International Journal of Coal Preparation and Utilization, 31: 273–288, 2011

ISSN: 1939-2699 print/1939-2702 online
DOI: 10.1080/19392699.2011.564595

DECISION MAKING ON MOST ECONOMICAL COAL FOR COAL-FIRED POWER PLANTS UNDER FLUCTUATING COAL PRICES

HOUZHANG TAN[1,2], XUEBIN WANG[1], YANG MIAO[1], HAIYU LIU[1], MOHAMED POURKASHANIAN[2], LIN MA[2], AND TONGMO XU[1]

[1]School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, China
[2]Centre for Computational Fluid Dynamics, University of Leeds, Leeds, United Kingdom

A long-term (8 years) experimental investigation has been carried out to analyze the effect of coal quality on the economy of power plants and to develop a predictive method for the determination of the most economical coal in a fluctuating coal market. The research results show that the facility maintenance costs, the combustion-supporting oil consumption, and the frequency of tube explosion increase exponentially with the ash content increasing, and the total maintenance costs increase sharply when the quality of the coal declining significantly from the designed coal. Taken into considerations the coal-purchasing costs, facility maintenance costs, emission costs, etc., a comprehensive mathematical model has been developed to predict the most economical coal, which is the coal with an ash content of 28.9% for the power plant investigated. Finally, a rapid calculation method has been

Received 30 December 2010; accepted 16 February 2011.

The present work was supported by the Natural Science Funds of China (No. 50976086). The authors also acknowledge Prof. Alan Williams in University of Leeds, who has provided great help and useful suggestions during the preparation of the article.

Address correspondence to Houzhang Tan, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, China 710049. E-mail: xuebinwang1984@yahoo.cn

proposed to determine the most economical coal in a fluctuating coal price market.

Keywords: Economical; Fluctuating coal price; Power plants

INTRODUCTION

More than 70%–80% of the total operational cost of a coal-burned power plant is for the purchase of coals. In China, the supply of coal is insufficient and the coal price rose sharply in recent years. Power plants are generally operating in the margin of deficit and most of them are unable to buy high-price designed coals. In order to control the power generation costs, power plants always try to use low-quality coals at relatively low costs. These coals usually have high-ash content, high-sulfur content, and a low volatile content. Moreover, to ensure the large quantity of the coal required, large power plants have to purchase coals from as many as 20 to 30 different small coal mines. The quality of the coals varies greatly and the coal price is fluctuating rapidly [1]. This results in various negative effects on power plant operation, such as an increase in system abrasion, increase in power consumption for coal pulverizing, increase in the consumption of ash-flushing water, increase in pollution discharge, decrease in the system efficiency of sulphur removal, causing ignition delay, high-ash carbon content, etc. [2–5]. Under the current complex situations of fluctuating coal prices, all coal-burned power plant operators face this urgent problem of determining the most economic coal that can keep the balance between safety, efficiency, and a low budget for coal purchase. In the long term, it is also required for them to determine how to select the coming coals at the most rational price, how to make a scientific estimation of various additional costs, etc. The overall objective is to ensure that power plants minimize both the costs on coal purchasing and the additional costs due to the combustion of low-quality coals.

There have been a number of previous researches on the optimization of operation parameters of coal combustion with coal quality to control the cost of power plant operation [6]. Most of the theoretical studies were carried out by using neural network and/or statistical methods, and based on this research some expert systems were developed in order to analyze the effect of coal quality on the efficiency of the furnace and the costs of coal purchasing [7–10]. In 2000, a computer-modelling program, "Integrated Environmental Control Model (IECM)", has been developed at the Carnegie Mellon University and the Department of Engineering & Public Policy (EPP) in the United States. It is capable of performing systematic cost and performance analyses of emission control equipments in a coal-fired power plant [11].

In the above research, the effect of the change in coal quality on the efficiency of combustion, coal-purchasing cost and the cost of air pollution charge has been considered. However, it did not consider the maintenance cost of the power plant. Since the maintenance cost is one of the most significant costs of power plant operation, if it is not included, then it will be less meaningful to perform optimization of coal quality to control the cost of power plant operation, and it will not be able to give a good guidance on coal purchase.

In this work, based on a long-term (8 years) experiment performed in a power plant, the effect of the change in coal quality on the economy of the power plant has been analyzed, and a comprehensive mathematical model has been developed, and in particular the effect of coal quality on the maintenance cost of the power plant has been included. A rapid calculation method is also proposed to determine the most economical coals for coal-burning power plants under complex fluctuating coal prices.

ANALYSIS OF THE IMPACT OF COAL QUALITY ON POWER PLANT OPERATIONAL COSTS

Description of the Test Power Plant

Experiments were performed in a 4×215 MW power plant in the Shanxi province in China from 2002 to 2009. Coal is burned using opposite swirl burners, and eight steel ball mills are fitted for each furnace. There is a wet desulfurization system and an ash-purging system using water, with no De-NOx system. Because the power plant is close to many collieries, the coals used are transported using trucks from more than 10 collieries nearby.

Worsening of the coal quality is usually characterized by an increase in ash content over the designed coal, thus leading to a huge increase in the total amount of coal burned. In addition, there is an excessive sulfur and nitrogen content in low-quality coals, resulting in a sharp increase in the sulfur-removing costs and an additional atmosphere pollution charge. Table 1 shows four coals used for the experiment, of which, No. 1 is the designed coal, Nos. 2–4 are typical coals that the power plant use with greater supply.

Table 1. Coal quality for experiments

	Coals			
	No. 1 (Design coal)	No. 2	No. 3	No. 4
Ash content (%)	19.77	24.69	28.93	33.72
Sulfur (%)	0.2425	1.140	1.360	2.740
Standard unit coal price (yuan/ton)	416.0	385.0	360.0	335.0
Converted whole year actual coal amount (10,000 tons)	273.54	293.07	329.92	377.83
Whole year expense for purchasing coals (10,000 yuan)	98038.7	91483.7	86641.2	83542.3
Total ash content amount (10,000 tons)	54.09	72.36	95.46	127.40

It can be seen from Table 1 that when converting to the same whole year power generation of 7.5 billion Kw · h, the actual total amount of No. 1 coal (designed coal) consumed is 2.7354 million tons, whereas that of No. 4 coal is 3.7782 million tons, an increase of 1.0428 million tons with 0.7331 million tons more ash. This means that an extra 1.0428 million tons of coal has to be conveyed, pulverized, fed and burned and the heating surface has to be subjected to the abrasion of a much greater amount of flue gas, an extra 0.7331 million tons of ash has to be treated with the electrostatic dust precipitator, and the fans have to consume a greater extra amount of plant-service power.

Furthermore, because of the greater amount of coal consumption, leading to a greater total amount of dust release and an increase in the dust release penalty. Though the nitrogen content of the coals for the experiment is basically the same, the total NO_x emission and the charge for NO_x emission are greatly increased due to the increase in the total coal consumption. As the high-ash content aggravates abrasion, facility maintenance cost caused by abrasion rises. Excessive ash content is also the greatest hidden danger threatening the safe operation of the boiler. As the ash content grows, the consumption of the combustion-supporting oil increases, resulting in a rise of the cost for purchasing oil. There is also an increase in the frequency of tube-explosion leaks, causing a more frequent boiler shutdown, which invokes a greater loss of profits. To sum up, major additional costs of the power plant operation incurred due to the worsening of coal quality consist of four types of costs, i.e., additional ash-discharge cost, additional atmosphere pollution charge, additional effluent discharge charge, and additional facility maintenance costs.

Mathematic Model of the Additional Costs Incurred From the Change in Coal Quality

Compositions of the additional costs incurred from the change in coal quality have been listed in Figure 1, in which the designed coal is taken as a baseline The additional costs incurred due to the worsening of coal quality refer to the differences it made in the four costs, i.e., ash increase cost, atmosphere pollution charge, effluent discharge charge, and facility maintenance cost, when compared with those for the designed coal. The change in coal quality not only affects various additional costs but affects the cost for coal purchasing. The total cost presented in the current article is the sum of the coal-purchasing cost and various other additional costs. The mathematical model concerned is described as follows:

$$F_{zh} = F_{gm} + F_{fj}, \tag{1}$$

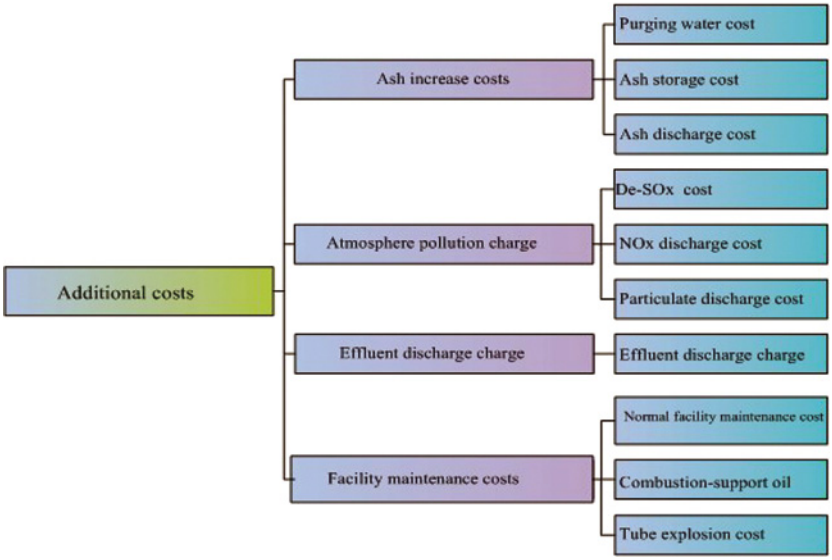

Figure 1. Additional costs incurred from the change in coal quality.

where F_{zh} is the total cost (yuan), F_{gm} is the coal-purchasing cost (yuan), F_{fj} is the additional cost incurred due to the worsening of coal quality (yuan), and

$$F_{fj} = F_{aic} + F_{apc} + F_{edc} + F_{fmc}, \tag{2}$$

where F_{aic} is the ash increase costs (yuan), $F_{\mathrm{aic}} = F_{\mathrm{pwc}} + F_{\mathrm{asc}} + F_{\mathrm{adc}}$, F_{apc} is the additional atmosphere pollution charge (yuan), $F_{\mathrm{apc}} = F_{\mathrm{sox}} + F_{\mathrm{nox}} + F_{\mathrm{particulate}}$, F_{edc} is the additional effluent discharge charge (yuan), $F_{\mathrm{edc}} = F_{\mathrm{COD}} + F_{\mathrm{PH}} + F_{\mathrm{fluoride}}$, and F_{fmc} is the additional facility maintenance costs (yuan), investigated by experiments and statistics.

F_{pwc} is the additional purging water cost (yuan), $F_{\mathrm{pwc}} = k_{\mathrm{pwc}} \times G \times A \times f_{\mathrm{chs}}$, in which k_{pwc} is a constant average value of tests for many years, means how many tons water is needed per ton ash, 4.41 in this experiment; G is the quantity of coal (ton); A is the content of ash in the coal (%); f_{chs} is the cost of purging water per ton ($\mathrm{yuan} \cdot \mathrm{ton}^{-1}$), $0.645 \mathrm{yuan} \cdot \mathrm{ton}^{-1}$ in this work.

F_{asc} is the additional ash storage cost (yuan), $F_{\mathrm{asc}} = f_{\mathrm{ca}} \times G_{\mathrm{A}}$, in which f_{ca} is the unit cost for the construction of the ash yard ($\mathrm{yuan} \cdot \mathrm{ton}^{-1}$), 11.5 $\mathrm{yuan} \cdot \mathrm{ton}^{-1}$ in this work; G_{A} is the total mass of the ash (yuan).

F_{adc} is the additional ash discharge cost (yuan), $F_{\mathrm{adc}} = k_{\mathrm{adc}} \times G_{\mathrm{A}}$, in which k_{adc} is the constant 4.1, means the charging fee from local government per ton ash, and it is charged by the rule of the local government.

F_{sox} is the additional desulfurization cost (yuan), $F_{\mathrm{sox}} = (1600000 \times G \times S \times f_{\mathrm{sox}})/0.95$, in which G is the amount of coal burned (kg), S is the content of sulfur in the coal (%), f_{SOX} is the unit cost of sulfur emission ($\mathrm{yuan} \cdot \mathrm{kg}^{-1}$), 0.6 $\mathrm{yuan} \cdot \mathrm{kg}^{-1}$ in this work, and 0.95 is a coefficient, ruled by the local environmental protection administration.

F_{nox} is the additional NO_x discharge cost (yuan), $F_{\mathrm{nox}} = (9950 \times G \times f_{\mathrm{nox}})/0.95$, in which f_{NOX} is the unit cost of NO_x emission ($\mathrm{yuan} \cdot \mathrm{kg}^{-1}$), and 0.95 is a coefficient, ruled by the local environmental protection administration.

$F_{\mathrm{particulate}}$ is the additional particulate discharge cost (yuan):

$$F_{\mathrm{particulate}} = \frac{G \times \left(A + 2\% \times \frac{Q_{net}}{33913}\right) \times (1 - \eta) \times f_{yc} \times 900}{2.18}, \tag{3}$$

in which A is the content of ash in coal (%), f_{yc} is the unit cost of particulate emission ($\mathrm{yuan} \cdot \mathrm{kg}^{-1}$), 0.6 $\mathrm{yuan} \cdot \mathrm{kg}^{-1}$ in this work and Q_{net} is the low heat value of coal ($\mathrm{kJ} \cdot \mathrm{kg}^{-1}$), excluding the latent heat.

F_{COD} is additional COD (Chemical Oxygen Demand) discharge cost (yuan), $F_{COD} = W_{hfs} \times N_{COD} \times f_{COD}/k_{COD}$, in which, W_{hfs} is the amount of waste water from ash yard (t), N_{COD} is the concentration of COD ($kg \cdot L^{-1}$), $0.03\,kg \cdot L^{-1}$ in this work, k_{COD} is the coefficient constant ($kg \cdot L^{-1}$), $1.0\,kg \cdot L^{-1}$ in this work, and f_{COD} is the unit cost of COD charges ($yuan \cdot t^{-1}$).

F_{PH} is the additional effluent discharge cost by PH value (yuan), $F_{PH} = W_{hfs} \times f_{PH}/k_{PH}$, in which f_{PH} is the unit cost of effluent emission by PH value ($yuan \cdot kg^{-1}$), and k_{PH} is the coefficient constant.

$F_{fluoride}$ is the additional fluoride discharge cost (yuan), $F_{fluoride} = W_{hfs} \times N_{fluride} \times f_{fluride}/k_{fluoride}$, in which $N_{fluoride}$ is the concentration of fluoride ($mg \cdot L^{-1}$), $f_{fluoride}$ is the unit cost of fluoride emission ($yuan \cdot kg^{-1}$), and $k_{fluoride}$ is coefficient constant.

DECISION MAKING ON THE MOST ECONOMIC COAL AT FIXED COAL PRICES

To investigate the effect of burning coals of different qualities on various additional costs of power plant operation, four coals with relatively greater differences in sulfur content were selected for experimentation. From Table 1, it can be seen that the unit price of the standard coal increases with the decrease in ash content and decreases with the increase in sulfur content. To quantitatively obtain the impact of the change in coal quality on the total cost, the key is to determine whether it is possible to quantitatively calculate the impact of the change in coal quality on various additional costs. As there are corresponding national standards of charge for ash production, atmosphere pollution, and effluent discharge from power plants, it is easy to determine these additional costs. The most difficult to work out is the relationship between the additional facility maintenance cost and the change in coal quality.

From the analysis of the experimental data and the statistics of the abrasion and maintenance costs, tube-explosion leak frequency and combustion-supporting oil consumption with respect to the change in coal quality from 2003 to 2006, it is found that there is a good exponential relationship between the global facility maintenance cost (including abrasion) and ash content, as shown in Figure 2.

It is also suggested that there is a good exponential correlation between the change of ash content in the coal and the tube-explosion

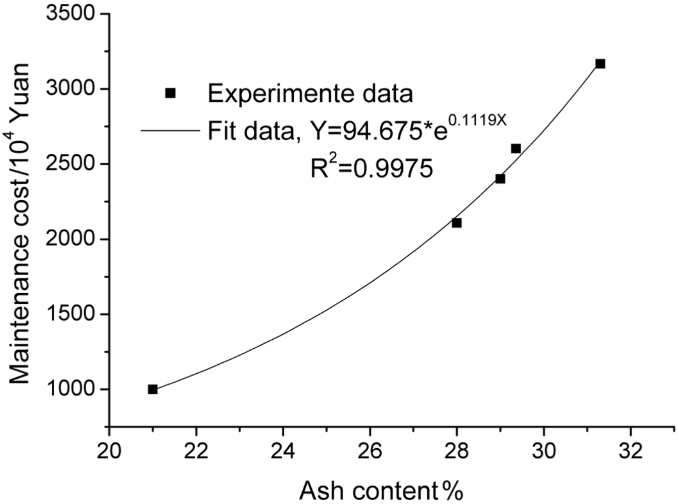

Figure 2. Trend of change of maintenance cost with ash content.

leak frequency, and the combustion-supporting oil consumption as shown in Figures 3 and 4, respectively. The change in coal quality is shown in Figures 3 and 4. The change in coal quality refers mainly to the change in ash content, sulfur content, and volatile content. Since the changes in sulfur content and volatile content do not significantly

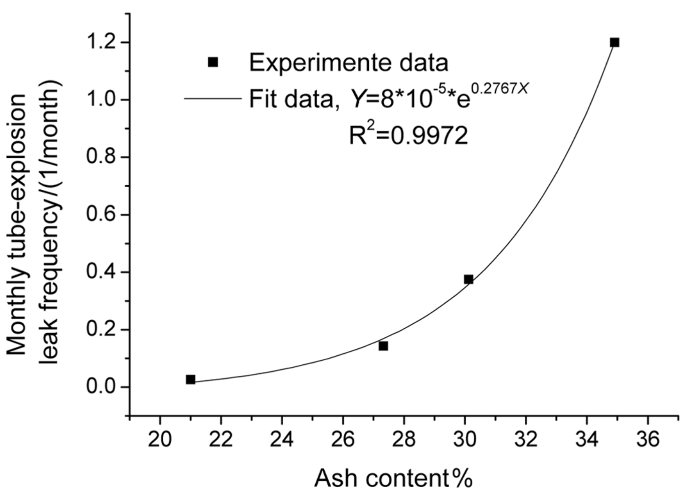

Figure 3. Relation between average monthly tube explosion leak frequency and ash content.

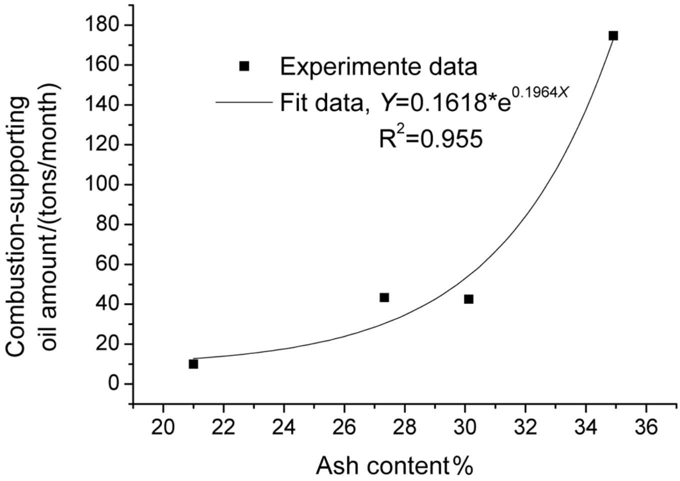

Figure 4. Relation between change in combustion-supporting oil amount and ash content.

affect the facility maintenance and service costs, therefore, the effect of coal quality on maintenance and service costs could be converted to the effect ash content in coal.

Figure 5 has depicted the additional discharge cost due to the changes in sulfur content. Along with the increase in the sulfur content, the additional cost involved increases. By superimposing the

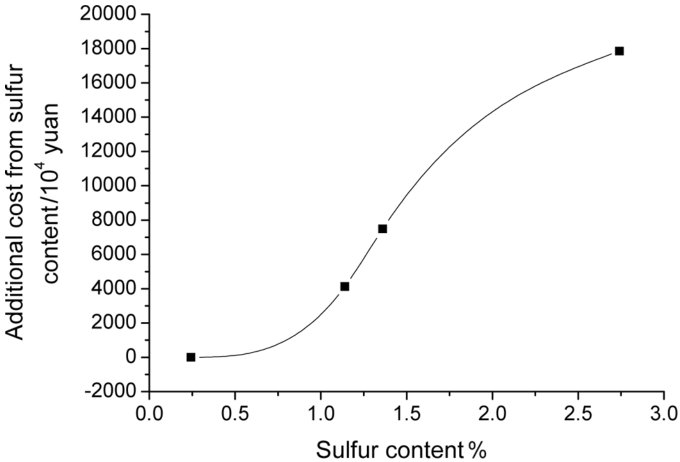

Figure 5. Relation between coals and additional costs incurred by change in sulfur content.

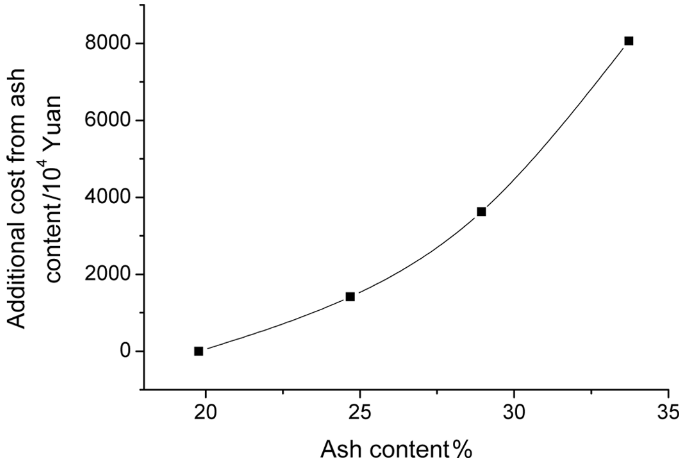

Figure 6. Relation between coal quality and additional costs incurred by ash content.

calculated values of the additional ash increase cost, atmosphere pollution charge, and effluent discharge charge incurred from the change in coal quality in Figures 2–4, the relation between the change in coal quality and the total additional costs can be obtained, as shown in Figure 5.

Figure 6 shows the additional costs of the four experimental coals incurred from the change in ash content. The plot shows that the higher the ash content, the greater the additional costs. The lowest point where the additional cost equals 0 is corresponding to the baseline coal, that is, the designed coal.

With the current unit price of the four coals shown in Table 1, we can find the trend of change in coal-purchasing cost in terms of the coal ash content as is shown in Figure 7. With the rise in coal ash content, the coal-purchasing cost decreases drastically. Apparently, the key measure to control the total cost is to bring the unit price of the standard coal under control.

The total cost is the sum of the coal-purchasing cost and various additional costs. So it is possible to obtain the relationship between the total costs and coal quality by superimposing the plots shown in Figures 5–7, and this results in Figure 8. The total costs are determined by using the mathematical model based on Equation (1). As is indicated in Figure 8, when burning low-quality coals, the cost may not necessarily

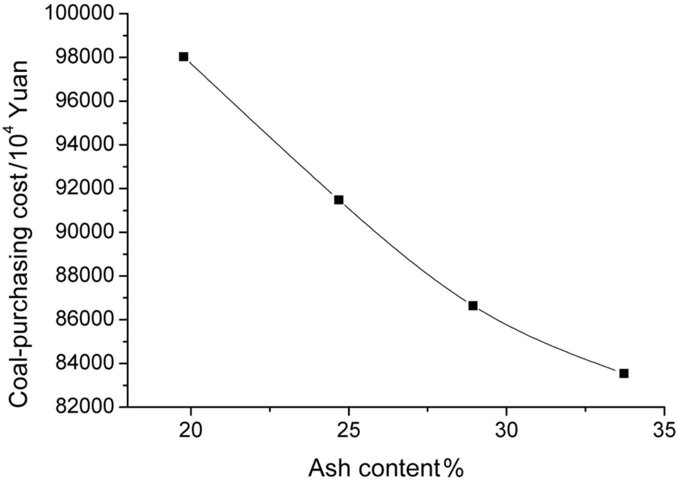

Figure 7. Purchasing cost for different coals.

be low, whereas when burning the high-quality coals, the cost may not necessarily be high. At the current standard coal unit price, the total cost of burning the No. 3 coal with an ash content of 28.93% is the most economical coal.

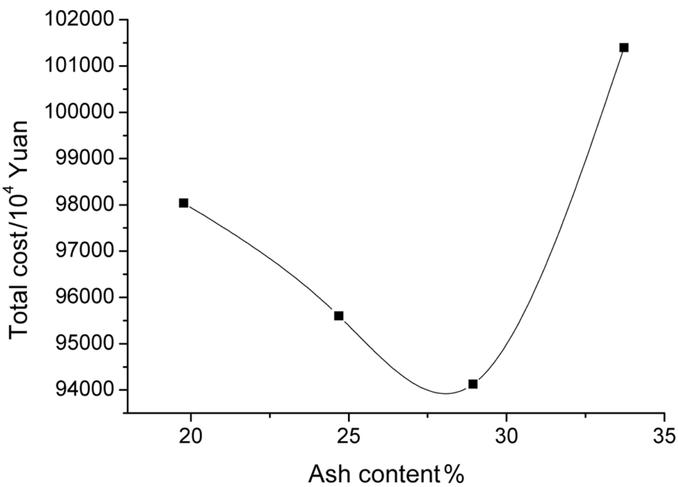

Figure 8. The total cost for coals with different qualities under the experimental working condition.

DECISION MAKING ON THE MOST ECONOMIC COAL UNDER FLUCTUATING COAL PRICE

The operational costs of a power plant are influenced directly by the fluctuation of the standard coal unit price. When the designed coal is used, the boiler efficiency is high, but the coal price is also high. Therefore, burning the designed coal is not always the most economical option. When the growth of the price for high-quality coal is less than that for low-quality coal, the advantage of the purchasing price for the low-quality coal is weakened and the most economical coal quality moves to the high-quality coal.

Figure 9 indicates the effect of coal quality changing on the price for the four experimental coals in seven environments (Curves 1–7) from 2002 to 2009, and correspondingly, Figure 10 shows the profiles of total cost obtained using the total cost mathematical model for the experiment performed. Curves 1–6 in Figure 9 are the real standard coal price, while Curve 7 is the standard coal unit price worked out artificially. The total cost corresponding to Curve 7 in Figure 10 is a straight line, and it indicates that under this condition, the total costs for all the experimental

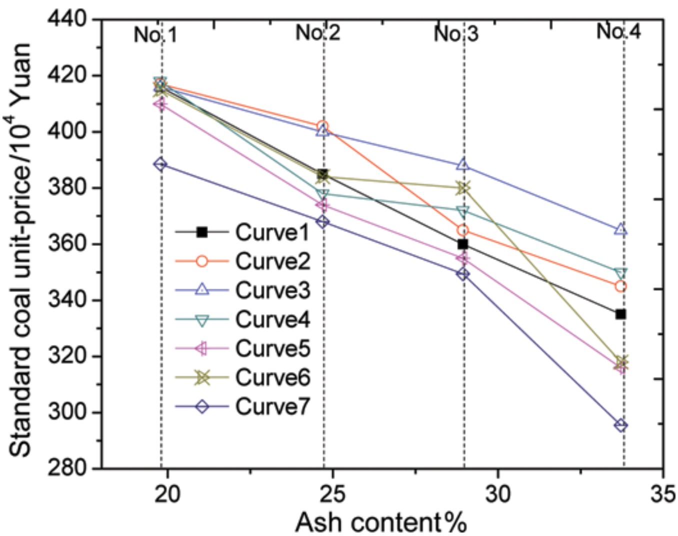

Figure 9. Relation between change in standard coal unit price and coal quality.

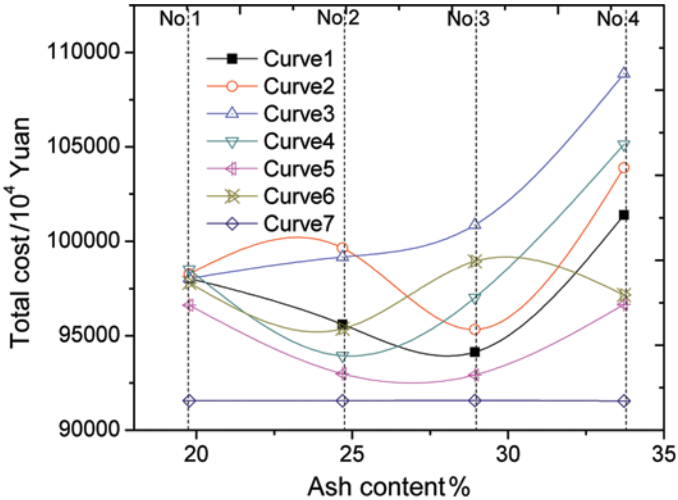

Figure 10. Change of comprehensive cost with coal quality.

coals are the same and there is not a most economical coal, so the power plant can buy any of them. The other total cost curves in Figure 10 have suggested some interesting results.

It is shown clear from Figure 9 that the actual price of the coals is frequently fluctuating. With Curve 7 as a baseline, the variation of the best coal quality with the change of the coal price is discussed as follows. As illustrated in Curve 5, the growths of coal price for the Nos. 2 and 3 coals are the same, but lower than that of the coal No. 1 with the lowest ash content and the coal No. 4 with the highest ash content. As a result, the ash content of the most economical coal should be between that of the No. 2 coal and the No. 3 coal.

If the increase of coal price for the high-quality coal is relatively larger, the most economical coal should move toward the low-quality coal. When the price increase of No. 2 coal is only higher than that of the No. 3 coal shown in Curve 1 of Figure 9, the trend of the total cost will evolve to Curve 1 in Figure 10, and the most economical coal will move to the No. 3 coal. When the price increase of the No. 2 coal is larger than that of both the No. 1 coal and No. 3 coal, the total cost will form a peak at that section and the trend of the total cost will evolve to Curve 2 in Figure 10. Under this condition, it is necessary to avoid buying coal in this section, but to select the designed coal whose quality is better than that of the No. 2 coal or the No. 3 coal with a more economical quality.

If the price increase of the low-quality coal is relatively larg, the most economical coal moves toward the high-quality coal with a higher price. Curve 4 in Figure 9 depicts this situation when the price increase of the No. 3 coal is greater than that of the No. 2 coal, and the most economical coal moves to the No. 2 coal in Figure 10. If the price increase of the No. 3 coal is greater than that of both the No. 2 coal and the No. 4 coal, the total cost will form a peak around the No. 3 coal quality, as shown by Curve 6 in Figure 10. In this situation, it should be avoided to buy coals in this section, but to select the No. 4 coal with the lowest quality or the No. 2 coal with a higher quality. If the growth of coal price is enlarged more with the increase of the ash content in the coal, the best quality coal No. 1 with least ash content should be the most economical coal, as denoted by Curve 3 in Figure 10.

Based on the above discussion, the model for determining the most economical coal under the condition of fluctuating coal price can be summarized as follows:

$$A = \{i | \min(c_i - c_i' | i = 1, 2, \ldots n)\}, \tag{4}$$

where A is the aggregation of coal serial number with the most economical quality, c_i' is the baseline of the standard coal unit price for No. i coal, and c_i is the current price of standard coal unit for No. i coal.

CONCLUSIONS

In this article, taking into consideration the maintenance cost together with the coal-purchasing cost and various emission costs, the effect of the coal quality on the economy of a power plant has been mathematically analyzed based on a long-term experimental investigation. The main conclusions are as follows:

1. Along with the worsening of coal quality and the increasing of ash content, the facility maintenance costs, the tube-explosion leak frequency, and the combustion-supporting oil consumption increase in an exponential correlation with the ash content. The total maintenance cost increases sharply when the quality of the coal declines significantly from that of the designed coal.

2. A comprehensive mathematical model has been developed and it is found that the quality of the most economical coal for the power plant is located between the designed coal and the low-quality coals. For the power plant investigated in this work, the ash content of the most economical coal is around 28.9%.
3. The quality of the most economical coal changes with the fluctuation of the coal price. A simple and rapid calculation method is developed to determine the coal of the most economical quality in a market with a fluctuating coal price. A criterion price is firstly calculated assuming that the total costs of all the coals are the same, and the current most economical coal is the one with the least difference between its price and the criterion price.

REFERENCES

1. Liao, Y., C. Wu, and X. Ma. 2005. New hybrid optimization modeling for power coal blending. In *Proceeding of 4th International Conference on Machine Learning and Cybernetics*, Guangzhou: IEEE.
2. Godoy, S. M., F. C. Lockwood, and J. Williamson. 2002. The effect of coal quality on NOx emissions: Early stages of devolatilization. *Clean Air* 3(4): 305–314.
3. Carpenter, A. M. 2002. Coal quality assessment the validity of empirical tests. In *International Journal of Coal Geology*, London: IEA Clean Coal Centre.
4. Helbleb, J., S. Niksa, J. Helble, M. Haradac, T. Ando, J. Shigeta, and I. Kajigaya. 2001. Coal quality impacts on alkali vapor emissions from pressurized fluidized bed coal combustors. *Combustion Science and Technology* 165: 229–247.
5. Patterson, J. H., and H. J. Hurst. 2000. Ash and slag qualities of Australian bituminous coals for use in slagging gasifiers. *Fuel* 79: 1671–1678.
6. Dong, X. 2006. Study on new control method for boiler combustion system. In *Proceedings of the 6th world congress on intelligent control*, Dalian: IEEE.
7. Xiong, J., C. Zhang, and H. Zhao. 2007. Global optimization of coal-burned power system based on structure theory of thermoeconomics. *Proceedings of the CSEE* 27(26): 65–71.
8. Wang, Y., L. Li, and W. Pan. 2006. Comprehensive evaluation index of economical operation in coal-fired power plant. *Journal of Changsha University of Science & Technology (Natural Science)* 3(1): 47–51.
9. Wang, J. 2006. Analysis of safety and economy for blend-burning with out-of-design coals at coal-burned plants. *Thermal Power Generation* 12: 25–29.

10. Ma, F., and Y. Liu. 2005. Quality control of coal jigging in a coal-preparing plant using MEBML method. *International Conference on Control and Automation*, Budapest, Hungary, June 26–29, 2005.
11. Berkenpas, M. B., J. J. Fry, K. Kietzke, and S. S. Rubin. 2001. *Getting Started: Integrated Environmental Control Model*. Pittsburgh: Carnegie Mellon University. Available at http://www.cmu.edu/epp/iecm/iecm_doc.html