Korean J. of Chem. Eng., 13(4), 384-392 (1996)

MODELING AND SIMULATION OF ENERGY DISTRIBUTION SYSTEMS IN A PETROCHEMICAL PLANT

Yeong Ho Yoo, Heui Seok Yi, Yeong-Koo Yeo†, Myung Kil Kim*, Hong Suk Yang* and Kwang Pil Chung*

Dept. of Chemical Engineering, Hanyang University, Seoul 133-791, Korea
*Yochon Plant, Daelim Industral Co., Yochon, Chunnam, Korea
(Received 23 February 1996 • accepted 30 April 1996)

Abstract – A systematic method for analysis and design of plant-wide energy distribution systems is proposed to minimize the net cost of providing energy to the plant. The method is based on the steady-state modeling and simulation of steam generation process and steam distribution network. Modeling of steam generation process and steam distribution network were performed based on actual plant operation data. Heuristic operational knowledges are incorporated in the modeling of steam distribution network. Newton's iteration method and a simple linear programming algorithm were employed in the simulation. The letdown amount from superheated high-pressure steam (SS) header and the amount of SS produced at the boiler showed good agreement with those of actual operational data.

Key words: Steam Distribution System, Steam Header, Distribution Network

INTRODUCTION

In petrochemical plants, energy is used in the form of steam and electrical power. Electrical power is purchased from electrical power company and part of it is produced at the plant site from turbine generators. Electrical power drives motors and is used directly in some processes. Steam is produced in boilers, generated in processes, or recovered from heat exchangers. Steam is a working fluid when powering turbines, a heat transfer media and sometimes injected directly into a process.

Energy requirements of the process units are not constant. Demands for energy also change as individual unit production rates change. Energy efficiencies of boilers change with loading and those of turbines likewise are a function of throughput. The cost of fuels burned in each boiler varies with the type of fuel and rate of consumption and the cost of power purchased from the electrical power company is a complex function of base consumption level, actual power consumption, peak demand, time of day and day of year.

To minimize the net cost of providing energy to the plant, the operations of the energy management system should be optimized. Many efforts have been devoted to the study of minimization and synthesis of heat integration and utility systems. Gordon and Hashemi [1978] presented a simple boiler-turbine system using steady-state mass and energy balances. Nishio et al. [1980] described a thermodynamic approach to steam-power system design with some numerical design examples. Clark and Helmick [1980] employed an iterative linear programming algorithm to the design of steam systems. They handled main components of steam systems such as deaerator and steam header except boiler system. Nishio et al. [1982] discussed a two-level approach determining the optimal supply and demand relationship of steam and power based on thermodynamic analysis of system performance. In their later work [1985] they used a linear programming method to solve a problem regarding the selection of heating devices under given loads. Petroulas and Reklaitis [1984] also utilized a linear programming method to solve problems of driver allocation and selection of header and power source. Maia et al. [1995] set up a combinatorial optimization problem by discrete representation of equipment capacities and steam conditions to solve the synthesis problem of utility systems.

As plant demands change, operating conditions that minimize energy costs also change, often requiring reoptimization many times a day. Therefore, for the optimization system to be successful, modeling and computational simulations for the energy distribution system are the essential prerequisite. The objective of the present work is to develop a model for energy distribution system to optimize the operations of the plant-wide energy management system.

STEAM DISTRIBUTION SYSTEM

The steam distribution system for a plant basically consists of a network of headers connecting the distribution system to the process units. The steam headers are a superheated high-pressure steam (SS) header, a high-pressure steam (HS) header, a medium-pressure steam (MS) header and a low-pressure steam (LS) header. Fig. 1 shows a steam distribution system of a typical petrochemical plant. Pressures and temperatures of each steam header are listed in Table 1.

SS is generated by one or more utility boilers and/or waste heat boilers in the proces units. The boiler feed water (BFW) is supplied from deaerator pumping systems. SS from the boiler is fed to a SS header. Turbine generators use SS to generate electricity and release MS, LS and steam condensate (SC). The

†To whom all correspondences should be addressed.

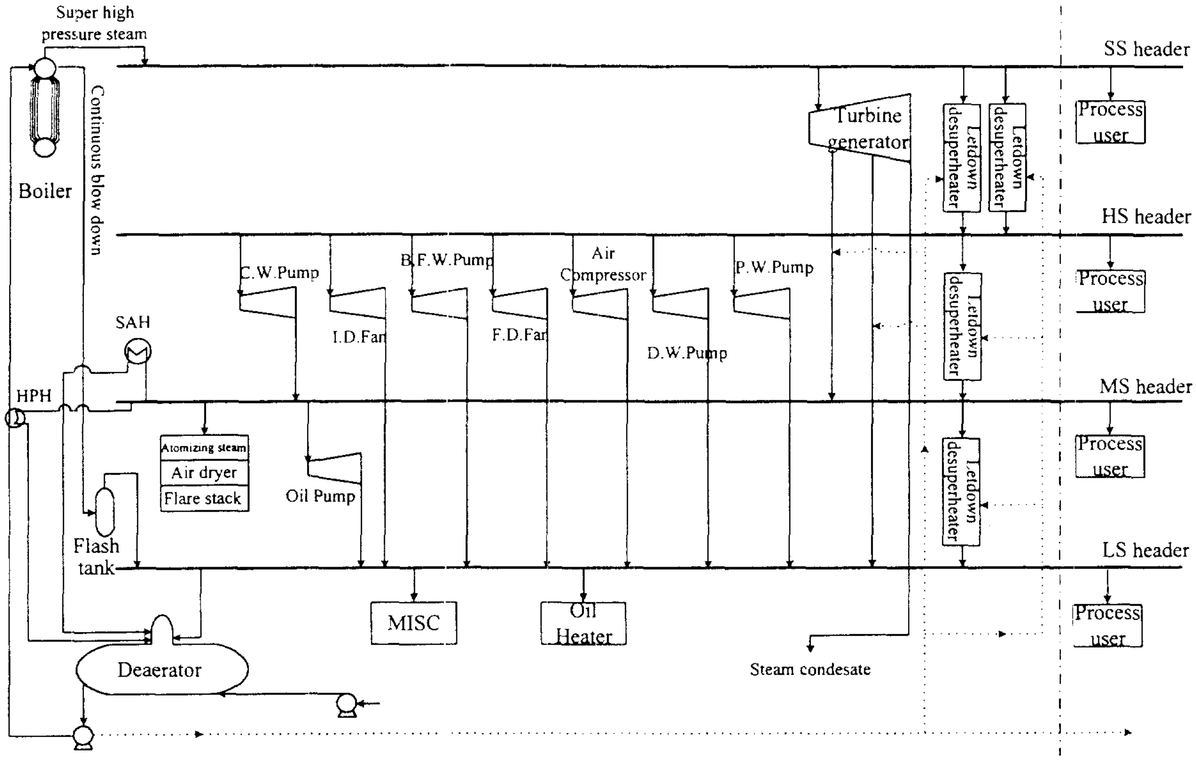

Fig. 1. Steam distribution process flow diagram.

Table 1. Temperature and pressure of each steam header

Type of steam	Temperature (K)	Pressure (bar)
Superheated high-pressure steam (SS)	798.0	118.7
High-pressure steam (HS)	663.0	41.2
Medium-pressure steam (MS)	568.0	16.7
Low-pressure steam (LS)	473.0	4.9

HS header is supplied with steam by SS/HS letdown desuperheaters. To maintain pressure and temperature of the HS header, SS is desuperheated by cooling water. The MS header is supplied with steam by HS/MS letdown desuperheaters and by release from turbine generators. MS is consumed by steam-air heater (SAH), high-pressure feed-water heater (HPH) and process units. The LS header is supplied with steam by MS/LS letdown desuperheaters, by release from turbine generators and by release from turbines connected to utility pumps.

Utility pumps are driven either by steam turbines or by electrical motors. For example, consider the simple steam distribution unit shown in Fig. 2. The boiler in the figure produces only HS which is used to drive BFW pump. LS header is supplied with steam by release from the BFW pump and by the HS/LS letdown. LS is consumed in process units. Suppose that there are three BFW pumps and that two of them are driven by steam turbines and the remaining one is driven by an electrical motor. Also suppose that one steam turbine consumes 10 ton/hr of steam and 25.5 ton/hr of steam is required in process units. If two BFW pumps are needed, there can be two operation modes as following:

mode (1): number of steam turbines=1, number of electrical motor=1, amount of steam from letdown=15.5 ton/hr.

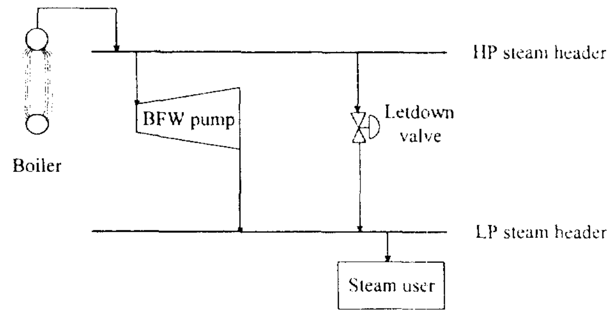

Fig. 2. A schematic of a simple steam distribution system.

mode (2): number of steam turbines=2, amount of steam from letdown=5.5 ton/hr.

Because the amount of steam from letdown is smaller in mode (2), we can say that the operation mode (2) is more effective.

In Fig. 2, the boiler blowdown rate is determined so as to maintain the specific boiler drum water characteristics. This rate is a function of the demineralized water quality, combined with the boiler steam output rate. The blowdown water is flashed in the boiler blowdown flash drum to produce LS and low pressure condensate effluent.

STEADY-STATE MODELING OF STEAM GENERATION PROCESS

The steady-state modeling of boiler is in essence heat and mass balances which make use of specified input operating parameters such as the boiler blowdown fraction, the steam loss from the deaerator and others. From the model we can estimate the amount of steam consumed in the steam-air heater, in the high-pressure feed-water heater, in the deaerator and the amount of the fuel (Bunker-C oil). Fig. 3 shows a schematic of a boiler system.

For the modeling, the boiler is regarded as consisting of three main parts: deaerator, steam generator and steam-air heater. The deaerator produces gas-free water to be used as BFW and process water in other units. The steam generator is supplied with BFW to produce SS (520°C, 118 kg/cm²). The steam generator consists of steam drum, water drum, water tubes, first superheaters and second superheaters. Bunker-C oil is used as fuel. In the steam-air heater, combustion air is preheated up to suitable temperature and fed to the gas-air heater. The preheating of air is required to avoid corrosion of the gas-air heater at low temperature when the fuel contains relatively large amount of sulfur.

1. Deaerator

Deaerator is used to separate gases from BFW. In the deaerator oxygen, hydrogen and CO_2 dissolved in the water is removed by introducing steam (259°C, 4 kg/cm²) into BFW. The gas-free water produced by the deaerator is fed into the steam generator, letdown units, turbine generator and process units. Fig. 4 shows a schematic of the deaerator. Simple mass balance on the deaerator gives

$$F_{BFW} + F_{PLT} = F_{WTR} + F_{SAH} + F_{DEA} + F_{HPH} \tag{1}$$

The water from the deaerator with temperature of 132.9°C and

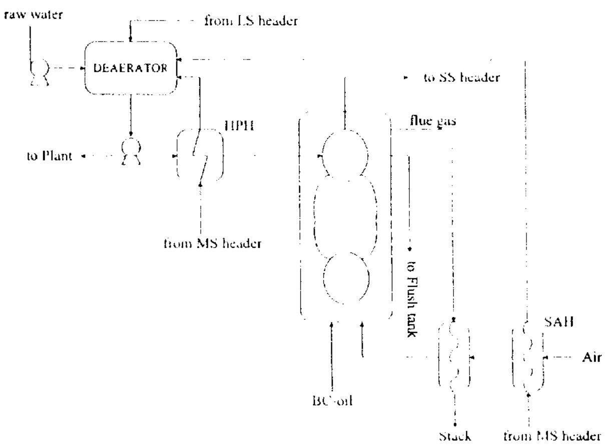

Fig. 3. A schematic of boiler system.

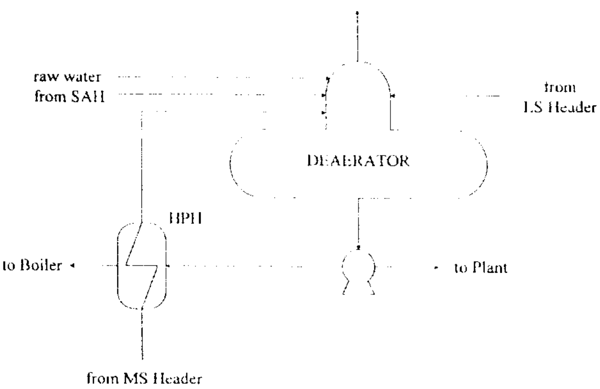

Fig. 4. Flow diagram of deaerator.

pressure of 2 kg/cm² is introduced into the high-pressure feed-water heater (HPH) via the high-pressure water-feed pump. The water in the HPH at 135.8°C and 140 kg/cm² is heated up to 195°C and 130.4 kg/cm² by MS and fed into the boiler. The MS consumed in the HPH condensates and is introduced into the deaerator.

Enthalpy balances around the deaerator and HPH give

$$(F_{BFW} + F_{PLT})H_{DEA} = F_{WTR}H_{WTR} + F_{HPH}H^{l}_{MS} + F_{DEA}H_{LS} + F_{SAH}H^{l}_{MS} \tag{2}$$

$$F_{BFW}(H^{l}_{HPH,o} - H^{l}_{HPH,i}) = F_{HPH}(H_{MS} - H^{l}_{MS}) \tag{3}$$

2. Steam Generator

The amount of the energy required in the feed water is equal to the difference between the enthalpy of the SS and blow-down water from boiler and that of the feed water. The blow-down rate is assumed to be 1% of the SS produced.

From mass balances on the steam generator we have

$$F_{CBD} = 0.01F_{SS} \tag{4}$$

$$F_{BFW} = F_{SS} + F_{CBD} \tag{5}$$

Substitution of (4) into (5) gives after some rearrangements

$$\Delta H = (H_{SS} + 0.01H_{CBD} - 1.01H_{BFW})F_{SS} \tag{6}$$

3. Steam-air Heater

In the steam-air heater the combustion air (15°C) is heated to 80°C and fed into the air heater (gas type). From enthalpy balance we have

$$F_{SAH}(H_{MS} - H^{l}_{MS}) = F_{Air}(H_{Air,o} - H_{Air,i}) \tag{7}$$

where

$$F_{Air,o}H_{Air,o} = (Cp^{80}_{O2}F_{O2} + Cp^{80}_{N2}F_{N2})\Delta T_o$$
$$F_{Air,i}H_{Air,i} = (Cp^{15}_{O2}F_{O2} + Cp^{15}_{N2}F_{N2})\Delta T_i$$

Substitution of above relations into (7) gives

$$F_{SAH}(H_{MS} - H^{l}_{MS}) = (Cp^{80}_{O2}F_{O2} + Cp^{80}_{N2}F_{N2})\Delta T_o - (Cp^{15}_{O2}F_{O2} + Cp^{15}_{N2}F_{N2})\Delta T_i \tag{8}$$

Typical value of the air temperature is 15°C at the inlet and 80°C at the outlet. The MS used in the steam-air heater is condensated and returns to the deaerator. Bunker-C oil is used as the fuel and the flow rate of the combustion air is determined by the flow rate of Bunker-C oil. The composition of Bunker-C oil is shown in Table 2.

By assuming x% excess air in the combustion, we can represent the flow rates of the combustion air and stack gas in terms of the flow rate of fuel as following:

$$F_{O2,i} = 3.1875(x+1)F_{BC}$$
$$F_{N2,i} = 10.6112(x+1)F_{BC}$$
$$F_{CO2} = 3.0744\,F_{BC}$$
$$F_{H2O} = 1.0281\,F_{BC}$$
$$F_{N2} = (10.6112\,x + 10.6162)F_{BC}$$
$$F_{SO2} = 0.08\,F_{BC}$$
$$F_{O2} = 3.1875 \times F_{BC}$$

Table 2. Composition of bunker-C oil

Comp.	Wt%	Heat of combustion Kcal/kg (Gross)	kg/kg combustible					
			Required for combustion			Flue products		
			O_2	N_2	Air	CO_2	H_2O	N_2
C	84.0	7828.24	2.66	8.86	11.53	3.66		8.86
H_2	11.5	33898.28	7.94	26.41	34.34		8.94	26.41
S	4.0	2212.44	1.0	3.29	4.29	so 2.00		3.29
N_2	0.5							
Bunker-C	100.0	10562.52	3.1875	10.6112	13.7987	3.0744/0.08	1.0281	10.6112

$$F_{Comb}=F_{CO_2}+F_{H_2O}+F_{N_2}+F_{SO_2}+F_{O_2}$$

From these relations we obtain

$$F_{SAH}=A'(x+1)F_{BC} \tag{9}$$

where

$$A'=\{3.1875(80Cp_{O_2}^{80}-15\,Cp_{O_2}^{15}) + 10.6112(80Cp_{N_2}^{80}-15Cp_{N_2}^{15})\}/(H_{MS}-H_{MS}^{l})$$

If we regard the boiler and the gas-type air heater as a single unit, the energy required for the BFW to be SS and blowdown water should be supplied from the Bunker-C oil and combustion air. Thus we can write

$$\Delta H+F_{Comb}H_{Comb,g}=F_{BC}H_{BC}+F_{Air}H_{Air}$$

where

$$F_{Comb}H_{Comb,g}=(Cp_{CO_2}F_{CO_2}+Cp_{H_2O}F_{H_2O}+Cp_{N_2}F_{N_2} +Cp_{SO_2}F_{SO_2}+Cp_{O_2}F_{O_2})\Delta T$$

$$F_{Air}H_{Air}=(Cp_{O_2}^{80}F_{O_2,i}+Cp_{N_2}^{80}F_{N_2,i})\Delta T$$

From these relations we have

$$\Delta H+(Cp_{CO_2}F_{CO_2}+Cp_{H_2O}F_{H_2O}+Cp_{N_2}F_{N_2}+Cp_{SO_2}F_{SO_2} +Cp_{O_2}F_{O_2})\Delta T=F_{BC}H_{BC}+(Cp_{O_2}^{80}F_{O_2,i}+Cp_{N_2}^{80}F_{N_2,i})\Delta T \tag{18}$$

The heat capacity of each gas component is given by

$$Cp=A+BT+CT^2+DT^3 \quad [J/mol\ K]$$

where values of A, B, C and D are given in Table 3.

Rearrangement of (18) by using the heat capacity relations gives

$$(F_{BC}H_{BC}-\Delta H)/T_S=(B'+C'x)F_{BC}$$

where

$$B'=3.0744a+1.0281b+10.6162c+0.08d-3.1875f-10.6112g$$
$$C'=10.6112c+3.1875e-3.1875f-10.6112g$$

Introducing (6) we have from the above equation

$$(F_{BC}H_{BC}-D'F_{SS})/T_S=(B'+C'x)F_{BC} \tag{19}$$

where

$$D'=H_{SS}+0.01H_{BC}-1.01H_{BFW}$$

From the actual operation data the following relation can be drawn out:

$$F_{BC}H_{BC}+(1+x)F_{Air}H_{Air}\propto$$

Table 3. Parameters of heat capacity of combustion gases

Component	O_2	CO_2	H_2O	N_2	SO_2
A	28.11	19.8	32.24	31.15	23.85
B	3.680e-2	7.344e-2	1.924e-3	1.357e-5	6.699e-2
C	1.746e-5	5.602e-5	1.055e-5	2.680e-5	4.961e-5
D	1.065e-8	1.715e-8	3.596e-9	1.168e-8	1.328e-8

$$F_{SS}H_{SS}+F_{CBD}H_{CBD}+F_{Comb}C_Pt_S \tag{20}$$

From the fact that H_{Air} is relatively constant, the flow rate of the combustion air is proportional to the flow rate of Bunker-C oil:

$$(1+x)F_{Air}H_{Air}\propto(a+bx)F_{BC}$$

Therefore we have

$$(a+bx+H_{BC})F_{BC}\propto F_{SS}H_{SS}+F_{CBD}H_{CBD}+F_{Comb}C_Pt_S$$

In the actual operation the amount of blowdown water is kept nearly constant. The flow rate of the stack gas can be represented in terms of the flow rate of Bunker-C oil.

$$F_{CBD}H_{CBD}=\alpha(\alpha=\text{constant})$$
$$(a+bx+H_{BC})F_{BC}\propto F_{SS}H_{SS}+c+(d+eF_{BC})t_S$$

Considering the efficiency of the boiler we finally have

$$F_{BC}=I+JF_{SS}+(K+LF_{BC})t_S \tag{21}$$

From Eq. (20) and (21) the flow rate of Bunker-C oil required in the production of given amount of SS can easily be computed.

RESULTS OF SIMULATION

Fig. 5 shows a flow diagram of boiler simulation. The mass flow rate of Bunker-C oil is assumed first and enthalpy of outlet (Out_H) from the boiler is computed. The computed value of stack gas temperature is compared with measured value and the mass flow rate of deaerator is obtained finally.

The amount of Bunker-C oil to be supplied to produce SS fed is plotted in Fig. 6 as a function of SS to be produced. During the combustion process in the boiler 15% of excess air is maintained.

Fig. 7 shows the boiler efficiency as a function of SS generated. The boiler efficiency is given by

$$\text{eff}=\frac{F_{SS}H_{SS}+F_{CBD}H_{CBD}-F_{BFW}H_{BFW}}{F_{BC}H_{BC}}=\frac{\Delta H}{F_{BC}H_{BC}} \tag{22}$$

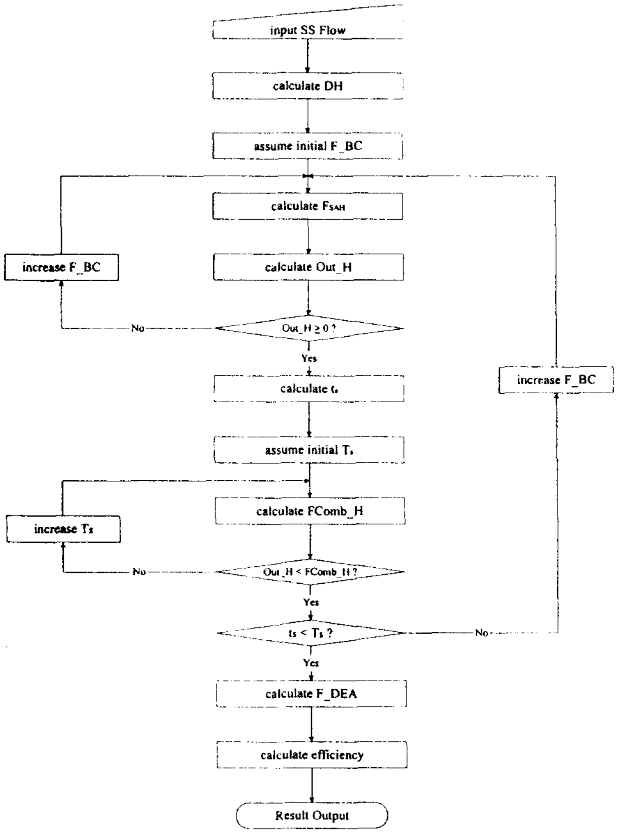

Fig. 5. Procedure of boiler simulation.

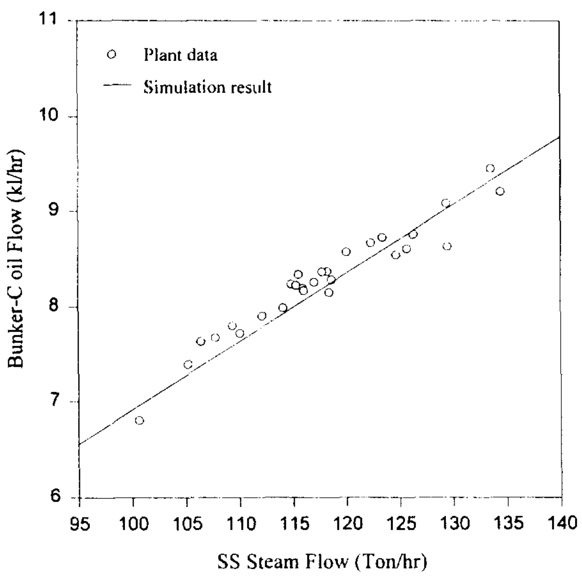

Fig. 6. Bunker-C oil flow (kl/hr).

As can be seen, the computed efficiency is about 88%. Fig. 8 shows the consumption rate of MS to preheat combustion air as a function of SS produced. The temperature at the inlet of steam air heater is 15°C and that at the outlet is 80°C. The consumption rate shows linear relationship as expected.

MS is used to maintain the temperature and pressure of boiler feed water as desired levels and Fig. 9 shows the amount of

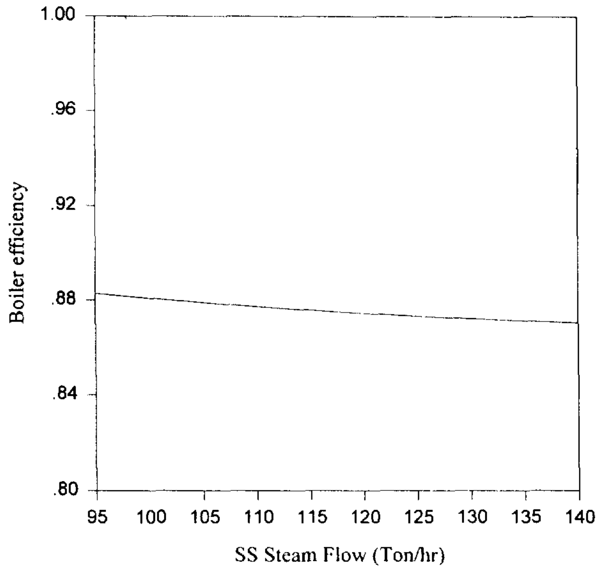

Fig. 7. Boiler efficiency.

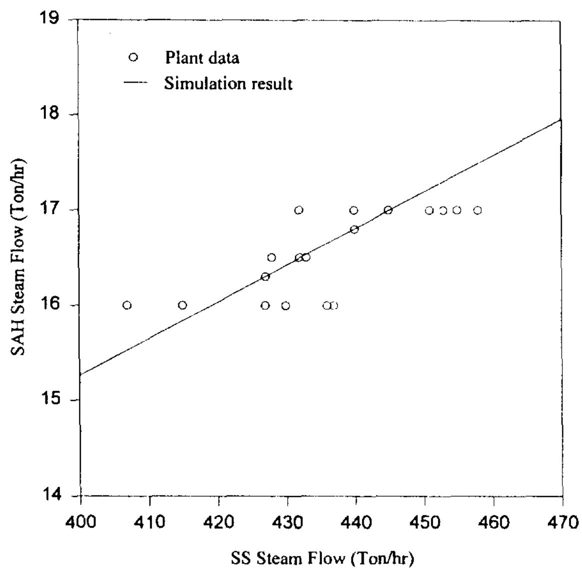

Fig. 8. SAH steam flow (Ton/hr).

MS consumed for this purpose. The boiler feed water extracted from deaerator is fed into the boiler via high-pressure heater (HPH). In order to remove gases solved in boiler feed water LS is mixed directly with feed water in the deaerator. The consumption rate of LS in the deaerator is shown in Fig. 10 as a function of SS generated.

MODELING AND SIMULATION OF STEAM DISTRIBUTION NETWORK

1. Modeling of Steam Distribution Network

In the steam distribution system of Daelim petrochemical plant shown in Fig. 1, there are four letdown units. As the amount of letdown increases, the loss of available energy increases and the overall energy efficiency of the plant decreases. In order to decrease letdown and to avoid unnecessary vent,

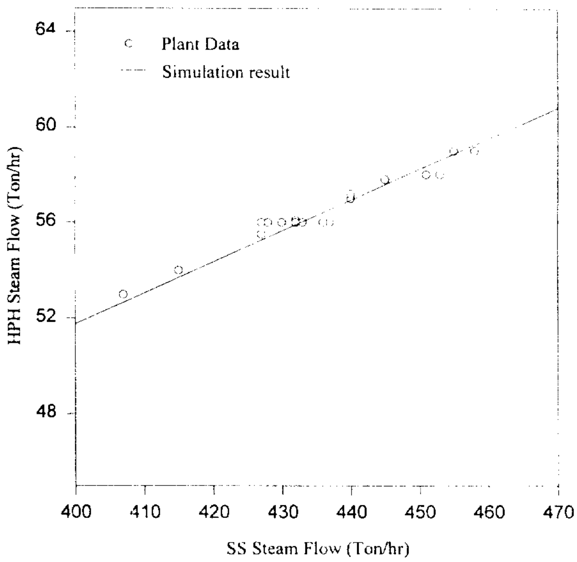

Fig. 9. HPH steam flow (Ton/hr).

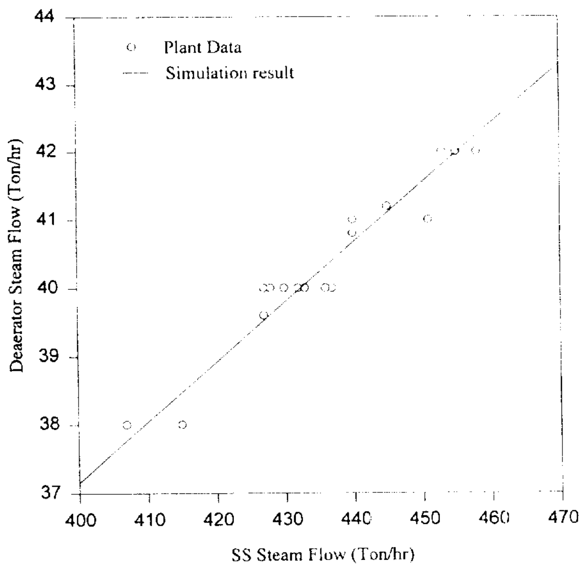

Fig. 10. Deaerator steam flow (Ton/hr).

precise adjustment of the amount of extraction through the steam turbine generator is imperative.

The steam turbine generator is driven by SS to generate electrical power. From the steam turbine generator MS, LS and steam condensate are released. From simple mass balance we have

$$m_{SS} = 0.658 * m_{MS} + 0.466 * m_{LS} + 2.667 * E + 24.0$$
$$m_{SS} = m_{MS} + m_{LS} + m_{SC}$$

Mass balances on each steam header give

$$m_{FT} + m_{OPump} + m_{Fan} + m_{BFWPump} + m_{FDFan} + m_{AC} + m_{DWPump} + m_{PWPump} + m_{LS}' + m_8 = m_{DEA} + m_{MISC} + m_{OH} + m_{LSUser}$$
$$m_{CWPump} + m_{MS}' + m_6 = m_{SAH} + m_{HPH} + m_{AS} + m_{AD} + m_{FS} + m_{OPump} + m_7 + m_{MSUser}$$
$$m_3 + m_4 = m_{CWPump} + m_{Fan} + m_{BFWPump} + m_{FDFan} + m_{AC} + m_{DWPump} + m_{PWPump} + m_5 + m_{HSUser}$$
$$m_{gen} = m_{SS} + m_1 + m_2 + m_{SSUser}$$

In the steam distribution system there are several desuperheaters through which water is introduced to keep temperature and pressure of each header constant. Mass and energy balances around letdown desuperheater gives

$$m_1 + m_{w1} = m_3$$
$$m_2 + m_{w2} = m_4$$
$$m_5 + m_{w5} = m_6$$
$$m_7 + m_{w7} = m_8$$
$$m_1H_1 + m_{w1}H_{w1} = m_3H_3$$
$$m_2H_2 + m_{w2}H_{w2} = m_4H_4$$
$$m_5H_5 + m_{w5}H_{w5} = m_6H_6$$
$$m_7H_7 + m_{w7}H_{w7} = m_8H_8$$

Because temperature and pressure of each steam header is kept constant, above relations can easily be solved to give

$$m_1 = 0.9167 * m_3,\ m_2 = 0.9167 * m_4,\ m_5 = 0.9359 * m_6,$$
$$m_7 = 0.9398 * m_8$$

The steam extracted from the steam turbine generator is fed to the desuperheater to adjust temperature and pressure of each header. Again mass and energy balances give

$$m_{MS} + m_{w3} = m_{MS}'$$
$$m_{LS} + m_{w4} = m_{LS}'$$
$$m_{MS}H_{MS} + m_{w3}H_{w3} = m_{MS}'H_{MS}'$$
$$m_{LS}H_{LS} + m_{w4}H_{w4} = m_{LS}'H_{LS}'$$

Solving these equations we have

$$m_{LS} = \left(\frac{H_{LS}' - H_{w4}}{H_{LS} - H_{w4}}\right) * m_{LS}' \tag{23}$$

$$m_{w3} = \left(\frac{H_{MS}' - H_{MS}}{H_{w3} - H_{MS}'}\right) * m_{MS}' \tag{24}$$

Some chemicals such as ammonia and hydrazin (N_2H_4) are used to remove air in the boiler feed-water. But these chemicals can cause the change of pH value which in turn results in damages to process units. Therefore the boiler should be operated within permissible range of water quality. To maintain the permissible range of water quality saturated water is continuously withdrawn from the boiler drum. The so-called continuous blowdown rate reaches up to 1% of SS produced and can be approximated by the relation

$$m_{FT} = \frac{1}{3} m_{cbd} \tag{25}$$

2. Optimization Strategy

The amount of steam required in each process unit depends on the production rate of products at each process unit. Daelim petrochemical plant in Yochon produces various petrochemical products and computation of the amount of steam required in the whole plant is a very intricate problem. In the present study the mean operation data were used.

Steam is also consumed in the boiler itself, which we call 'self steam consumption'. Especially steam is consumed in the high-pressure feed-water heater, in the steam-air heater, in the deaerator and in the oil heater. In order to minimize the amount of letdown from MS header to LS header, we have to solve a minimization problem given by (26).

$$\max.\ [\mathbf{A}^T\mathbf{B}+\mathbf{C}^T\mathbf{D}] \tag{26}$$

$$\text{Subject to} \begin{bmatrix} \mathbf{A}^T\mathbf{B}+\mathbf{C}^T\mathbf{D}\le \mathrm{W} \\ \mathrm{A}_i=0,1,2,3\cdots\cdots \\ \mathrm{C}_i=0,1,2,3\cdots\cdots \end{bmatrix} \tag{27}$$

A is a vector whose elements are the number of steam turbine which is operated and their elements must be integer. **B** is a vector whose elements are steam consumption of steam consumption of steam turbine to drive a pump. $\mathbf{A}^T\mathbf{B}$ means the net amount of steam consumed by steam turbines. **C** is a vector whose elements are the number of steam turbine which is not operated. **D** is a vector whose elements are steam consumed to warm up the steam turbine. The number of steam turbine which is operated and is not operated must be calculated.

As stated before, MS is released from the cooling water pump and extracted from the steam turbine generator. There are four cooling water pumps in Daelim plant. But because of high capacity of each of cooling water pump it is almost impossible to reduce or increase the amount of letdown of MS header. So the letdown amount from the desuperheater is computed first and the result is compared with the preassigned maximum value. If the computed value is greater than the maximum value, we can increase the number of pumps driven by steam turbine or adjust MS extraction to decrease the amount of letdown.

3. Results of Simulation

The model equations were solved by using Newton's iteration method. The computational procedure is shown in Fig. 11. In simulations the amount of steam consumption at each process unit should be known in advance in addition to the amount of exhausted steam from turbine generators. Three typical cases considered in the simulation are listed in Table 4. For each one of the three cases the amount of letdown steam and SS produced in the boiler were computed and compared with actual operation data. Results are summarized in Table 5.

From the results we can reduce the letdown amount from headers and enhance the overall energy efficiency of the steam distribution system. We can also decrease the operational cost of utility plant by reducing the SS generation. The operational cost of utility plant is composed of the cost of bunker-C oil and industrial water. Therefore the operational cost of utility unit is given by

$$\begin{aligned} \text{operational cost}= &\{\text{cost of bunker-C oil}\} \\ &*\{\text{bunker-C fuel to generate steam}\} \\ &+\{\text{cost of industrial water}\}*\{\text{BFW to generate steam}\} \\ =&15245.81 m_{gen}+40508.75 \end{aligned} \tag{28}$$

By using Eq. (28) we can compare the actual operational cost with the cost obtained from simulation and the result is represented in Table 6. From the results we can see that the operational cost is reduced about 2-5%.

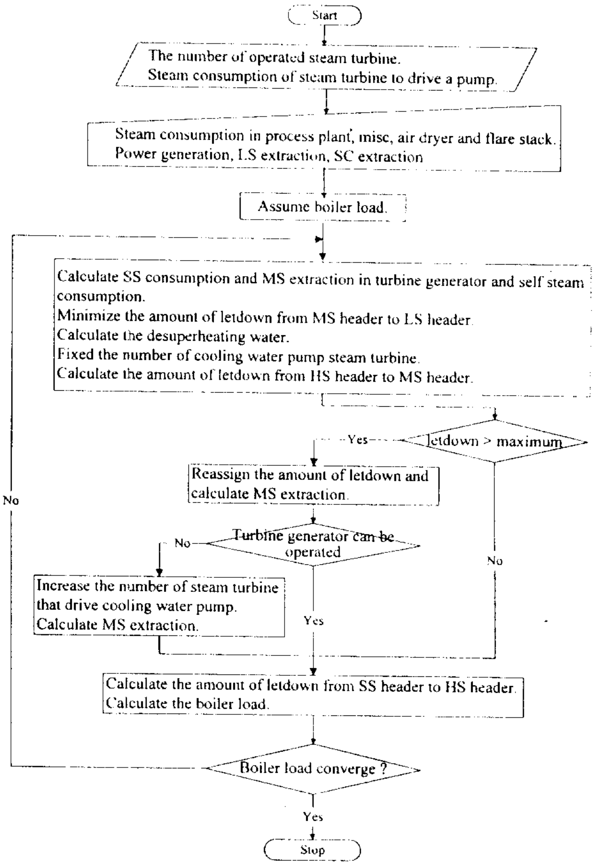

Fig. 11. Computational procedure of steam distribution system.

Table 4. Three typical operation cases

Items	Case I	Case II	Case III
SS consumption in process units	170.0 (ton/h)	175.0 (ton/h)	175.0 (ton/h)
HS consumption in process units	-104.7 (ton/h)	-130.0 (ton/h)	-32.0 (ton/h)
MS consumption in process units	167.3 (ton/h)	201.6 (ton/h)	221.8 (ton/h)
LS consumption in process units	51.8 (ton/h)	74.2 (ton/h)	75.9 (ton/h)
Steam consumption at air dryer	0.3 (ton/h)	0.3 (ton/h)	0.3 (ton/h)
Steam consumption at flare stack	1.0 (ton/h)	1.0 (ton/h)	1.0 (ton/h)
Steam consumption at MISC	4.0 (ton/h)	4.0 (ton/h)	0.0 (ton/h)
Electricity produced at turbine generator	24.5 MW	25.5 MW	25.5 MW
LS amount at turbine generator	12.0 (ton/h)	20.0 (ton/h)	26.0 (ton/h)
SC extraction at turbine generator	41.0 (ton/h)	28.0 (ton/h)	28.0 (ton/h)

CONCLUSIONS

Steady-state modeling and simulation of steam generation

Table 5. Results of simulation based on raw operation data

Amount of steam (ton/hr)	Case I		Case II		Case III	
	Data	Simulation	Data	Simulation	Data	Simulation
Letdown from SS header	56	54.9	53	53.9	88	86.3
Letdown from HS header	12	1.52	30	7.48	16	4.6
Letdown from MS header	7	2.41	10	4.76	10	2.39
SS produced at the boiler	440.	423.3	453.	443.75	505	479.7

Table 6. Comparison of operational cost

unit(thousand ₩/hr)

	Case I		Case II		Case III	
	Data	Simulation	Data	Simulation	Data	Simulation
The operational cost	6748.7	6494.1	6946.9	6805.9	7739.6	7353.9

process and plant-wide steam distribution network were performed to minimize the net cost of providing energy to the plant. Heuristic operational knowledges and actual plant operation data were incorporated in the modeling of steam distribution network. Newton's iteration method and a simple linear programming algorithm were employed in the simulation. The letdown amount from superheated high-pressure steam (SS) header and the amount of SS produced at the boiler showed good agreement with those of actual operational data. The boiler efficiency is given by a function of SS and was about 88%. Three typical operation cases were considered in the simulation. For each one of three cases the amount of letdown steam and SS produced in the boiler were computed and compared with actual operation data.

NOMENCLATURE

A' : a value defined in Eq. (9)
A, B, C, D : Cp constants defined in Table 3
A : number of turbines being operated
B : steam consumption of steam turbine to drive a pump [ton/h]
C : number of turbines not being operated
D : steam consumption of steam turbine to warm up [ton/h]
E : power generation [MW]
F : mass flow rate [kg/hr]
H : enthalpy [kcal/kg]
m : steam flow [ton/h]
m' : steam flow that is desuperheated [ton/h]
m_w : water flow to desuperheat steam [ton/h]
t_s : real stack gas temperature [K]
T_s : simulated stack gas temperature [K]
W : constant determined from mass balance and minimum steam flow rate of letdown desuperheater [ton/h]
x : the rate of excess air (%)
a, b, c, d, e, f, g, I, J, K, L : constant

Subscripts

AC : air compressor
AD : air dryer
Air : combustion air
BC : Bunker-C oil
BFW : boiler feed water
BFWPump : boiler feed water pump
cbd : continuous blow down
CBD : continuous blow down water
Comb : combustion
CWPump : cooling water pump
DEA : deaerator
DWPump : demineralized water pump
Fan : fan
FDFan : forced-draft fan
FS : flare stack
FT : flash tank output steam
gen : generation
HPH : high pressure feed water heater
HS : high-pressure steam
HSUser : process units that consume high-pressure steam
LS : low-pressure steam
LSUser : process plants that consume LS
MISC : miscellany
MS : medium-pressure steam
MSUser : process units that consume medium-pressure steam
OH : oil heater
OPump : oil pump
PLT : plant feed water
PWPump : polished water pump
SAH : steam air heater
SC : SC extraction from turbine generator
SS : super-heated high-pressure steam
SSUser : process plants that consume SS
WTR : raw water
l : condensated steam
i : inlet
o : outlet
1, 2, 3, 4, 5, 6, 7, 8 : steam letdown

REFERENCES

Clark, J. K. and Helmick, N. E., "How to Optimize the Design of Steam Systems", *Chemical Engineering,* March, 116 (1980).

Gordon, E. and Hashemi, M. H., "A Versatile Steam Balance Program", *Chemical Eng. Progress,* July, 51 (1978).

Maia, L. O. A., Vidal de Carvalho, L. A. and Qassim, R. Y., "Synthesis of Utility Systems by Simulated Annealing", *Computers Chem. Engng.*, **19**, 481 (1995).

Nishio, M., Itoh, J., Shiroko, K. and Umeda, T., "A Thermodynamic Approach to Steam-Power System Design", *Ind. Eng. Chem. Process Des. Dev.*, **19**, 306 (1980).

Nishio, M., Koshijima, I., Shiroko, K. and Umeda, T., "Synthesis of Optimal Heat and Power Supply Systems for Energy Conversation", *Ind. Eng. Chem. Process Des. Dev.*, **24**, 19 (1985).

Nishio, M., Shiroko, K. and Umeda, T., "Optimal Use of Steam and Power in Chemical Plants", *Ind. Eng. Chem. Process Des. Dev.*, **21**, 640 (1982).

Petroulas, T. and Reklaitis, G. V., "Computer-Aided Synthesis and Design of Plant Utility Systems", *AIChE J.*, **30**, 69 (1984).