Plant-wide Optimal Byproduct Gas Distribution and Holder Level Control in the Iron and Steel Making Process

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Abstract−A new plant-wide multiperiod optimization approach is proposed for optimal byproduct gas distribution to prevent unfavorable byproduct gas emission and equipment trip and simultaneously to maximize the efficiency of energy resource usage in the iron and steel making process. Compared with the previous approach, the proposed approach finds the optimal trade off among conflicting objectives such as holder level control, minimization of oil consumption and number of burner switching, and the maximization of generating electricity. To consider the different fuel load change operation according to the fuel types, both integer and continuous variables are used. Case studies were performed to verify the usefulness of the proposed approach, and the results show good performance in terms of the reduced number of burner switching which leads to the reduction of total cost and producing operation-easy solutions.

Key words: Plant-wide Optimization, Byproduct Gas, Holder Level Control, Optimal Distribution, Iron and Steel Making Process

INTRODUCTION

Energy cost constitutes about 20% of the total operation cost in the iron and steel making process. Thus efficient use of energy is very important. In the iron and steel making process, several types of energy sources such as byproduct gases, oil, electricity, and LNG (Liquefied Natural Gas) are used. The byproduct gases are generated as byproducts, and are used as important energy sources without paying additional cost to purchase.

However, there exist unbalances between the amount of the generation and consumption of the byproduct gases at time scale, and byproduct gas holders serve as a buffer unit to solve temporal unbalances between the generation and consumption of byproduct gases. Because of the limit on holder capacity, temporal excess or shortages of byproduct gas happen. As shown in Fig. 1, the excess or shortage of byproduct gases can be adjusted by changing the supply of byproduct gases from gas holders to power plant, where byproduct gases are used to generate process steam and electricity. In the power plant, each boiler has different efficiencies. Therefore, the optimal operation that can prevent, or at least minimize, the loss of byproduct gases and efficient use of byproduct gases is very important and indispensable in the iron and steel making process.

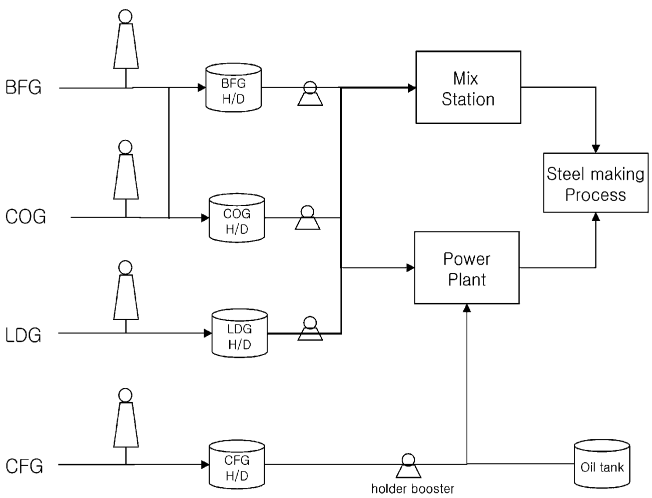

Fig. 1. Simplified byproduct gas flow in the iron and steel making process.

Although much research has been done on the optimization of iron and steel making processes, it is mainly on scheduling and production planning problems, and little is reported on the optimization of the byproduct gas supply and distribution.

Akimoto et al. [1991] proposed an MILP (Mixed Integer Linear Programming) model for optimal byproduct gas supply in the iron and steel making process. The optimization model reflects process constraints by assigning appropriate penalty functions for the situation that is not preferred such as excess or shortage of byproduct gases, oil usage, fluctuation of gas amount in the holder, simultaneous changeover of fuels etc. In this model, total amount of fuel load change is determined by optimization model, but the distribution of fuels to each boiler is not calculated because no consideration was given to the efficiencies of boilers and demands for steam and electricity. Fukuda et al. [1986] proposed an optimal energy distribution control method for the steel works by energy demand forecasting and optimization. ARMAX (Auto Regressive Moving Average with Exogenous variable) model was used for forecasting, and gradient descent method was used for optimization. Bemporad and Morari [1999] proposed a framework for modeling and controlling the mixed logical dynamical systems, and applied it to the gas sup-

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ply system at the steel works. Sinha et al. [1995] used MILP to optimally allocate the resource for profit maximization, and significant amount of benefit is reported by applying it to Tata Steel.

Consideration of the startup and shutdown cost in the optimization formulation was introduced in the optimization modeling. Hui and Natori [1996] presented a mixed integer programming model for an industrial utility system that includes startup and shutdown costs to find more exact optimum solutions by introducing equipment startup and shutdown costs. Iyer and Grossmann [1997, 1998] proposed the bilevel decomposition method to solve the multiperiod optimization problem for utility plants and considered the switching cost between periods. Kim and Han [2001] proposed a heuristics combined dynamic programming approach to solve the multiperiod planning problem for a utility plant. Yi et al. [2000] also used this concept in planning problems. Lee et al. [2001] proposed an MILP model for scheduling of non-sequential batch processes. Singh et al. [2000] proposed time horizon based real time optimization (RTO) approach for the gasoline blending process, which is similar to model predictive control (MPC). Blending horizon and stochastic model of disturbances were incorporated into the optimization model.

In this paper, an improved model is proposed for solving optimal byproduct gas distribution in the iron and steel making process where discrete fuel load changes, penalty for startup and shutdown of the burner. Compared with the previous approach, this research simultaneously optimizes the holder levels that are inter-correlated and byproduct gas distribution of the supplied byproduct gases in terms of total cost reduction. A case study was performed to verify the usefulness of the proposed approach.

PROCESS DESCRIPTION

As shown in Fig. 1, several types of byproduct gases such as Blast Furnace Gas (BFG), Coke Oven Gas (COG), Lindz-Donawitz Gas (LDG), and Corex Furnace Gas (CFG) are produced as a byproduct in the iron and steel making process. The byproduct gases are primarily supplied to the steel making process, and some are supplied to the power plant. The patterns of the generation of each byproduct gases are different. Some of byproduct gases are generated irregularly, and others with a constant generation pattern and amount. The consumption of byproduct gases at the steel making process is performed according to the production schedule, and there is little flexibility to change it.

Owing to the combination of limited capacity of byproduct gas holders and irregular generation of byproduct gases, excess or shortage of byproduct gases at holder occurs. This can result in the holder booster trip or unfavorable byproduct gas emission to air, which is an economic loss. These unbalances are compensated for by changing the supply of byproduct gases from each gas holder to the power plant by changing the rate of byproduct gas consumptions at each boiler. Byproduct gases supplied to boilers at the power plant generate steam to be used for generating electricity and process steams. Oil is used when the byproduct gases are insufficient to supply for generating the required amount of electricity, but it is not preferable because additional fuel cost is required.

Each boiler in the power plant has different characteristics in capacities, efficiencies, and available fuel types. Therefore, an optimal allocation of byproduct gases considering the different condition of each boiler is required to maximize the efficiency of byproduct gas usage. The stable operation of the boiler to avoid backfires or incomplete combustion from unstable operation is also important. For the stable operation of the boiler, frequent switching of the burner such as turn-on or turn-off is not favorable. Optimum operation in terms of byproduct gas supply system as a whole requires the following conditions.

1. The Holder level of each byproduct gas should be kept within the operation range to avoid unfavorable byproduct gas emission and holder booster trip.
2. Minimum number of startup/shutdown of a boiler is desired.
3. Minimum amount of oil consumption is preferred.
4. Minimum fluctuation of holder level is preferred.
5. Efficient use of a boiler to produce more electricity considering efficiencies of boilers and turbines is required.
6. The supply of total energy to each boiler to generate electricity should be larger than the required amount of electricity demand to avoid paying high penalty to a power company.

The optimization model resulting from considering various objectives becomes a multi-objective programming model. Tradeoff among conflicting objectives exists and the optimal tradeoff should be found for the total cost minimization. For example, to reduce the holder level deviation from the normal operation level, a large number of fuel load change is required, but this is not preferable in terms of boiler operation.

Fig. 2 shows the holder level control by optimal fuel load change during the planning horizon. For the system where G types of byproduct gas holders exist, fuel load change for each burner during the planning horizon is determined to minimize the total cost.

MATHEMATICAL FORMULATION FOR OPTIMAL BYPRODUCT GAS DISTRIBUTION

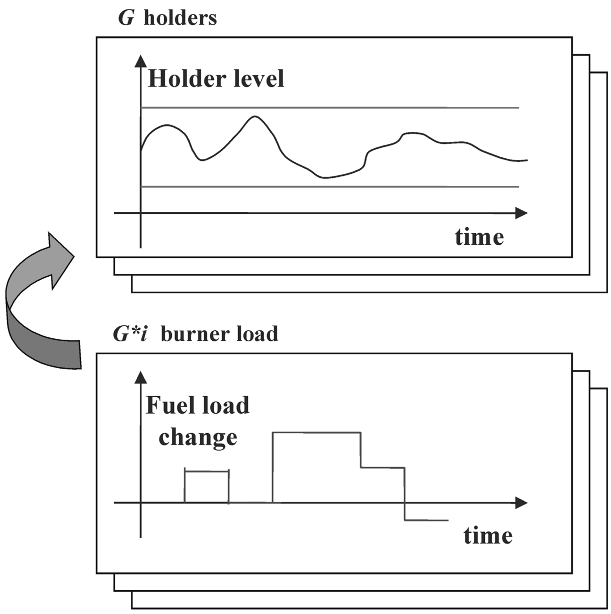

Fig. 2. Holder level control by optimal fuel load change.

Objective Function

$$= \min_{N^G_{i,t}, F^{Oil}_{i,t}} \Bigg\{ C^{Oil}\sum_{t=1}^{P}\sum_{i=1}^{NB} F^{Oil}_{i,t} + \sum_{t=1}^{P}\sum_{G} w^G_{HH} S^G_{HH,t} + \sum_{t=1}^{P}\sum_{G} w^G_{LL} S^G_{LL,t} + \sum_{t=1}^{P}\sum_{G} w^G_{H} S^G_{H,t}$$
$$+ \sum_{t=1}^{P}\sum_{G} w^G_{L} S^G_{L,t} + \sum_{t=1}^{P}\sum_{G} w^G_{d+} S^G_{d+,t} + \sum_{t=1}^{P}\sum_{G} w^G_{d-} S^G_{d-,t} + \sum_{t=1}^{P}\sum_{i=1}^{NB}\sum_{G} w^G_{SW}\Delta N^G_{i,t}$$
$$+ \sum_{t=1}^{P}\sum_{i=1}^{NB}\sum_{G}[w^{2s}(j^{G+}_{2,i,t} + k^{G-}_{2,i,t}) + w^{3s}(j^{G+}_{3,i,t} + k^{G-}_{3,i,t})] - \sum_{t=1}^{P} C^{elec}(PG_t - PD_t) \Bigg\} \tag{1}$$

Constraints

$$F^G_t = \sum_i F^G_{i,t} \quad \text{for } \forall G, t \tag{2}$$

$$\sum_G F^G H^G_{i,t} + F^{Oil}_{i,t} H^{Oil} \geq Q^B_{i,t} \quad \text{for } \forall i, t \tag{3}$$

$$h^G_{min} - h^G_{tr,t} \leq h^G_t \leq h^G_{max} + h^G_{e,t} \quad \text{for } \forall G, t \tag{4}$$

$$h^G_t = h^G_{t-1} + \left\{ G_{t-1} - C_{t-1} - \sum_i F^G_{i,t-t_d} \right\} * \Delta t \tag{5}$$

$$F^S_{i,t}(H^{steam}_{out,i,t} - H^{steam}_{in,i,t}) = \left(\sum_G Cp^G F^G_{i,t} + Cp^{Oil} F^{Oil}_{i,t} \right) \eta_{i,t} \quad \text{for } \forall i, t \tag{6}$$

$$h^G_t - h^G_{max} = S^G_{HH,t} - S^G_{HH-,t} \quad \text{for } \forall t$$
$$S^G_{HH,t}, SG^G_{HH-,t} \geq 0 \quad \text{for } \forall G, t \tag{7}$$

$$h^G_t - h^G_H = S^G_{H,t} - S^G_{H-,t} \quad \text{for } \forall t$$
$$S^G_{H,t}, SG^G_{H-,t} \geq 0 \quad \text{for } \forall G, t \tag{8}$$

$$h^G_{min} - h^G_t = S^G_{LL,t} - S^G_{LL-,t} \quad \text{for } \forall t$$
$$S^G_{LL,t}, SG^G_{LL-,t} \geq 0 \quad \text{for } \forall G, t \tag{9}$$

$$h^G_L - h^G_t = S^G_{L,t} - S^G_{L-,t} \quad \text{for } \forall t$$
$$S^G_{L,t}, SG^G_{L-,t} \geq 0 \quad \text{for } \forall G, t \tag{10}$$

$$h^G_t - h^G_N = d^{G+}_t - d^{G-}_t \quad \text{for } \forall t \; d^{G+}_t, d^{G-}_t \geq 0 \tag{11}$$

$$N^G_{i,t} = N^G_{i,t-1} + N^{G+}_{i,t} - N^{G-}_{i,t} \quad \text{for } \forall G, t \tag{12}$$

$$N^{G+}_{i,t} = j^{G+}_{1,i,t} + j^{G+}_{2,i,t} + j^{G+}_{3,i,t} \quad \text{for } \forall G, t \tag{13}$$

$$j^{G+}_{1,i,t} \geq j^{G+}_{2,i,t} \geq j^{G+}_{3,i,t} \quad \text{for } \forall i, t \tag{14}$$

$$N^{G-}_{i,t} = k^{G-}_{1,i,t} + k^{G-}_{2,i,t} + k^{G-}_{3,i,t} \quad \text{for } \forall G, t \tag{15}$$

$$k^{G-}_{1,i,t} \geq k^{G-}_{2,i,t} \geq k^{G-}_{3,i,t} \quad \text{for } \forall i, t \tag{16}$$

$$N^G_{i,t} - N^G_{i,t-1} = SW^{G+}_{i,t} - SW^{G-}_{i,t} \quad \text{for } \forall G, i, t$$
$$SW^{G+}_{i,t}, SW^{G-}_{i,t}, SW^{Oil+}_{i,t}, SW^{Oil-}_{i,t} \geq 0 \quad \text{for } \forall G, i, t \tag{17}$$

$$F^G_{min} \leq F^G_{i,t} \leq F^G_{max} \quad \text{for } \forall i, t \tag{18}$$

The objective is to minimize the total cost during the planning horizon, which is composed of fuel cost, various penalty costs, and steam production benefit. Fuel cost is composed of oil consumption cost and byproduct gas consumption cost. Because byproduct gas does not require additional purchasing cost, it has zero operation cost. The penalty cost is imposed on the holder booster trip, unfavorable byproduct gas emission, frequent boiler burner on/off, simultaneous fuel load change in the same boiler, and deviations from the normal operation holder levels for each byproduct gas. The linear penalty function is used for the deviation from the normal average operation level for reduced computation time. According to the relative importance among each cost function, the weight for each cost function is differently imposed. General integer variables $N^G_{i,t}$ are used to represent the number of burners used at each boilers, and binary variables $j^{G+}_{1,i,t}$, $j^{G+}_{2,i,t}$, $j^{G+}_{3,i,t}$, $k^{G-}_{1,i,t}$, $k^{G-}_{2,i,t}$, $k^{G-}_{3,i,t}$ are used to represent the multiple burner on and off at the same boiler. Because a rather large number of fuel load changes are required to adjust the byproduct gas holder level, discrete amount of fuel load change, burner level fuel load change, is made and the use of integer var- iables reflects this operation heuristic. On the whole, fuel load change for oil is represented by continuous variables due to its continuous fuel load change. The optimal byproduct gas distribution for the planning horizon is found to minimize the total cost given holder level prediction, electricity demand prediction, and the present opera- tion data. As the operation situation changes, such as the unit fuel cost change, the relative importance among each cost function changes, and this changing information is reflected by changing weights. The relative weights among cost functions can be determined by process experts. The optimal trade among conflicting cost functions is found for the pre-determined coefficients.

Eq. (2) shows the material balance between the total amount of byproduct gases at the ith boiler and its total consumption. Eq. (3) is the constraints for supplying more energy with byproduct gases or oil than electricity demands at the *i*th boiler at period t. Eq. (4) shows the holder operation range to avoid holder booster trip or unfavorable byproduct gas emission. Eq. (5) shows the time varying byproduct gas amount relationship with generation, consumption of byproduct gases at the iron and steel making process, and flow rate entered into the power plant. Eq. (6) shows the energy balance for the steam production at *i*th boiler. Eqs. (7)-(10) show the constraints for maintaining holder level within the operation range. According to the deviation of holder level, a different penalty is imposed. For the holder level which goes over the maximum and minimum operation level, the largest penalty is imposed, and the holder level which is within the high or low operation region, a large penalty is imposed. For the deviation within the operation range a small penalty is imposed [Eq. (11)]. Slack variables are used to represent the gas emission, holder booster trip, high or low operation, and deviation. Eq. (12) shows the number of operating burners at the *i*th boiler and at time *t* using byproduct gas G. Eqs. (13) to (16) check the simultaneous (two at a time or three at a time) burner level changes. Eq. (17) shows the number of switchings of burners between time periods from t−1 to t at each boiler using byproduct gas G. Eq. (18) shows the minimum byproduct gas input at each boiler for the stable operation of boilers at time t.

CASE STUDY

A case study was performed to verify the usefulness of the proposed approach using the simulated model of an iron and steel making process, and the results were compared with those by a previous approach [Akimoto et al., 1991], which determines the total fuel load change at each period and no optimal distribution is made. The distinguishing difference between the previous and proposed approach is the optimization model structure. The previous one uses continuous variables for fuel load change, while the proposed one uses both discrete and continuous variables according to the fuel types used in the process. To compare the performance of the proposed approach with the previous approach, it is assumed that the total amount of adjusting byproduct gases that is determined from the previous approach is distributed to each boiler considering efficiencies, energy demand, and the number of switchings of burner with continuous fuel load change. The planning horizon is composed of five periods, and each period is five minutes.

Fig. 2 shows the gas flow diagram for the case study. Two types of byproduct gases are generated from the process, and some portion of the byproduct gas is supplied to the steel making process, and the remaining are sent to the power plant. Four boilers exist at the power plant. Table 1 shows the operation range of holders to reflect the operation heuristic of using classified holder level region for the holder level maintenance. Table 2 shows the fuel load change unit for byproduct gases at each boiler. Table 3 shows the low heating values of fuels. Table 4 shows the different efficiencies of each boiler at the power plant. The case study deals with the situation where both byproduct gas holders are expected to experience the unfavorable emission or shortage of gases.

Table 1. Operation limit of the byproduct gas holder

	A Gas	B Gas
LL operation limit (Nm^3/h)	40,000	30,000
L operation limit (Nm^3/h)	50,000	40,000
Center operation (Nm^3/h)	70,000	60,000
H operation limit (Nm^3/h)	90,000	80,000
HH operation limit (Nm^3/h)	100,000	90,000

Table 2. Burner level of byproduct gas fuel load change (Nm^3/h)

	Boiler 1	Boiler 2	Boiler 3	Boiler 4
A Gas	27,000	27,000	27,000	27,000
B Gas	10,000	10,000	10,000	10,000

Table 3. Low heating value of fuels

	A gas (kcal/Nm^3)	B gas (kcal/Nm^3)	Oil (kcal/L)
Low heating value	750	2,000	9,300

Table 4. Efficiencies of each boiler

	Boiler 1	Boiler 2	Boiler 3	Boiler 4
Efficiency	0.8	0.85	0.82	0.87

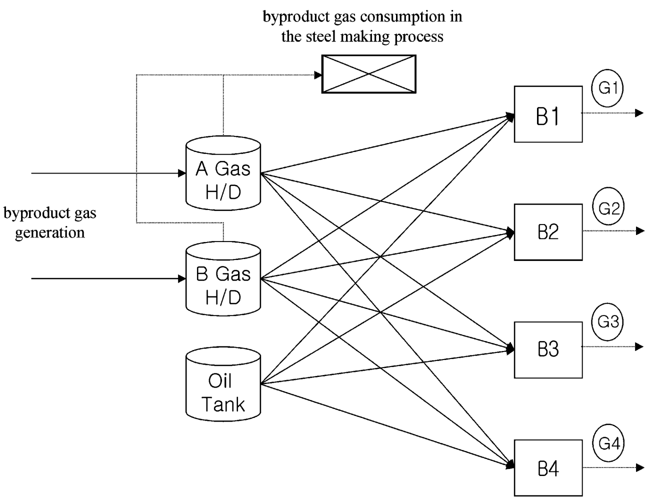

Fig. 3. Process diagram of the case 1.

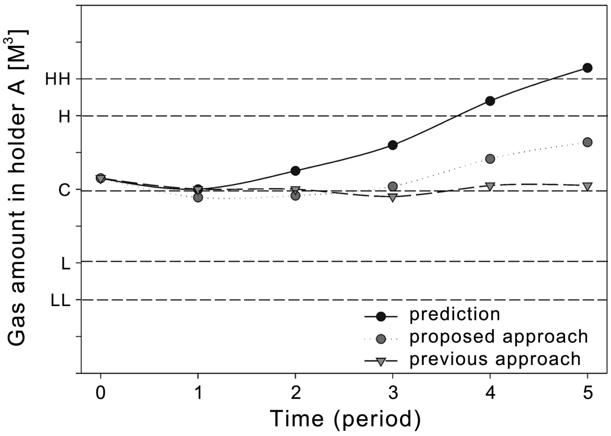

Fig. 4. Comparison of A gas holder level change.

Fig. 3 and Fig. 4 show the holder level prediction and the optimized result for proposed approach and the previous approach for A gas and B gas, respectively. The holder level prediction shows that A gas is expected to increase and gas discharge is expected at time period 5. On the whole, the B gas holder level operates at a less low level, and it is expected to go to the lower risky region at time period 3. Therefore, to avoid gas discharge and holder booster trip, optimization is performed. The result shows that both holder levels are fluctuating within the operation limit during the planning horizon, but the deviation of the holder level from the normal operation level by proposed approach shows larger deviation than the previous approach. This is because the proposed one determines the optimum point by considering the penalty for the frequent burner on/off and discrete load change while previous approach does not consider the frequent fuel load change.

Fig. 5 and Fig. 6 show the optimum fuel flow rate results during the planning horizon by the proposed approach, and Fig. 7 and Fig. 8 show the result by the previous approach, respectively. The pro-

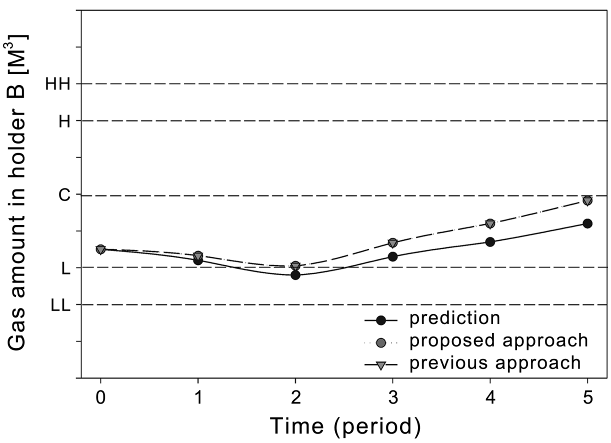

Fig. 5. Comparison of B gas holder level change.

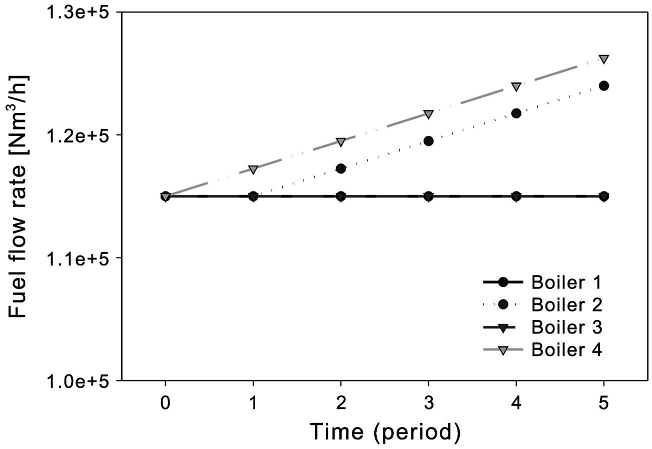

Fig. 6. A gas flowrate change by proposed approach.

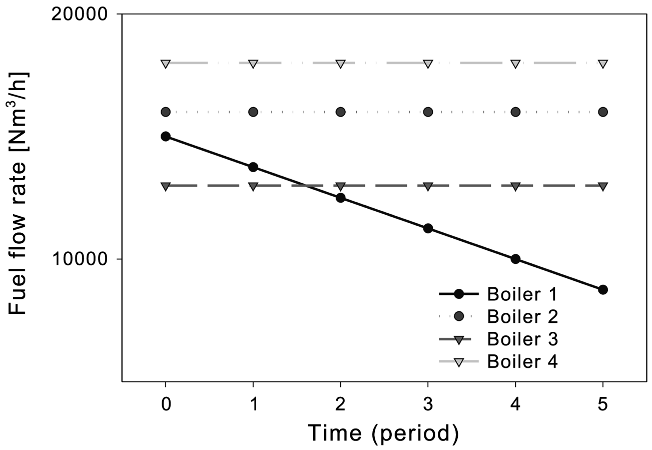

Fig. 7. B gas flowrate change by proposed approach.

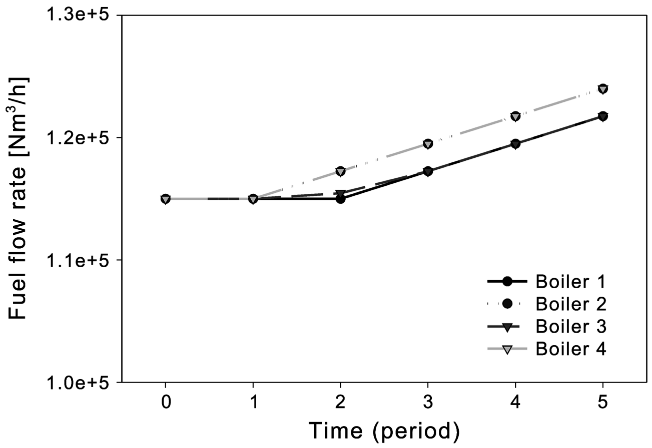

Fig 8. A gas flowrate change by previous approach.

posed approach performs the three times burner switching: B gas burner turn-off at the first period, and two A gas burner turn-on at the second period. The result from the previous approach experiences six times of switching: B gas burner turn-off at the first period, and five A gas burner turn-ons at the second and third periods. Comparing the fuel load change result shows that the proposed approach performs a reduced number of switchings than the previous approach. By changing the flow rates of the byproduct gases by turning the burner on or off, the holder levels are maintained within the operation range, and also the electricity demands for each boiler at each period are satisfied. Simultaneous turn off of the burner at the same boiler, which is not good in terms of the fuel load increasing time than the distributed fuel load increasing, was avoided.

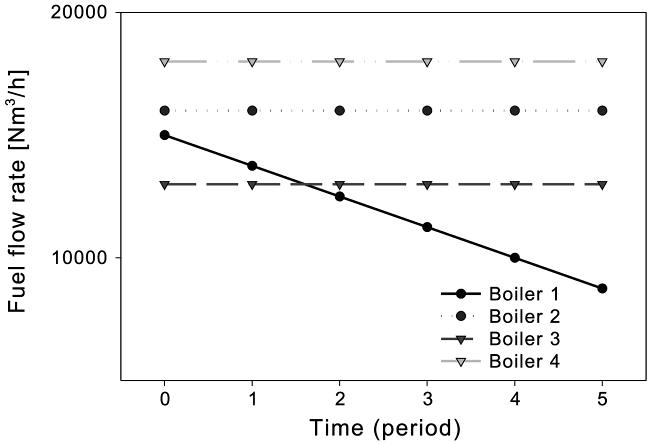

Fig. 9. B gas flowrate change by previous approach.

Fig. 9 shows the distribution of byproduct gas to each boiler at period 3. The byproduct gas distribution result shows that the distribution is made to maximize the efficiency of energy use. The largest amount of heat energy of byproduct gases is allocated to the boiler that has the highest efficiency (Boiler No. 4). The result also shows that the fuel load change is performed by considering the efficiency of the boiler. When the fuel load is increased, the most efficient burner (burner in No. 4 boiler) is first turned on, and then the next efficient one (burner in No. 2 boiler) is turned on. On the contrary, when reducing the fuel load, the most inefficient one (burner in No. 1 boiler) is first turned off, and then the next inefficient one is turned off. Here, we assumed the efficiency of the burner is same as in the same boiler.

Table 5 shows the cost comparison of the two approaches. The results show that oil was not used, holder booster trip and byproduct gas emission did not occur, and simultaneous changeover was not carried out in both results. The difference is in the switching cost, deviation, and electricity generated. The previous approach shows a small deviation cost and a little more profit from electric-

Table 5. Cost comparison (Won)

	Previous	Proposed
Oil consumption cost	0	0
Holder booster trip penalty	0	0
Unfavorable byproduct gas emission	0	0
High operation penalty	0	0
Low operation penalty	0	0
Deviation penalty	441,875	573,125
Burner switching cost	420,000	210,000
Electricity generation benefit	−321,334	−317,727
Total cost	540,541	465,897
Annual total cost difference	129,648,000 won/yr	

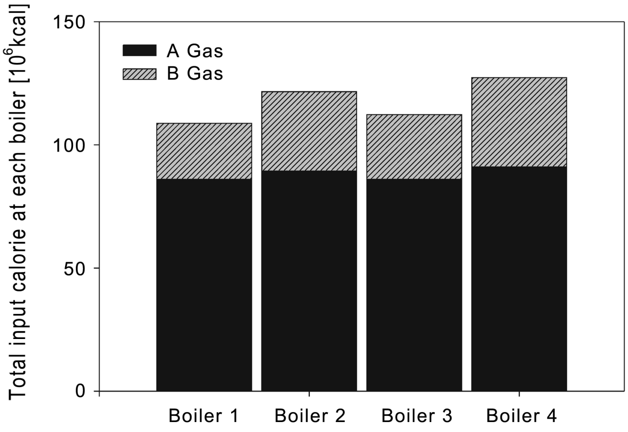

Fig. 10. Byproduct gas distribution result at period 3.

ity generation, but loses much by the frequent burner operation. The previous approach focuses on the reduction of the oil consumption, maintaining the normal operation gas amount that is related with the holder part, but a consideration of the optimal operation of the power plant usage was not included. Overall, the proposed approach finds the optimal trade off among several costs, and it shows the lower total cost.

CONCLUSION

To achieve plant-wide optimal operation under the fluctuating unbalance of byproduct gas amount and operation condition change in the iron and steel making process, a new multi-period optimization model was proposed. The proposed approach simultaneously optimizes the byproduct gas holder level and the distribution of the byproduct gases to each boiler to minimize the total cost. Compared with the previous approach, the proposed approach shows good performance in terms of the total cost reduction by searching optimal trade off among conflicting objectives, and produces an operation-easy optimum solution.

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NOMENCLATURE

C : unit cost [won]
Cp : heat capacity [kcal/Nm^3]
d : deviation of byproduct gas amount from normal amount [Nm^3]
F : flow rate [Nm^3/h]
H : enthalpy [kcal/kg]
h : gas amount in the holder [Nm^3]
SW : burner switching [-]
t : time period [min]

Greek Letters

η_i : efficiency of ith boiler [-]
w : penalty weight [won/penalty]

Superscripts and Subscripts

2s : two burner experience simultaneous switching at the same boiler
3s : three burner experiences simultaneous switching at the same boiler
G : byproduct gases
H : high level operation
HH : unfavorable byproduct gas emission
i : boiler
L : low level operation
LL : holder booster trip
oil : heavy oil
stm : steam

General Integer Variables

$N^G_{i,t}$: number of operating burner at boiler i at time t
$SW^{G+}_{i,t}$: number of G gas burner turn on at boiler i at time t
$SW^{G-}_{i,t}$: number of G gas burner turn off at boiler i at time t

Binary Integer Variables

$$j^{G+}_{1,i,t} = \begin{cases} 1 & \text{if one G gas burner turned on at boiler i at time t} \\ 0 & \text{else} \end{cases}$$

$$j^{G+}_{2,i,t} = \begin{cases} 1 & \text{if two G gas burner simultaneously turned on at the same boiler i at time t} \\ 0 & \text{else} \end{cases}$$

$$j^{G+}_{3,i,t} = \begin{cases} 1 & \text{if three G gas burner simultaneously turned on at the same boiler i at time t} \\ 0 & \text{else} \end{cases}$$

$$k^{G-}_{1,i,t} = \begin{cases} 1 & \text{if one G gas burner turned off at boiler i at time t} \\ 0 & \text{else} \end{cases}$$

$$k^{G-}_{2,i,t} = \begin{cases} 1 & \text{if two G gas burner simultaneously turned off at the same boiler i at time t} \\ 0 & \text{else} \end{cases}$$

$$k^{G-}_{3,i,t} = \begin{cases} 1 & \text{if three G gas burner simultaneously turned off at the same boiler i at time t} \\ 0 & \text{else} \end{cases}$$

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