change over time	Load following (variable over time)
Handling of mixed heat sources	Mixed use with gas-fired absorption chiller-heater and boiler possible	Possible linkage with other heat sources (e.g., electric chillers) as well as equipment in left column
Handling of multiple heat sources and generators	Treated as a single unit by aggregating the capacities of each	Capable of allocating operating hours individually where multiple units are split up

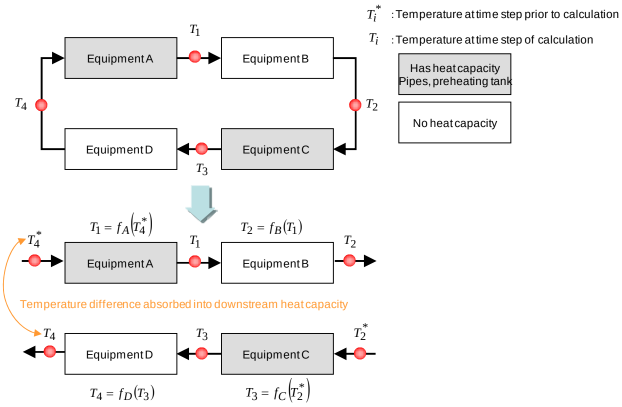


Figure 2 Basic algorithm

3. Modeling of cogeneration system

The components of the model considered in this study are shown in Figure 1. As the BEST algorithm allows flexible connection of modules such as equipment, controllers, and boundary conditions, systems are basically freely configurable. The system considered in this study consisted of a generator, systems that utilize exhaust heat (space cooling, space heating, and water heating), a surplus exhaust heat radiator, auxiliary equipment, and a controller.

(1) Generator

A model was developed using a gas engine and a gas turbine for the generator. As one example, Figure 3 shows the input and output parameters for the gas engine.

The equipment specifications consisted of those typically found in catalogs and engineering data. As partial load efficiency at two representative points is inputted along with rated efficiency, the partial load characteristic curve of these three points is interpolated by quadratic equation when a simulation is actually performed. For this study, the characteristic expression for partial loads was developed as a quadratic curve as shown in Figure 4 based on the numeric values for power generation efficiency at three points according to the literature [2] (at 75% and 50% of rated load). Gas consumption and exhaust heat utilization were found according to power output.

Almost the same model was used for the gas turbine, except that the increase in power generation output as outside air temperature rises was taken into account. With the exception of the modeling of dynamic characteristics, this model may also be applied to a phosphoric acid fuel cell following the same logic used for a gas engine.

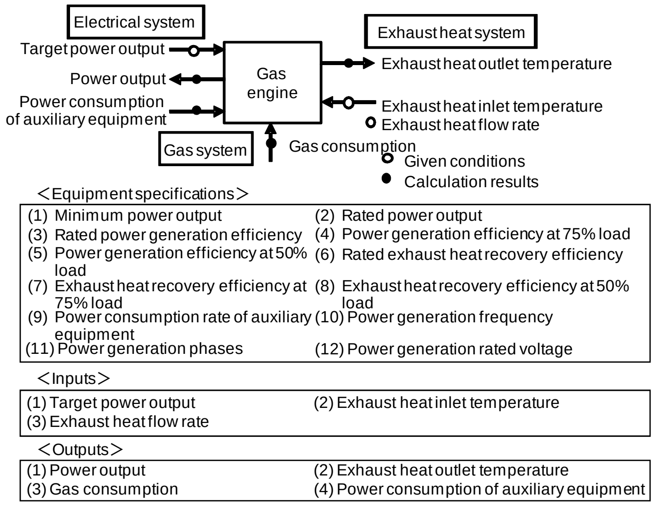


Figure 3 Input and output parameters of gas engine

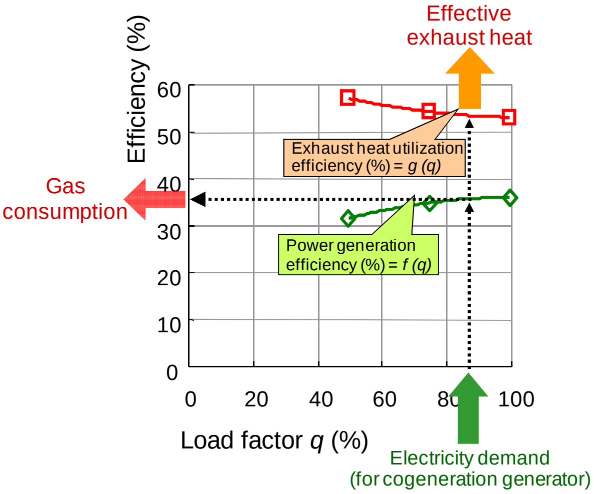


Figure 4 Modeling of partial load characteristics of gas engine

(2) Controller

In addition to the generator controller, a multi-unit controller capable of master control of multiple generators was developed.

Figures 5 and 6 show in overview how control of the gas engine generator works. To control output level, a control signal is sent to the generator being controlled to indicate that target power output should equal the rated power output of the generator concerned. In the case of load following, on the other hand, target power output is obtained by the logic shown in Figure 4 and a control signal is sent to the controlled generator.

An example of control by means of a multi-unit controller is shown in Figure 7, which is for a multi-unit system consisting of four 1,000 kW generators. This shows the output of each generator to meet power demand where the first unit is operated at fixed output and subsequent units are operated on a load-following basis with a minimum output of 600 kW.

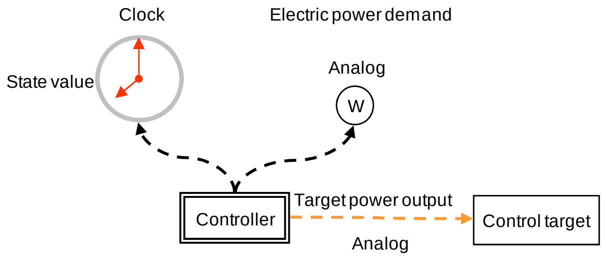


Figure 5 Role of generator controller

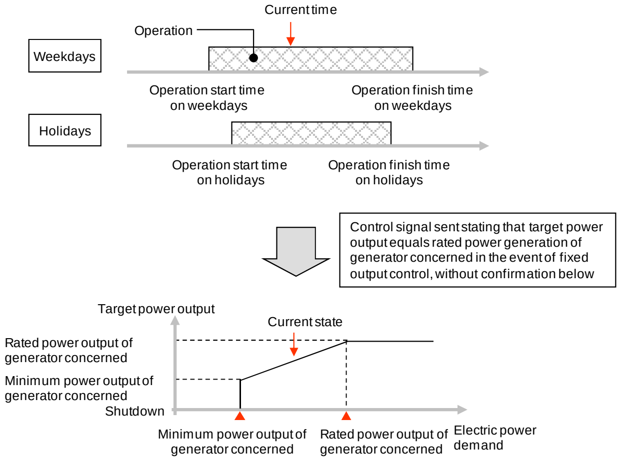


Figure 6 Method of controlling target output of generator

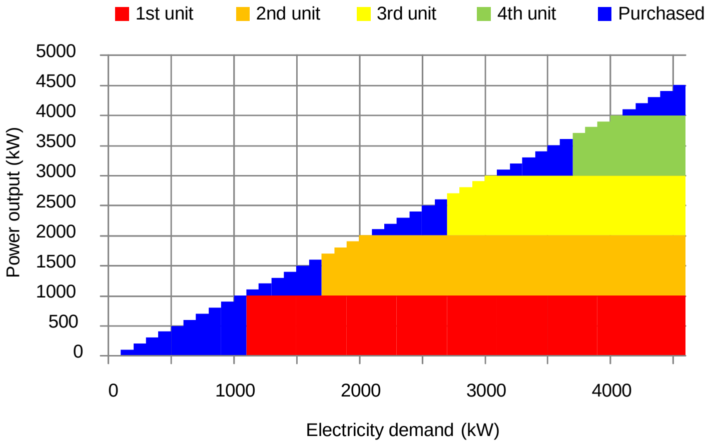


Figure 7 Example of multi-unit generator controller

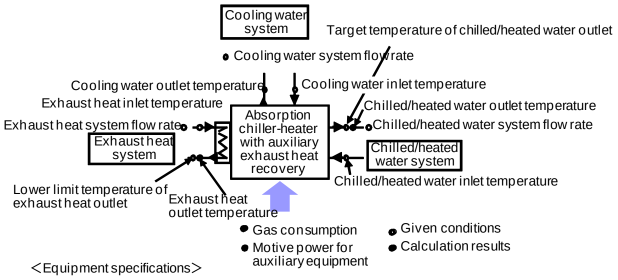
(3) Absorption chiller-heater with auxiliary exhaust heat recovery

The input and output parameters of the absorption chiller-heater with auxiliary exhaust heat recovery are as shown in Figure 8. In this study, only those types that use exhaust heat from heated water were considered.

The steps in the calculations are shown in Figure 9. Chilled water demand is given by the controller, and exhaust heat recovery is calculated according to this demand and exhaust heat potential (exhaust heat inlet temperature and exhaust heat flow rate). Given exhaust heat recovery, it is possible to calculate the gas consumption and outlet temperature of each system.

Exhaust heat recovery is calculated by first calculating recoverable exhaust heat from the inlet temperature and flow rate of each system, based on which the exhaust heat outlet temperatures are checked and ultimate exhaust heat recovery is calculated. Gas consumption is obtained by deducting exhaust heat utilization from gas consumed during operation as a direct-fired absorption chiller-heater without utilizing exhaust heat.

The exhaust heat recovery of absorption chiller-heaters varies according to load factor, exhaust heat temperature, and exhaust heat flow rate. As Figure 10 shows, the equipment characteristics are replicated so that chilled water is generated using exhaust heat alone when operating at a load below a certain level. However, when the load factor rises and demand for chilled water can no longer be met by inputting exhaust heat alone, exhaust heat input is lowered and supplementation by gas is gradually increased.



＜Equipment specifications＞

(1) Rated cooling capacity
(2) Rated heating capacity
(3) Rated cooling gas consumption
(4) Rated heating gas consumption
(5) Rated cooling power consumption
(6) Rated heating power consumption
(7) Rated exhaust heat inlet temperature
(8) Lower limit temperature of exhaust heat outlet
(9) Rated exhaust heat heated water flow rate
(10) Rated exhaust heat recovery
(11) Target temperature of chilled water outlet
(12) Rated temperature of chilled water inlet
(13) Rated chilled water flow rate
(14) Target temperature of heated water outlet
(15) Rated temperature of heated water inlet
(16) Rated heated water flow rate
(17) Rated temperature of cooling water inlet
(18) Rated cooling water flow rate

＜Inputs＞

(1) Target temperature of chilled/heated water outlet
(2) Chilled/heated water system flow rate
(3) Chilled/heated water inlet temperature
(4) Exhaust heat inlet temperature
(5) Lower limit temperature of exhaust heat outlet
(6) Exhaust heat system flow rate
(7) Cooling water inlet temperature
(8) Cooling water system flow rate

＜Outputs＞

(1) Chilled/heated water outlet temperature
(2) Cooling water outlet temperature
(3) Exhaust heat outlet temperature
(4) Gas consumption
(5) Motive power for auxiliary equipment

Figure 8 Input and output parameters of absorption chiller-heater with auxiliary exhaust heat recovery

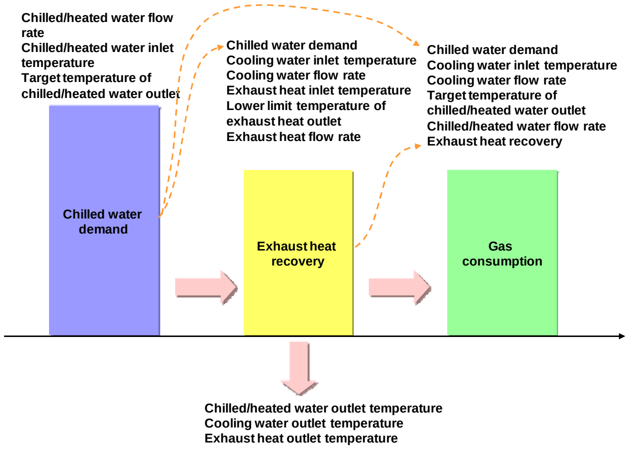


Figure 9 Steps in calculations for chiller-heater with auxiliary exhaust heat recovery

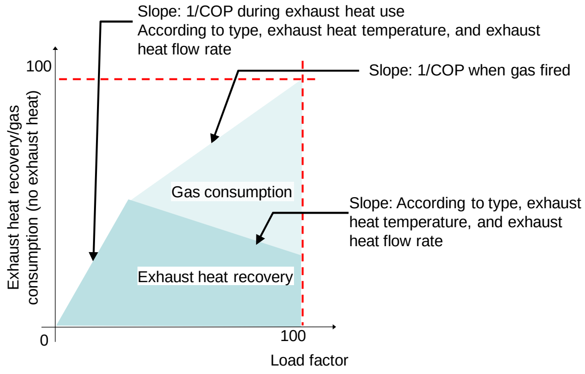


Figure 10 Computational concept for absorption chiller-heater with auxiliary exhaust heat recovery

4. Coupled calculation

In this section, we describe a simulation performed for the sample system.

In this case, the simulation was performed under the following conditions and for the case shown in Table 2. Heat and power demands (space cooling, space heating, and electricity) were modeled using CASCADE III and load data created at five-minute intervals.

The secondary air-conditioning system was excluded from calculations.

The heat exchanger was modeled by varying heat transfer availability according to flow rate. Calculations were made for typical days (weekdays and holidays) each month.

(1) Simulation settings

The simulation was performed using the settings shown in Table 2. A cogeneration system was adopted. A gas engine was employed for the generator and the exhaust heat of heated water having a temperature of approximately 90degC was used by an absorption chiller-heater with auxiliary exhaust heat recovery. Any surplus exhaust heat at this time is released into the atmosphere by a cooling tower.

(2) Simulation results

Figure 11 shows the results of the simulation for a typical summer’s day in Japan. It can be seen that, as the gas engine was configured to operate on a load-following basis, output varies according to the time of day. As can be seen from the exhaust heat outlet/inlet temperatures of the gas engine, the simulation replicates the fall in the temperature of the pipes (which function as the system’s heat carrier when shut down at night) to around outside air temperature and inflow of cooled exhaust-heated water to the gas engine. The absorption chiller-heater is entirely direct gas-fired and makes no use of exhaust heat immediately after the gas engine starts up, as the temperature of the exhaust heat system is low. It can also be seen that the equipment characteristics are replicated so that exhaust heat utilization increases slightly and gas consumption falls when the amount of heat of chilled/heated water gradually declines from around 18:00.

Table 2 Simulation settings

Item	Setting
Overall	Gas type: City gas 13 A
	Heating value: 45 MJ/m^3 (HHV)
Building	Total floor area: 9,919 m^2 (12 floors)
	Ceiling height: 2.6 m
	Zoning: 8 zones with air conditioner in each
Operating schedule	Operating hours: 08:00-22:00 (Monday-Friday)
	Heating/cooling periods: cooling (May-November), heating (December-April)
Gas engine	Rated power output: 350 kW
	Rated power generation efficiency/rated exhaust heat recovery efficiency (LHV basis): 40.5%/34.5%
	Auxiliary equipment motive power: 17.5 kW
	Control method: load following
Absorption chiller-heater with auxiliary exhaust heat recovery	When cooling (rated capacity/gas consumption (no exhaust heat)/power consumption/rated exhaust heat recovery): 1,055/822/5.1/326 kW
	When heating (rated capacity/gas consumption/power consumption): 692/822/4.8 kW
Heat exchanger for space heating	Capacity 298 kW
Pump	Chilled/heated water pump Flow rate: 3,024 l/min; power consumption: 30 kW
	Cooling water pump Flow rate: 5,000 l/min; power consumption: 22 kW
	Heated water pump Flow rate: 855 l/min; power consumption: 11 kW
	Exhaust heat circulating pump Flow rate: 481.8 l/min; power consumption: 3.7kW
	Cooling water pump for exhaust heat cooling Flow rate: 963.6 l/min; power consumption: 7.5 kW
Cooling tower	Cooling water flow rate: 5,000 l/min
	Fan: 16.5 kW

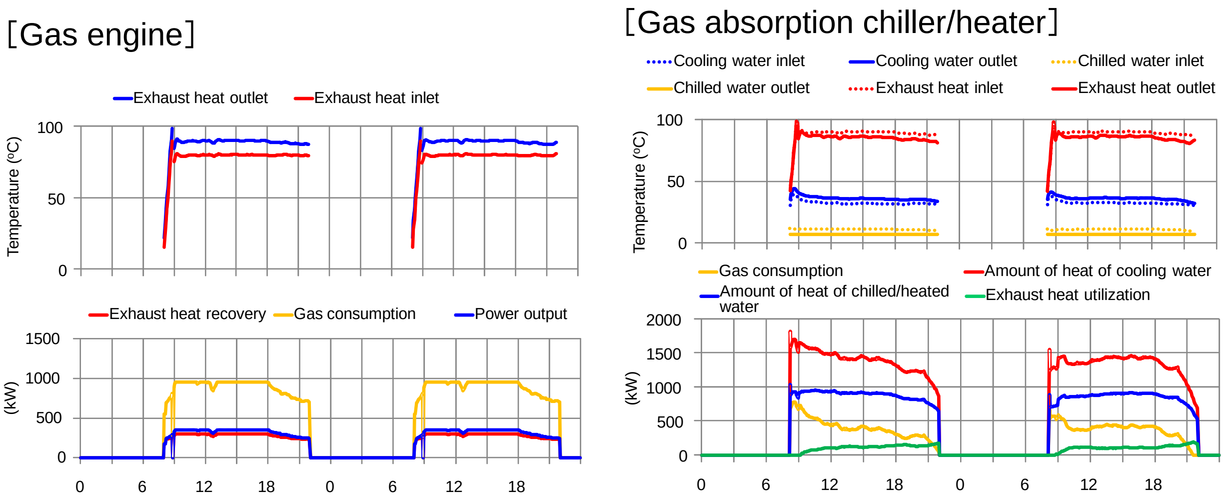


Figure 11 Example of cogeneration system simulation results for typical summer days in Japan

Figure 12 shows the relationship between load factor and the efficiency of power generation capacity and exhaust heat recovery when the gas engine is in operation during two months (July and August) of the one-year simulation. The figure includes power generation efficiency and exhaust heat recovery efficiency at the inputted rated load, 75% load, and 50% load, and it could be confirmed that the expected results were obtained by quadratic interpolation of efficiency at partial load for all power generation and exhaust heat recovery efficiency.

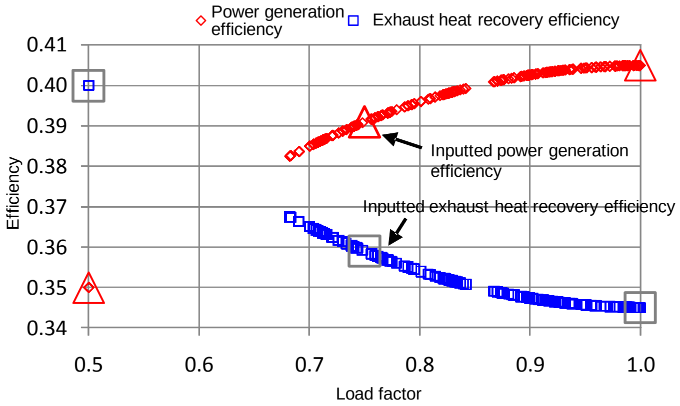


Figure 12 Relationship between gas engine load factor and efficiency of power generation, and exhaust heat recovery

Confirmation of the heat balance of the exhaust heat system was conducted over a two-month summer period in order to verify the validity of the forward method used for the system simulation. Results showed the difference between the exhaust heat recovery of the gas engine and demand (equal to the sum of the exhaust heat recovery of the absorption chiller-heater with auxiliary exhaust heat recovery and the amount remaining unused) to be around 3%, which is within the practically acceptable range. Examined more closely, an imbalance was found to occur when the system commences operation.

This is due to the use of the forward method; for although the circulation of exhaust heat should cause the system temperature to gradually rise after the five-minute time interval used for calculations, the forward method allows exhaust heat to circulate only once during the simulation at the time concerned. It also treats the exhaust heat of the gas engine as theoretically being entirely stored in the pipes that are the system’s heat carrier. Another reason for this is that the stability conditions between exhaust heat recovery and pipe heat capacity are disregarded. Although the integrated error for the period is around 3% as noted above, the above factors may give rise to errors that can no longer be ignored when frequency of operation increases, and this will need to continue to be verified in the future.

7. Conclusions and future research

The computational model for facilities and equipment was determined on the basis of existing models and interviews with manufacturers. When calculations were performed with these connected, a problem was found to occur in the form of a heat imbalance due to the size of the circulation flow rate and the heat capacity to be absorbed. This will have to be dealt with by such means as modifying the order of calculations and adopting realistic flow rates. The system heat balance is generally good, and the indications are that a method of system simulation by means of a simple method of calculation has been successfully developed.

Attention now needs to turn to the following points to enable simulations to be performed in a more versatile manner.

(1) Expansion of components

Actual buildings often employ a greater range of heat source devices that operate under multi-unit control. It is therefore necessary to create an environment in which system simulations for entire buildings can be performed by expanding the range of heat source devices and components of air systems.

(2) Improvement of versatility

The algorithm employed in this study was a simple forward method. As the results of calculations using this method can differ considerably depending on the order of calculations for facilities and equipment, a method of sequencing calculations more robustly or a switch to an algorithm for performing simple convergences (if versatility is to be raised) will be required.

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