Korean J. Chem. Eng., **25**(3), 409-418 (2008)

Modeling and simulation of motor/turbine processes in utility plant

Sang Hun Oh and Yeong Koo Yeo†

Department of Chemical Engineering, Hanyang University, Seoul 133-791, Korea
(*Received 30 May 2007 • accepted 2 August 2007*)

Abstract−To achieve safe operation and to improve economics it is imperative to monitor and analyze demand and supply of utilities and to meet utility needs in time. The main objective of motor/turbine processes is to manipulate optimal balances on steam and electricity in utility plants. The optimal operation of motor/turbine processes is by far the most important to improve economics in the utility plant. In order to analyze motor/turbine processes, steady state models for steam generation equipment and steam distribution devices as well as turbine generators are developed and analyzed in this work. In addition, heuristics concerning various operational situations are incorporated in the models. The motor/turbine optimal operation system is based on utility models and operational knowledgebase, and provides optimal operating conditions when the amount of steam demand from various steam headers is changed frequently. The optimal operation system also produces optimal selection of driving devices for utility pumps to reduce operating cost.

Key words: Utility Plant, Motor/Turbine Process, Optimization, Steam Header, Knowledgebase

INTRODUCTION

Utility is the energy source required in the operation of plants. “Utility system” refers to the various facilities related to the supply of utility. Utilities such as electricity, steam, process water, air and various gases used in the plant operation are supplied by the utility system. The effective management and maintenance of the utility system affect the safe operation and economics of the plant most significantly. Steam is the most important energy source in most plants among various utilities supplying energy needed in the operation. Steam generated in the boiler is important heat transfer medium and is used in safe and steady supply of heat energy. Therefore the management of steam affects demand and supply of electricity and process water in the plant. Because the amount of steam needed in the plant varies frequently according to the operating situations and weather conditions, it is very important to perform accurate identification of the magnitude of steam variation as well as to accomplish optimal distribution of steam needed for safe operation and economics. But complicated operational knowledge about distribution mechanism, turbine generator and motor/turbine units makes precise and rapid distribution very difficult.

So far, many useful results concerning the operation of utility plants have been published. Use of steady-state mass balances about simple steam distribution processes and linear programming schemes were early practices, but those results could not be applied practically because of the simple target processes and insufficient modeling of turbine generators [1-3]. Many researchers paid attention to the use of MILP or MINLP to minimize operation costs, but lack of the consideration of conditions for safe operation prohibited actual application [4-8]. Nishio et al. computed the optimal amount of steam generation and electricity for steam-dominant case and power-dominant case by using a two-level approach [10] used the LP method to propose a synthesis and design scheme for utility systems. They employed PPROPS system for calculation of steam properties to give optimal steam header pressure, but they did not take into account the operating cost [1] used the simulated annealing (SA) algorithm to analyze synthesis of optimal utility system.

In the present study we mainly focus on the motor/turbine processes which adjust balances on steam and electricity and greatly affect the economics of the plant. In order to analyze the motor/turbine process we need to identify models about overall steam generation and steam distribution facilities as well as operational knowledge about various situations. The optimal operation system for the motor/turbine process is based upon the models on utility devices and operational knowledgebase, and provides optimal operation conditions for each utility facility when the amount of steam changes at various steam headers. We need to select suitable drivers for utility pumps according to the changes of steam required so that we can save on the operating cost.

In this work we first establish models of each unit process in the utility plant and then construct an operating knowledgebase about the motor/turbine process. The optimal operation system constructed in this way provides optimal operating conditions for each utility facility when there are changes in supply and demand of steam at various steam headers such as low pressure header, medium pressure header, high pressure header and very high pressure header.

1. Modeling of the Utility Plant

1-1. Modeling of Steam Generation Process

In general, a boiler generates steam by using heat from the combustion of fuel or from other heat sources. A typical boiler consists of a deaerator, a high-pressure heater (HPH), a steam-air heater (SAH), superheaters, a boiler drum, an oil heater and a flash tank. Fig. 1 shows a schematic of a typical steam generation unit. The boiler feedwater should be treated carefully to prevent corrosion and accumulation of wastes within boiler units. In the deaerator, gases dissolved in the boiler feedwater are removed by introduction of steam to prevent explosion due to the expansion of gases dissolved in the

†To whom correspondence should be addressed.
E-mail: ykyeo@hanyang.ac.kr

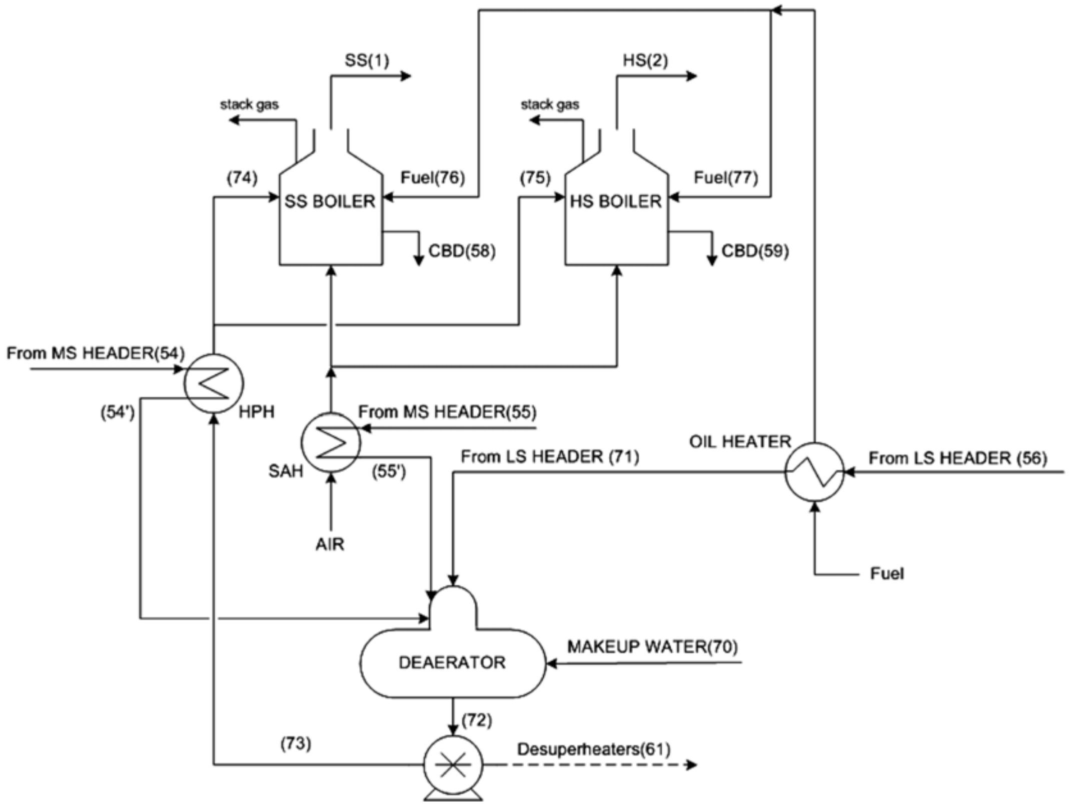

Fig. 1. The Schematic diagram of steam generation units.

feedwater.

The main assumptions used to develop the model are as follows:

i) In the model homogeneity is maintained, i.e., only time derivatives of variables are included in the model and spatial derivatives are not considered.

ii) Polynomial fits to steam tables were used to establish the relations between steam parameters such as enthalpy, entropy, density, temperature and pressure.

iii) Superheated steam and furnace exhaust gases were treated as ideal gases.

iv) Constant volumetric flow is assumed in downcomer by circulation pumps.

v) Mass flow dynamics for riser and reheater are considered as 1^{st} order lags.

vi) The model includes only main parts of the boiler using lumped characteristics for those parts which consist of more than one section.

In addition to the assumptions described above, the variables in the model are assumed to satisfy basic physical thermodynamic relations. For example, the heat balance for a heat exchanger is given by

$$Q_{in}+w_{in}h_{in}=w_{out}h_{out}+V\frac{d}{dt}(\rho_{out}h_{out}) \quad (1)$$

And the mass balance can be written as

$$w_{in}-w_{out}=\frac{d}{dt}(\rho_{out}V) \quad (2)$$

The friction loss is simply represented as

$$P_{in}-P_{out}=\gamma\frac{w_{in}^2}{\rho_{in}} \quad (3)$$

The heat transfer due to radiation can be represented by using Stefan-Boltzmann law as

$$Q=K\theta w_g T_g^4\frac{1}{\rho_g} \quad (4)$$

By assuming turbulent combustion gas flow, we can describe the heat transfer between gas and metal wall of the combustion chamber as

$$Q=Kw_g^{0.6}(T_g-T_m) \quad (5)$$

Again, by assuming turbulent steam flow, we can describe the heat transfer between steam and metal wall of the combustion chamber as

$$Q=Kw_s^{0.8}(T_m-T_s) \quad (6)$$

or

$$Q=K_r(T_m-T_s)^3 \quad (7)$$

1-1-1. Boiler Modules

The boiler can be divided into five interconnected subsystems which consist of a furnace, risers, a downcomer, a drum and superheaters/attemporator. Fig. 2 is the overall block diagram for the boiler and shows interconnections between modules in the boiler model.

For the furnace, the mass balance and the heat balance for combustion are given, respectively, by

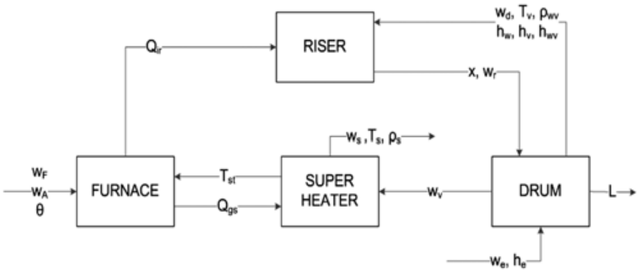

Fig. 2. Boiler-block diagram.

$$w_F + w_A - w_{EG} = V_F \frac{d}{dt}\rho_{EG} \tag{8}$$

$$C_F w_F + h_A w_A - Q_{ir} - Q_{is} - w_{EG} R_s\left(1 + \frac{y}{100}\right) h_{EG} = V_F \frac{d}{dt}(\rho_{EG} h_{EG}) \tag{9}$$

For the riser, the mass balance and the heat balance are given, respectively, by

$$w_d - w_r = V_r \frac{d}{dt}\rho_r \tag{10}$$

$$Q_r + w_d h_w = w_r h_r + V_r \frac{d}{dt}(\rho_r h_r) \tag{11}$$

In the riser, the flow relation can be written by

$$\frac{d}{dt} w_r = \frac{w_d - w_r}{\tau_r} \tag{12}$$

For the boiler drum, the liquid mass balance and the liquid heat balance are given, respectively, by

$$w_d - w_r = V_r \frac{d}{dt}\rho_r \tag{13}$$

$$w_e + (1-x) w_r - w_d - w_{ec} = \frac{d}{dt} m_{dl} \tag{14}$$

$$w_e h_e + (1-x) w_r h_{wv} = w_d h_w - w_{ec} h_v + \frac{d}{dt}(m_{dl} h_w) \tag{15}$$

The steam mass balance in the boiler drum is represented as

$$w_{ec} + x w_r = w_v + \frac{d}{dt}(V_v \rho_v) \tag{16}$$

The mass and heat balances for the superheater and attemporator can be represented as follows:

$$\text{Mass balance: } w_v - w_s + w_a = V_s \frac{d}{dt}\rho_s \tag{17}$$

$$\text{Gas tube heat balance: } Q_{gs} = Q_s + M_s C_{st} \frac{d}{dt} T_{st} \tag{18}$$

Heat balance for steam:

$$Q_s + w_v h_v = w_s h_s - (h_a - h_f) w_a + V_s \frac{d}{dt}(\rho_v h_s) \tag{19}$$

The boiler feedwater can be represented as the sum of superheated steam and CBD (continuous blow down). CBD is the continuous extraction of saturated water from the boiler drum. The amount of CBD is about 1% of overall steam production rate. Balances around the superheated steam boiler (SS boiler) are given by

$$m_{58} = 0.01 m_1 \tag{20}$$

$$m_{74} = m_1 + m_{58} \tag{21}$$

$$\Delta H = m_1 H_1 + m_{58} H_{58} - m_{74} H_{74} \tag{22}$$

From Eqs. (20) and (21) we have

$$m_{74} = 1.01 m_1 \tag{23}$$

Substitution of Eq. (23) into (22) gives

$$\Delta H = (H_1 + 0.01 H_{58} - 1.01 H_{74}) m_1 \tag{24}$$

Similarly, balances around the high pressure steam boiler (HS Boiler) are given by

$$m_{75} = 1.01 m_2 \tag{25}$$

$$\Delta H = (H_2 + 0.01 H_{59} - 1.01 H_{75}) m_2 \tag{26}$$

1-1-2. Oil Heater and Steam-Air Heater (SAH)

Bunker-C oil is the most popular fuel used in boilers. Because the viscosity of Bunker-C oil is relatively high, an oil heater is used to increase the oil temperature in order to decrease the viscosity of the fuel and to improve fluidity and combustion efficiency. Balances around the oil heater and SAH are given by:

Oil Heater:

$$(H_{76} - H_{fuel}) m_{76} - (H_{56} - H_{71}) m_{56} = 0 \tag{27}$$

$$(H_{77} - H_{fuel}) m_{77} - (H_{56} - H_{71}) m_{56} = 0 \tag{28}$$

Steam-Air Heater (SAH):

$$(H_{air'} - H_{air}) m_{air} - (H_{55} - H_{55'}) m_{55} = 0 \tag{29}$$

1-1-3. Deaerator and High-Pressure Heater (HPH)

The boiler feedwater is introduced into the deaerator to which condensates from SAH, HPH and oil heater are added. Most of the feedwater from the deaerator is routed to the upper boiler drum. By storing the feedwater, the deaerator manages sudden fluctuations in the feedwater. HPH preheats the high pressure feedwater by using medium-pressure steam which is condensed and directed into the deaerator. Balances around the deaerator and HPH are given by:

Deaerator:

$$m_{54'} + m_{55'} + m_{70} + m_{71} = m_{72} \tag{30}$$

$$H_{54'} m_{54'} + H_{55'} m_{55'} + H_{70} m_{70} + H_{71} m_{71} = H_{72} m_{72} \tag{31}$$

High-Pressure Heater (HPH):

$$(H_{74} + H_{75} - H_{73}) m_{73} - (H_{54} - H_{54'}) m_{54} = 0 \tag{32}$$

1-2. Modeling of Steam Distribution Units

1-2-1. Steam Headers

The steam header supplies the steam generated in the boiler to each unit process. The steam header is classified as superheated steam header, high-pressure header, medium-pressure header and low-pressure header according to the header pressure. In general, all these four headers are connected to the turbine generator, utility turbines and desuperheaters. The superheated steam generated in the boiler is transferred to the superheated steam header from which some of the superheated steam is used in some processes, or is fed into the

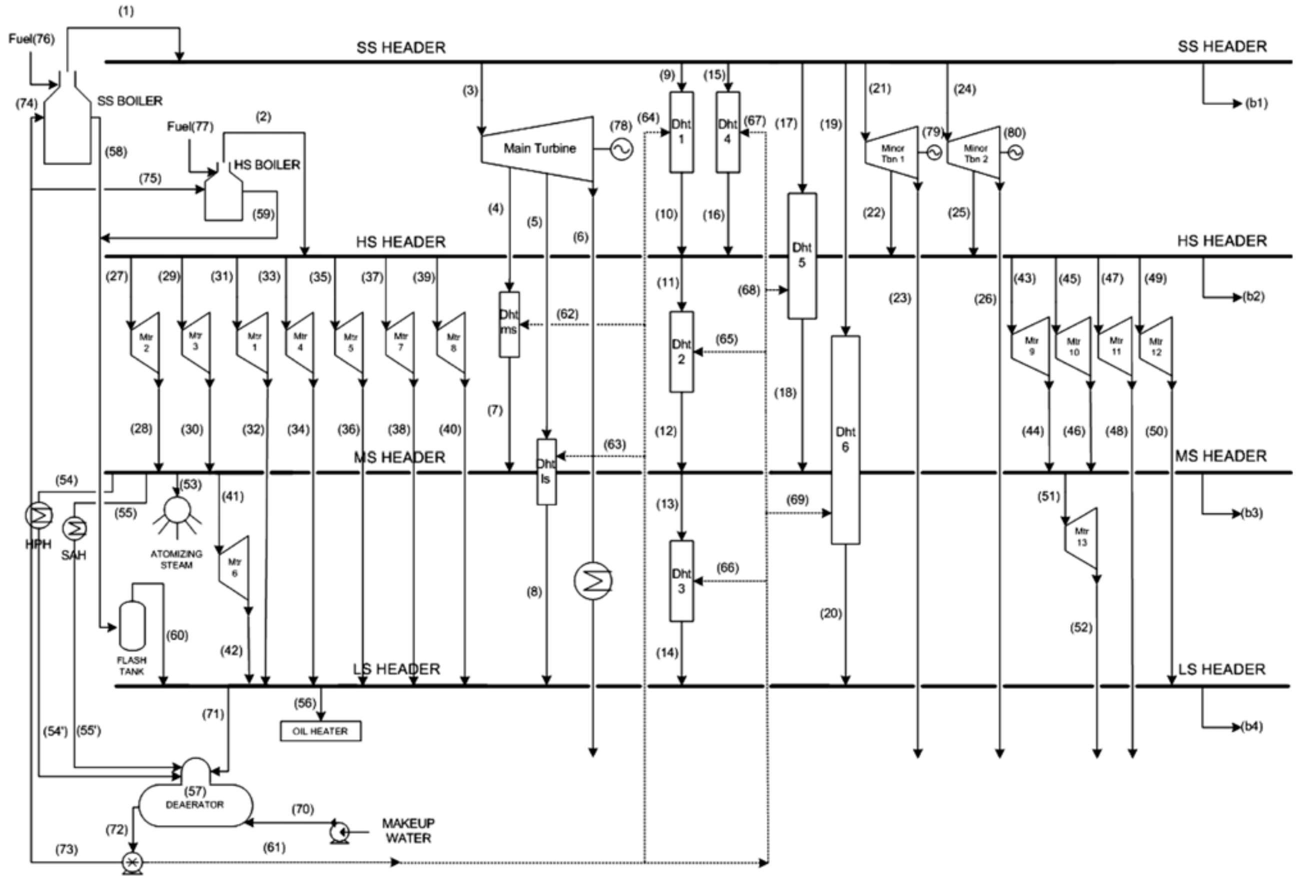

Fig. 3. The flow diagram of steam in steam distribution plant.

desuperheater to be transferred to the high-pressure header. The remainder is supplied to the turbine generator to be extracted into the medium-pressure header and the low-pressure header. The high-pressure steam from the desuperheater can be supplied to the turbines driving utility pumps to be extracted to the medium-pressure or the low-pressure header. Part of the medium pressure steam supplied from the utility turbines and desuperheaters is used to drive fuel pump turbines, the high-pressure feedwater heater and the steam-air heater and the remainder of the supplied steam is routed to the low-pressure header through desuperheaters. The low-pressure steam from the turbine generators, desuperheaters, the flash tank and utility turbines is fed into the deaerator, steam-air preheater and various processes demanding the low-pressure steam (see Fig. 3). Balances at each header are as follows:

Superheated Steam Header:

$$m_3+m_9+m_{15}+m_{17}+m_{19}+m_{21}+m_{24}-m_1=-b_1 \quad (33)$$

High-pressure Steam Header:

$$m_{11}+m_{27}+m_{29}+m_{31}+m_{33}+m_{35}+m_{37}+m_{39}+m_{43}+m_{45}+m_{47}+m_{49} -m_2-m_{10}-m_{16}-m_{22}-m_{25}=-b_2 \quad (34)$$

Medium-pressure Steam Header:

$$m_{13}+m_{41}+m_{51}+m_{53}+m_{54}+m_{55} -m_7-m_{12}-m_{18}-m_{28}-m_{30}-m_{44}-m_{46}=-b_3 \quad (35)$$

Low-pressure Steam Header:

$$m_{56}+m_{71}-m_8-m_{14}-m_{20}-m_{32}-m_{34}-m_{36} -m_{38}-m_{40}-m_{42}-m_{50}-m_{60}=-b_4 \quad (36)$$

1-2-2. Desuperheaters

The desuperheater is the most popular device used to adjust the header pressure. Normally, it changes high temperature and high pressure steam into lower temperature and lower pressure steam. The desuperheater is relatively simple to handle and does not require complicated operational techniques. Fig. 4 shows a schematic of a desuperheater. Balances on the desuperheater are given by

$$m_{in}+m_w=m_{out} \quad (37)$$

$$H_{in}m_{in}+H_wm_w=H_{out}m_{out} \quad (38)$$

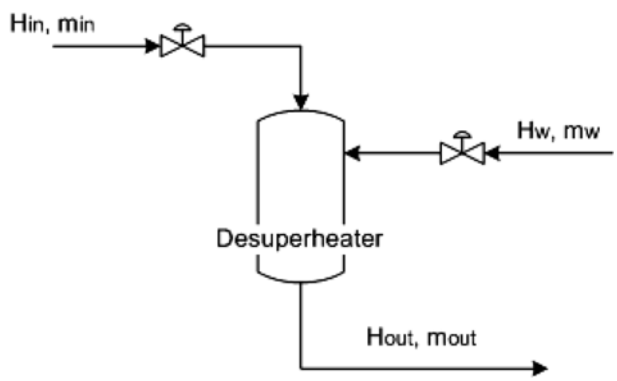

Fig. 4. The schematic diagram of the desuperheater.

The relationship between inlet water or outlet water and spray water can be obtained from Eqs. (37) and (38) as

$$m_w = \frac{(H_{out} - H_{in})}{(H_w - H_{out})} m_{in} \tag{39}$$

The overall mass balance for the spray water is given by

$$m_{62}+m_{63}+m_{64}+m_{65}+m_{66}+m_{67}+m_{68}+m_{69}=m_{61} \tag{40}$$

1-2-3. Turbine Generator

In the modeling of the steam turbine we assume that the superheated steam behaves like an ideal gas and that the kinetic energy of the steam introduced into each pressure level can be neglected. Based on these assumptions the generation of the electricity at the turbine generator can be represented as

$$W = \sum_i \eta_i (\Delta m_i \Delta H_i) \tag{41}$$

The amount of the electricity generated in the generator can be changed according to the variation of the amount of steam extraction. Balances around each turbine generator are given by

$$m_3=m_4+m_5+m_6 \tag{42}$$

$$m_{21}=m_{22}+m_{23} \tag{43}$$

$$m_{24}=m_{25}+m_{26} \tag{44}$$

Equations for the efficiency of the generator can be derived from the regression of the operation data concerning flow rates of the superheated steam, amounts of each extracted steam and the amount of the electricity generated.

$$\eta_1=c_1+c_2e^{-6}m_3H_3+c_3e^{-6}m_4H_4+c_4e^{-6}m_5H_5 \tag{45}$$

$$\eta_2=c_5+c_6e^{-6}m_{21}H_{21}+c_7e^{-6}m_{22}H_{22} \tag{46}$$

$$\eta_3=c_8+c_9e^{-6}m_{24}H_{24}+c_{10}e^{-6}m_{25}H_{25} \tag{47}$$

In these equations c_1-c_{10} are constants.

1-3. Results of Simulations of Steam Generation Units

Table 1 shows results of simulations of steam generation units described above. The production rates of steam from the superheated steam boiler and the high-pressure steam boiler are 571.253 t/h and 10 t/h, respectively. Electricity is generated from three turbine generators with the rate of 23.000 MWh, 28.830 MWh and 20.365 MWh at each generator. The pressure of the superheated steam is reduced into high-pressure, medium pressure and low pressure by turbines, desuperheaters and motor/turbine processes described later. Results of the simulations depend upon the amount of the steam demand in various processes of the plant.

Table 1. Results of simulations of steam generation units

Equipment		Item	Unit	Value
Boiler	SS	SS (1)	t/h	571.253
		fuel (76)	t/h	39.845
		CBD (58)	t/h	5.713
		HPH (54)	t/h	74.263
		SAH (55)	t/h	21.708
		deaerator (57)	t/h	52.955
		oil Heater (56)	t/h	2.281
		attemporator (53)	t/h	6.044
	HS	HS (2)	t/h	10.000
		fuel (77)	t/h	0.622
		CBD (59)	t/h	0.100
Turbine generator	Main	SS (3)	t/h	163.007
		MS before (4)	t/h	109.440
		MS after (7)	t/h	112.723
		LS before (5)	t/h	12.000
		LS after (8)	t/h	12.360
		condensed water (6)	t/h	41.567
		water MS (62)	t/h	3.283
		water LS (63)	t/h	0.360
		electricity (78)	MWh	23.000
	Minor 1	SS (21)	t/h	206.730
		HS (22)	t/h	149.210
		condensed water (23)	t/h	57.520
		electricity (79)	MWh	28.830
	Minor 2	SS (24)	t/h	180.530
		HS (25)	t/h	126.710
		condensed water (26)	t/h	53.820
		electricity (80)	MWh	20.365
Desuperheater	1	in (9)	t/h	19.823
		out (10)	t/h	21.624
		water (64)	t/h	1.801
	2	in (11)	t/h	9.510
		out (12)	t/h	10.161
		water (65)	t/h	0.651
	3	in (13)	t/h	0
		out (14)	t/h	0
		water (66)	t/h	0
	4	in (15)	t/h	17.564
		out (16)	t/h	19.160
		water (67)	t/h	1.596
	5	in (17)	t/h	0
		out (18)	t/h	0
		water (68)	t/h	0
	6	in (19)	t/h	0
		out (20)	t/h	0
		water (69)	t/h	0

1-4. Utility Pump Processes

A typical problem arising frequently in the analysis of steam systems is to determine the supply strategy of low-pressure steam. We have to make a decision whether the high-pressure steam is routed to a desuperheater or to a steam turbine. For the decision to be optimal, data for costs of electricity and fuel, efficiency of the steam turbine, physical properties of steam and the boiler efficiency are needed. For the motor/turbine process shown in Fig. 5, we can devise two operation modes for the pump being driven by the electrical motor and the steam turbine.

Mode 1: Drive the pump by the steam turbine with low-pressure steam.

Mode 2: Drive the pump by the electrical motor and supply the low-pressure steam through a desuperheater.

(1) Mode 1

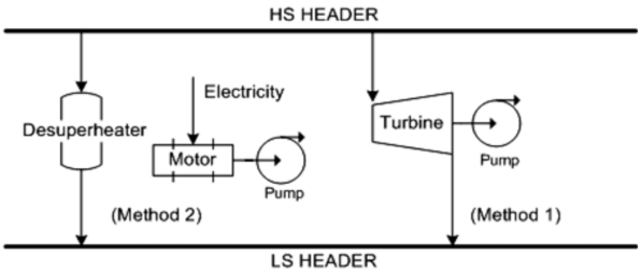

Fig. 5. The schematic diagram of the Motor/Turbine.

In this mode electricity is not required to drive the motor because steam is used to drive the turbine. If steam demands from each steam turbine or from process units increase, the driving source for utility pumps is switched to electrical motors before additional production of steam in the steam generation units

(2) Mode 2

The electricity needed to drive electrical motors should be generated additionally from turbine generators. The amount of steam needed to generate the additional electricity can be determined from the extracts of condensates of medium-pressure and low-pressure

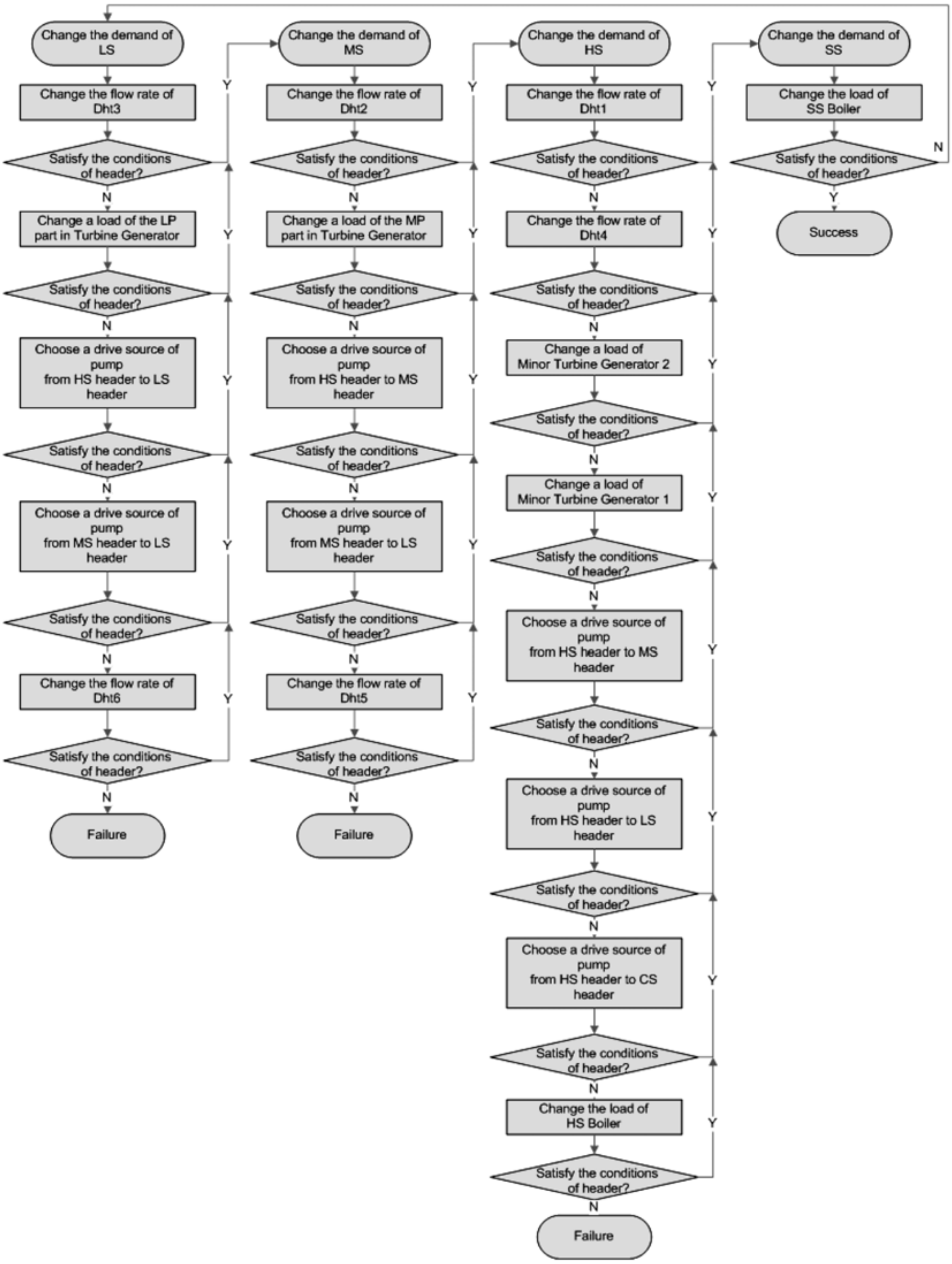

Fig. 6. The flow chart of the operation knowledgebase.

steam. The excess steam fed into the process units is used to drive utility pumps.

2. The Steam Distribution Process Based on Operational Knowledgebase

Steam is fed into process units through each steam header connected with desuperheaters, turbine generators and steam turbines driving utility pumps. If the process units are adjusted to fulfill the amount of variation of low-pressure steam, other steam headers are affected instantaneously. Normally, the steam distribution operation is initiated from the low-pressure header followed by medium-pressure header and high-pressure header. During the steam distribution operation self-consumed steam, the amount of electricity generated, relations between motor and steam demand, and the efficiency of the turbine generator should be considered.

Typical operational procedure for steam distribution can be summarized as follows. Fig. 6 shows these procedures.

(1) Change of demand for the low-pressure steam:

① Change the amount of effluent from the desuperheater 3(Dht3).

② Change the amount of extract of low-pressure steam from turbine generators.

③ Select the driving source for the utility turbine from the high-pressure header to the low-pressure header.

④ Select the driving source for the utility turbine from the medium-pressure header to the low-pressure header.

⑤ Change the amount of effluent from the desuperheater 6(Dht6).

At each step we have to check the header balance. If the balance is satisfied, change of demand for the medium-pressure steam is examined.

(2) Change of demand for the medium-pressure steam:

① Change the amount of effluent from the desuperheater 2(Dht2).

② Change the amount of extract of high-pressure steam from turbine generators.

③ Select the driving source for the utility turbine from the high-pressure header to the medium-pressure header.

④ Select the driving source for the utility turbine from the medium-pressure header to the low-pressure header.

⑤ Change the amount of effluent from the desuperheater 5(Dht5).

At each step we have to check the header balance. If the balance is satisfied, change of demand for the high-pressure steam is examined.

(3) Change of demand for the high-pressure steam:

① Change the amount of effluent from the desuperheater 1(Dht1) and the desuperheater 4(Dht4).

② Change the amount of extract from the turbine generator 2 (MinorTbn2).

③ Change the amount of extract from the turbine generator 1 (MinorTbn1).

④ Select the driving source for the utility turbine from the high-pressure header to the medium-pressure header.

⑤ Select the driving source for the utility turbine from the high-pressure header to the low-pressure header.

⑥ Select the driving source for the utility turbine from the high-pressure header to the condensate.

⑦ Change the load of the high-pressure boiler.

At each step we have to check the header balance. If the balance is satisfied, change of demand for the superheated steam is examined.

Table 2. Specifications of Motor/turbine and driving state

Equipment	Motor/Turbine	Driving state
Mtr 1	1M/1T	1M/1T
Mtr 2	2M/3T	1M/1T
Mtr 3	1M/1T	1M/1T
Mtr 4	2M/4T	1M/2T
Mtr 5	4M/4T	2M/2T
Mtr 6	1M/2T	1M/1T
Mtr 7	4M/4T	2M/2T
Mtr 8	2M/2T	1M/1T
Mtr 9	3M/3T	1M/1T
Mtr 10	3M/2T	1M/1T
Mtr 11	2M/2T	1M/1T
Mtr 12	3M/1T	1M/1T
Mtr 13	2M/1T	1M/1T

M: Motor/T: Turbine

(4) Change of demand for the superheated steam:

① Change the load of the superheated steam boiler.

② Display results if balances at each header and boiler loads converge. Go back to the case (1) if the convergence is not achieved.

The distribution procedures described above were applied to a target process. Different values of demands at each header are to be satisfied according to the distribution procedures. The present operation status of the utility plant is given in Table 2. We assumed changes of steam demands at each header as follows:

	SS	HS	MS	LS
①	Increase of 5t/h	Increase of 11t/h	Decrease of 12t/h	Decrease of 8t/h
②	No change	Increase of 20t/h	Decrease of 20t/h	Decrease of 15t/h
③	Decrease of 39t/h	No change	Increase of 47t/h	Increase of 50t/h

Changes of operation mode of motor/turbine processes are examined according to the driving state in the order of ①→②→③. Results of simulations are shown in Table 3.

Table 3. The simulation results of distribution operation

Equipment	Driving state	Distribution system		
		①	②	③
Mtr 1	1M/1T	1M/1T	1M/1T	0M/2T
Mtr 2	1M/1T	1M/1T	1M/1T	1M/1T
Mtr 3	1M/1T	1M/1T	2M/0T	2M/0T
Mtr 4	1M/2T	1M/2T	1M/2T	1M/2T
Mtr 5	2M/2T	2M/2T	0M/4T	0M/4T
Mtr 6	1M/1T	2M/0T	1M/1T	0M/2T
Mtr 7	2M/2T	3M/1T	2M/2T	0M/4T
Mtr 8	1M/1T	1M/1T	1M/1T	1M/1T
Mtr 9	1M/1T	1M/1T	2M/0T	2M/0T
Mtr 10	1M/1T	1M/1T	1M/1T	1M/1T
Mtr 11	1M/1T	1M/1T	1M/1T	1M/1T
Mtr 12	1M/1T	1M/1T	1M/1T	1M/1T
Mtr 13	1M/1T	1M/1T	1M/1T	1M/1T

M: Motor/T: Turbine

3. Optimal Steam Distribution

The optimization of the steam distribution is a typical MINL (mixed-integer nonlinear) problem. It is a mixed integer problem because the operation status of each motor/turbine is described by an integer (1 or 0). It is a nonlinear problem because of some nonlinear constraints originating from process models. Various routines contained in commercial packages such as MATLAB can be effectively used to handle the optimal steam distribution problem.

The optimization was performed for 9 different operation cases. The optimization involves 80 variables and 54 constraints. The objective function can be constructed as

$$\min f = C_{water}(m_1+m_2)+C_{fuel}(m_{77}+m_{78}) \tag{48}$$

where C_{water} denotes the water cost and C_{fuel} represents the cost for Bunker-C fuel. Equality and inequality constraints can be summarized as follows:

Equality constraints

$m_3+m_9+m_{15}+m_{17}+m_{19}+m_{21}+m_{24}-m_1=-b_1$

$m_{11}+m_{27}+m_{29}+m_{31}+m_{33}+m_{35}+m_{37}+m_{39}+m_{43}+m_{45}+m_{47}+m_{49}$
$\quad -m_2-m_{10}-m_{16}-m_{22}-m_{25}=-b_2$

$m_{13}+m_{41}+m_{51}+m_{53}+m_{54}+m_{55}$
$\quad -m_7-m_{12}-m_{18}-m_{28}-m_{30}-m_{44}-m_{46}=-b_3$

$m_{56}+m_{71}-m_8-m_{14}-m_{20}-m_{32}-m_{34}-m_{36}$
$\quad -m_{38}-m_{40}-m_{42}-m_{50}-m_{60}=-b_4$

$m_1+m_2+m_{57}-m_{54}-m_{55}-m_{70}-m_{71}=0$

$m_{54}+m_{55}+m_{70}+m_{71}-m_{57}-m_{72}=0$

$m_{62}+m_{63}+m_{64}+m_{65}+m_{66}+m_{67}+m_{68}+m_{69}-m_{61}=0$

$m_{61}+m_{72}-m_{73}=0$

$m_{64}+m_{75}-m_{73}=0$

$m_{58}+m_{59}-m_{60}=0$

$m_1+m_{58}-m_{74}=0$

$m_2+m_{59}-m_{75}=0$

$m_3-m_4-m_5-m_6=0$

$m_7-m_4-m_{62}=0$

$m_8-m_5-m_{63}=0$

$m_{21}-m_{22}-m_{23}=0$

$m_{24}-m_{25}-m_{26}=0$

$m_{10}-m_{64}-m_9=0$

$m_{12}-m_{65}-m_{11}=0$

$m_{14}-m_{66}-m_{13}=0$

$m_{16}-m_{67}-m_{15}=0$

$m_{18}-m_{68}-m_{17}=0$

$m_{20}-m_{69}-m_{19}=0$

$m_{27}-m_{28}=0$

$m_{29}-m_{30}=0$

$m_{31}-m_{32}=0$

$m_{33}-m_{34}=0$

$m_{35}-m_{36}=0$

$m_{37}-m_{38}=0$

$m_{39}-m_{40}=0$

$m_{41}-m_{42}=0$

$m_{43}-m_{44}=0$

$m_{45}-m_{46}=0$

$m_{47}-m_{48}=0$

$m_{49}-m_{50}=0$

$m_{51}-m_{52}=0$

$0.069885m_1-m_{76}=0.077024$

$0.069885m_2-m_{77}=0.077024$

$0.0106m_1-m_{53}=0.0117$

$0.13m_1-m_{54}=0$

$0.038m_1-m_{55}=0$

$0.004m_1-m_{56}=0.044$

$0.0927m_1-m_{57}=0$

Inequality constraints

$W_{79}-0.3750m_3+0.2470m_4+0.1749m_5+8.9999\leq 0$

$W_{80}-0.3420m_{21}+0.2595m_{22}+8.1498\leq 0$

$W_{81}-0.3301m_{24}+0.2519m_{25}+7.0584\leq 0$

$m_{62}-0.03m_4\leq 0$

$m_{63}-0.03m_5\leq 0$

$m_{64}-0.0833m_{10}\leq 0$

$m_{65}-0.0641m_{12}\leq 0$

$m_{66}-0.0602m_{14}\leq 0$

$m_{67}-0.0833m_{16}\leq 0$

$m_{68}-0.0162m_{18}\leq 0$

$m_{69}-0.1935m_{20}\leq 0$

Table 4 shows the results of the optimization. The column titled "Before Optimization" represents the operation costs estimated based on the normal operation. From the optimization a new set of operating conditions is computed. These "optimal" operating conditions are applied to the steam distribution process to give optimal opera-

Table 4. The results of optimization

No.	Demand of steam header (t/h)				Before optimization (₩/h)	After optimization (₩/h)	Difference
	LS	MS	HS	SS			
1	10−	14-	30+	0	247,837	243,771	−4,067
2	10−	12-	13-	40+	248,934	243,625	−5,309
3	5−	8+	6−	22+	253,878	244,021	−9,858
4	0	0	5+	2.5+	247,606	243,603	−4,003
5	0	30+	5−	2−	254,037	244,000	−10,036
6	10+	20+	30−	5+	245,124	243,155	−1,969
7	20+	3.5−	12−	5+	247,626	243,599	−4,027
8	30+	20−	5+	2−	248,895	243,361	−5,534
9	50+	20−	15−	0	248,789	243,381	−5,408

+: Increase, −: Decrease

tion states. The operation costs can be estimated based on these optimal operation status and the results are given in the column titled "After Optimization" in Table 4. For all the 9 operation cases operational cost savings were achieved. The maximum saving rate was 10,036₩/h (No. 5) and the minimum saving rate was 1,969₩/h (No. 6), illuminating significant cost savings by the solution obtained from the optimization.

CONCLUSIONS

An accurate and rapid steam distribution model based on the utility process models and the operational knowledgebase has been presented in this paper. In order to analyze motor/turbine processes, steady state models for steam generation equipment and steam distribution devices as well as turbine generators are developed and analyzed in this work. In addition, heuristics concerning various operational situations are incorporated in the models. The motor/turbine optimal operation system is based on utility models and operational knowledgebase and provides optimal operating conditions when the amount of steam demand from various steam headers is changed frequently. The optimal operation system also produces optimal selection of driving devices for utility pumps to reduce operating cost. For all operation cases considered in the present study, significant cost savings were achieved.

ACKNOWLEDGMENTS

The authors would like to acknowledge partial support from the Energy Technology Research Program (2006-000-0000-3314) under the Ministry of Commerce, Industry and Energy.

NOMENCLATURE

b_1 : balance of superheated steam header [t/h]
b_2 : balance of high-pressure steam header [t/h]
b_3 : balance of medium-pressure steam header [t/h]
b_4 : balance of low-pressure steam header [t/h]
C_F : fuel calorific value [J/kg]
C_{fuel} : cost of bunker fuel oil C [₩/l]
c_i : constant of efficiency equation [-]
C_{st} : heat capacitance of superheater tubes [J/kg·K]
C_{water} : cost of water [₩/t]
f : objective function [₩/h]
H_{air} : specific enthalpy of air [kJ/kg]
h_A : air specific enthalpy [J/kg]
h_a : specific enthalpy of attemporation water [J/kg]
H_{fuel} : specific enthalpy of fuel [kJ/kg]
h_{EG} : gas specific enthalpy [J/kg]
h_e : feedwater specific enthalpy [J/kg]
h_f : specific enthalpy of evaporation [J/kg]
H_i : specific enthalpy at position label [kJ/kg]
H_{in} : specific enthalpy of steam to desuperheater [kJ/kg]
h_{in} : inlet specific enthalpy [J/kg]
H_{out} : specific enthalpy of steam from desuperheater [kJ/kg]
h_{out} : outlet specific enthalpy [J/kg]
h_r : specific enthalpy of liquid-vapor mixture [J/kg]
h_s : specific enthalpy of superheated steam [J/kg]
h_v : specific enthalpy of saturated steam [J/kg]
H_w : specific enthalpy of water to desuperheater [kJ/kg]
h_w : specific enthalpy of downcomer and drumwater [J/kg]
h_{wv} : specific enthalpy of saturated water [J/kg]
K : an experimental coefficient [-]
m_{air} : mass flow rate of air [t/h]
m_{dl} : drum liquid mass [kg]
m_i : mass flow rate at position label [t/h]
m_{in} : mass flow rate of steam to desuperheater [t/h]
m_{out} : mass flow rate of steam from desuperheater [t/h]
M_s : mass of superheater tubes [kg]
m_w : mass flow rate of water to desuperheater [t/h]
P_{in} : inlet pressure [Pa]
P_{out} : outlet pressure [Pa]
Q : heat flow [J/s]
Q_{gs} : heat supplied to the superheater [J/s]
Q_{in} : incoming heat flow [J/s]
Q_{ir} : heat transferred by radiation to risers [J/s]
Q_{is} : heat transferred by radiation to the superheater [J/s]
Q_r : heat transferred to steam [J/s]
Q_s : heat transferred to the steam [J/s]
R_s : stoichiometric air/fuel volume ratio [-]
T_g : gas temperature [K]
T_m : metal temperature [K]
T_s : steam temperature [K]
T_{st} : metal tube temperature [K]
V : volume [m^3]
V_F : combustion chamber volume [m^3]
V_r : riser volume [m^3]
V_s : superheater volume [m^3]
V_v : vapor volume [m^3]
W : electric power amount [MWh]
w_A : air flow [kg/s]
w_a : attemporator water mass flow [kg/s]
w_d : downcomer water mass flow [kg/s]
w_e : feedwater flow [kg/s]
w_{ec} : drum liquid mass evaporation [kg/s]
w_{EG} : gas mass flow through the boiler [kg/s]
w_F : fuel flow [kg/s]
w_{in} : inlet mass flow [kg/s]
w_{out} : outlet mass flow [kg/s]
w_r : risers liquid-vapor mixture mass flow [kg/s]
w_s : steam mass flow out from the superheater [kg/s]
w_v : steam mass flow to the superheater [kg/s]
x : steam quality (from the risers) [-]
y : the percentage excess air level [%]

Greek Letters

γ : friction coefficient [-]
η_i : efficiency of turbine generator [-]
ρ_{EG} : gas density [kg/ m^3]
ρ_g : density of combustion gases [kg/ m^3]
ρ_{out} : outlet specific density [kg/ m^3]
ρ_r : liquid-vapor mixture density at the riser [kg/ m^3]
ρ_s : superheated steam density [kg/ m^3]
ρ_v : steam density [kg/ m^3]
τ_r : an empirical flow time constant [s]

θ : spherical angle [-]

REFERENCES

1. T. V. R. Maria, *Hydrocarbon Process*., **56**(7), 111 (1977).
2. P. A. Pilavakis and M. A. Perring, *Hydrocarbon Process*, **6**(7), 89 (1983).
3. Bouilloud, Ph., *Hydrocarbon Process*, **48**(7), 127 (1969).
4. R. Nath, D. J. Libby and H. J. Duhon, *Chem. Eng. Prog*., **82**(5), 31 (1986).
5. J. B. Poje and A. M. Smart, *Chem. Eng. Prog*., **82**(5), 39 (1986).
6. G. D. Stacy, L. D. Gaines and F. Collis, *Hydrocarbon Process*, **60**(10), 75 (1981).
7. J. K. Jr. Clark and N. E. Helmick, *Chem. Eng. Prog*., **76**(11), 116 (1980).
8. M. S. Díiaz and J. A. Bandomi, *Computers Chem. Engng*, **20**(5), 531 (1996).
9. M. Nishio, K. Shiroko and T. Umeda, *Ind. Eng. Chem. Process Des. Dev*., **21**(4), 640 (1982).
10. T. Petroulas and G. V. Reklaitis, *AIChE J*., **30**(1), 69 (1984).
11. A. W. Ordys, A. W. Pike, M. A. Johnson, R. M. Katebi and M. J. Grimble, *Modelling and simulation of power generation plants*, Springer-Verlag London Limited (1994).
12. G. Harrell, Steam System Survey Guide, DOE (U.S.) (2002).
13. W. O. Lee, *A study on the optimal operation and modeling of utility process*, Hanyang Univ. (2002).
14. D. Lindsley, *Boiler control systems*, McGraw-Hill (1991).
15. L. O. A. Maia, L. A. Vidal de Carvalho and R. Y. Qassim, *Computers Chem. Engng*, **19**, 481 (1995).
16. M. Nishio, J. Itoh, K. Shiroko and T. Umeda, *Ind. Eng. Chem. Process Des. Dev*., **19**(2), 306 (1980).
17. S. A. Papoulias and I. E. Grossmann, *Computers Chem. Engng*., **7**(6), 695 (1983).
18. Y. H. Yoo, H. S. Yi, Y. K. Yeo, M. K. Kim, H. S. Yang and K. P. Chung, *Korean J. Chem. Eng*., **13**, 348 (1996).
19. H. S. Yi, *The development of expert system for steam distribution in utility plant*, Hanyang Univ. (2002).