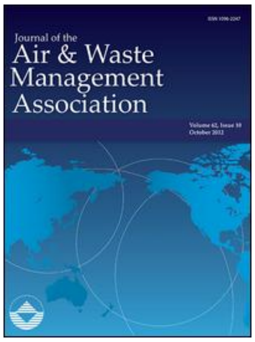

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Journal of the Air & Waste Management Association

ISSN: 1096-2247 (Print) 2162-2906 (Online) Journal homepage: http://www.tandfonline.com/loi/uawm20

Energy consumption and energy-saving potential analysis of pollutant abatement systems in a 1000MW coal-fired power plant

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Abstract

The pollutant abatement systems are widely applied in the coal-fired power sector and the energy consumption was considered an important part of the auxiliary power. An energy consumption analysis and assessment model of pollutant abatement systems in a power unit was developed based on the dynamic parameters and technology. The energy consumption of pollutant abatement systems in a 1000 MW coal-fired power unit which meet the ultra-low emission limits and the factors of operating parameters including unit load and inlet concentration of pollutants on the operating power were analyzed. The results show that the total power consumption of the pollutant abatement systems accounted for 1.27% of the gross power generation during the monitoring period. The WFGD system consumed 67% of the rate while the SCR and ESP systems consumed 8.9% and 24.1%. The power consumption rate of pollutant abatement systems decreased with the increase of unit load and increased with the increase of the inlet concentration of pollutants. The operation adjustment was also an effective method to increase the energy efficiency. For example, the operation adjustment of slurry circulation pumps could promote the energy-saving operation of WFGD system.

Keywords

energy consumption; pollutant abatement systems; ultra-low emission; coal-fired power plant; energy-saving

Introduction

About half of the coal in China is used for power generation, which is considered as one of the main emission sources of atmospheric pollutants(NBS, 2014; Zhao et al., 2008). In 2013, the emission of SO_2, NO_x and PM in coal-fired power sector are estimated to be 6.34Mt, 8.62Mt and 1.84Mt, which accounted for 31%, 38.7% and 14.4% of total pollutants emission in China, respectively (MEPC, 2015). The power demand of the eastern coastal area is greater than other regions in China, which is the most flourishing economic and densely populated region. This results in the huge amount of the unit capacity, and the emission of power plant was considered as one of main reasons of the frequent occurrence of atmospheric haze in the eastern coastal area.

In recent years, the Chinese government has promulgated several laws and regulations to promote the installation and application of pollutant abatement systems in coal-fired power sector to reduce the emission, such as the GB13223-2011 emission standard for thermal power plant, and more stringent local standards for the key regions, including the Beijing-Tianjin-Hebei region (BTH region), the Yangtze River Delta region (YRD region), and the Pearl River Delta region (PRD region) (MEPC, 2011).

The operation of pollutant abatement systems increases the power consumption rate in coal-fired power plant, which affects the economy of the power plant. So it is important to figure out the accurate energy consumption and the influence of the pollutant abatement systems on power plant. The energy consumed by the limestone-gypsum wet flue gas desulfurization (WFGD), electrostatic precipitator (ESP) and selective catalytic reduction (SCR) system accounted of about 1-2% of the total power generation based on the self-monitoring of power plant. The impact of the application of different SO_2 and NO_x technologies on power generation efficiency is investigated and the power consumption proportion for WFGD and SCR system of the total power generation is 1-2% and 0.5%, respectively (Graus & Worrell, 2007). WFGD system is considered as the main energy consumption system, and the energy consumption is far more than other pollutant abatement systems. The increasing of power consumption rate in power plant caused by the operation of pollutant abatement systems increases the net coal consumption rate and the power generation cost. So the investigation of the energy consumption characteristics of pollutant abatement systems is essential.

Many studies on the energy consumption and efficiency have been conducted at the national and regional levels and the overall conditions of typical industry sector. Some studies involved the impact of different energy policies and technologies on energy efficiency in different sectors(Geller, Harrington, Rosenfeld, Tanishima, & Unander, 2006; Mannsbart, 1997; Thollander, Danestig, & Rohdin, 2007; Wei, Liao, & Fan, 2007; Zhou, Levine, & Price, 2010). Other studies analyzed the energy-saving potential of different industrial sectors and benefits from energy-saving (Gielen & Taylor, 2009; Hepbasli & Ozalp, 2003; Worrell, Bernstein, Roy, Price, & Harnisch, 2008). Besides, there were also many studies which analyzed the energy consumption characteristics and energy efficiency of the energy system especially the air-conditioning system and illuminating system in commercial and official buildings(Chang, Zhao, & Zhu, 2011; Fasiuddin, Budaiwi, & Abdou, 2010; Ma & Wang, 2009). These different policies and technologies improve the energy efficiency and reduce the cost of production. However, before the applications of energy-saving technologies and implement of energy policies, the barriers and drivers for energy efficiency measures should be studied and the government and managements can get the targeted solutions (Hasanbeigi, Menke, & du Pont, 2009; Rohdin, Thollander, & Solding, 2007; Sardianou, 2008; Thollander & Ottosson, 2008). However, the pollutant abatement system is a little different from the traditional production equipment. The output of the pollutant abatement system is the reduction of pollutant, while the energy consumption indicators for other sectors is the energy consumption per unity unit products. For example, the energy consumption indicator in the iron and steel industry is the energy intensity, which represents the total energy consumption of the production of a ton of crude steel (Tanaka, 2008).

Few studies have been conducted involving the energy consumption characteristics and influence on the power generation of power unit. Although there are some empirical data and self-monitoring data provided by the engineering and managerial personnel, the impact of the operating condition and main operating parameters on the energy consumption characteristic has not been studied. The application of the Ultra-low emission limits will further increase the power consumption rate in power plant. Hence, in order to analyze the energy consumption characteristics and energy-saving potential of pollutant abatement systems in coal-fired power plant, the dynamic operating data of a coal-fired power plant in China which achieves the ultra-low emission limits was collected and preprocessed, and then the energy consumption analysis and assessment model was developed based on the dynamic operating data and system process to analyze the real-time operation conditions and the energy consumption of different equipment and subsystems of the pollutant abatement systems. This model also analyzed the energy-saving potential of operation optimization. This paper is structured as follows: Section 2 describes the methodology used in the energy consumption analysis. Section 3 investigates the energy consumption characteristics of the pollutant abatement systems and the related influencing factors. Section 4 analyzes the energy-saving optimization strategies. Finally, Section 5 highlights the conclusions and future work.

Data and Methodology

This study was based on the survey of a 1000 MW power unit which achieved the ultra-low emission limits. In this case, the operating data of this power unit in the monitoring period was investigated for the energy consumption analysis. The monitoring period is three months. During the monitoring period, the power unit keeps on the normal operating condition without any downtime. Besides, the operating of the energy-consumed equipment and the removal effect of pollutants were also analyzed.

The main pollutant abatement systems for coal-fired power plant are SCR, ESP and WFGD system. The flue gas, containing high concentration of pollutants, first pass through SCR system and about 70-85% of NO_x in the flue gas is converted into nitrogen which is non-toxic and the major component of air. The air pre-heater recycles some energy from the flue gas because the temperature is still high. The ESP system has a high removal efficiency of dust control and more than 99.9% of the particulate matters is separated from the flue gas. Then about 98% of all SO_2 in the flue gas is removed in the WFGD system. The process is depicted in Figure 1 and the emission concentration of different pollutants is depicted in Figure 2. Table 1 lists the subsystems for the SCR, ESP, and WFGD system. The energy consumption of WESP system is not analyzed in this paper due to lack of data.

Figure 1 here

Figure 2 here

Table 1 here

The energy consumption of pollutant abatement systems can be calculated by Eq. (1). The energy consumption is replaced by the operating power to simplify the estimation process:

$$E = E_{NO_x} + E_{PM} + E_{SO_2} \quad (1)$$

where E is the total operating power of pollutant abatement systems, E_{NOx} is the total operating power of SCR system, E_{PM} is the total operating power of ESP system, E_{SO2} is the total operating power of WFGD system. Considering that the SCR, ESP and WFGD system contains different electrical equipment and electricity consumed for different purposes, the energy consumed by different systems in estimation model are described separately and the details are explained in the following.

The energy consumption of SCR system is mainly caused by the operation of ammonia supply system, SCR reactor and flue gas system. The main energy consumption equipment of ammonia supply system is the dilution fan. The energy consumption of SCR reactor is caused by the dust blower for catalysts and related illumination and inspection system. The energy consumption of flue gas system in SCR system is used for overcoming the extra flow resistance caused by the SCR reactor. The total energy consumption or operating power of SCR system can be calculated by the Eq. (2):

$$E_{NO_x} = \sum E_{NH_3} + \sum E_{reactor} + \sum E_{fluegas} \quad (2)$$

where $\sum E_{NH3}$ is the operating power of ammonia supply system, $\sum E_{reactor}$ is the operating power of reaction system, $\sum E_{fluegas}$ is the operating power of flue gas system.

The energy consumption of ESP system is mainly caused by the operation of low-voltage system, high-voltage system and flue gas system. Low-voltage system supplies power for ash handling and rapping, while high-voltage system is the main equipment in ESP system, which creates the electric fields to capture the dust particles. Similar to SCR system, the energy consumption of flue gas system is also used for overcoming the resistance caused by ESP system. The total operating power of ESP system can be calculated by Eq. (3):

$$E_{PM} = \sum E_{low} + \sum E_{high} + \sum E_{fluegas} \quad (3)$$

Where $\sum E_{low}$ is the operating power of low-voltage system, $\sum E_{high}$ is the operating power of high-voltage system, $\sum E_{fluegas}$ is the operating power of flue gas system.

The energy-consuming equipment and system in WFGD system contains the absorbent preparation system, flue gas system, absorption tower, gypsum dehydration system, waste disposal system and other devices. The absorbent preparation system consumes energy to produce the limestone slurry as the absorbent. The flue gas system in WFGD system is similar to ESP system, while the resistance of WFGD system is much larger. Most of the energy consumption of booster fan is used for overcoming the resistance of WFGD system. Absorption tower is the main system in which the absorption of SO_2 occurred, and most energy is consumed for the operation of the slurry circulating pump, oxidation air blower and limestone slurry agitator. Gypsum dehydration system is used for removing water from gypsum slurry discharged from absorption tower. Other energy consumption devices are some illumination, refrigeration, inspection equipment etc. The total operating power of WFGD system can be calculated by Eq. (4):

$$E_{SO_2} = \sum E_{ab} + \sum E_{fluegas} + \sum E_{abt} + \sum E_{gd} + \sum E_{wd} + \sum E_{others} \quad (4)$$

Where $\sum E_{ab}$, $\sum E_{fluegas}$, $\sum E_{abt}$, $\sum E_{gd}$, $\sum E_{wd}$, and $\sum E_{others}$ are the operating power of different subsystems of the WFGD system, which is mentioned in Table 1.

To analyze the energy consumption characteristics in different working conditions, the assessment index for the operating power of each pollutant abatement system is established based on the real-time operating condition and the system process of the pollutant abatement systems. The assessment index contains the operating power, energy consumption per unit power generation (EPG) and energy consumption per unit pollutants reduction (EPR). The operating power is defined as the operating power of one certain system for average or real-time, which can be calculated according to the Eq. (5):

$$P_i = \sum_{j=1}^{n} P_{i,j} = \sum_{j=1}^{k} P_{i,j} + \sum_{j=k+1}^{n} P_{i,j} \cdot F(t) \quad (5)$$

where P_i is the real-time operating power of the *ith* pollutant control system and i is from 1 to 3 which means SCR, ESP and WFGD system, and $P_{i,j}$ is the *jth* equipment in the *ith* system and there are n equipment in all. In all these equipment, there are n-k equipment which operate non-continuously and the others operate continuously. This paper defines a judgement function $F(t)$ for non-continuously operating equipment, if these devices are operating, $F(t)$ equals 1, if not, $F(t)$ equals 0.

Based on the real-time operating power, the total energy consumption can be calculated by the Eq. (6) accurately and the average operating power of the pollutant abatement systems by the Eq. (7):

$$E_i = \int_0^T P_i dt = \sum P_i \cdot \Delta t = \bar{P}_i \cdot T \quad (6)$$

$$\bar{P}_i = E_i / T \quad (7)$$

where E_i is the total energy consumption during the monitoring period and P_i is the average power of the *ith* pollutant abatement system during the monitoring period, and T is the length of time of the monitoring period. The monitoring data are collected and processed to obtain the hourly average data, so the time interval Δt can be confirmed.

The EPG can be calculated by the following equations. The average EPG is calculated by the Eq. (8) and the real-time EPG by the Eq. (9) at the same time:

$$A_i = \frac{E_i}{GE} \quad (8)$$

$$a_i(t) = \frac{P_i}{UL} \quad (9)$$

where A_i is the average EPG of the *ith* pollutant control system during the monitoring period and $a_i(t)$ is the real-time EPG of *ith* pollutant control system, GE is the total power generation during the monitoring period and UL is the real-time unit load and is a time function.

The EPR can be calculated by the analogous method. The average EPR is calculated by the Eq. (10) and the real-time EPR by the Eq. (11) at the same time:

$$B_i = \frac{E_i}{\int_0^T Q(t)(c_{i,in}(t) - c_{i,out}(t))dt} \quad (10)$$

$$b_i = \frac{P_i}{Q(t)(c_{i,in}(t) - c_{i,out}(t))} \quad (11)$$

where B_i is the average EPR of the *ith* pollutant control system during the monitoring period and b_i is the real-time EPR of the *ith* pollutant control system, $Q(t)$ is the real-time flue gas flow and $c_{i,in}(t)$ and $c_{i,out}(t)$ are the inlet and outlet concentration of pollutant, respectively.

Energy consumption characteristics

Energy consumption of pollutant abatement systems

Based on the estimation model described in section 2, the energy consumption characteristics were analyzed. The energy consumption of SCR, ESP and WFGD system and the subsystems of each system during the monitoring period is shown in Figure 3. The energy consumption of SCR, ESP and WFGD system is 1703.7MWh, 4626.3MWh and 12858.6MWh, respectively. The total energy consumption of the pollutant abatement systems is 19188.6MWh. Combined with the operation condition of the power unit in the monitoring period, the auxiliary power ratio is 1.27%. For SCR system, the average operating power, the average EPG and the average EPR is 814.9KW, 0.11% and 1702.1kWh/t. The energy consumption of each subsystem in SCR system is 124.52MWh, 127.81MWh and 1375.05MWh, respectively. The flue gas system consumes 84.5% of total energy consumed by SCR system. For ESP system, the average operating power is 2326KW and the average EPG is 0.31%. The energy consumption of each subsystem in ESP system is 553.16MWh, 3225.23MWh and 875.21MWh, respectively. The main energy consumption system of ESP system is electric precipitation transformer system and consumes 69.3% of total energy consumed by ESP system. For WFGD system, the average operating power, the average EPG and EPR is 6436KW, 0.85% and 1913kWh/t, respectively. The energy consumption of each subsystem in WFGD system is 681.8MWh, 4558.83MWh, 6066.68MWh, 701.46MWh, 369.2MWh and 480.62MWh, respectively. The main energy consumption system of WFGD system is absorption tower system, occupying the 47.2% of total energy consumption of WFGD system, and the second is the flue gas system which occupying the 35.5% of total energy consumption of WFGD system. The operation of slurry circulating pumps and booster fans have a great influence on the total energy consumption of WFGD system.

Figure 3 here

Analysis of influence factors

The energy consumption of pollutant abatement systems is affected by some factors such as the real-time power unit load, pollutants inlet concentration and the running state of equipment when the emission concentration achieves the standard. The load of power unit and the pollutant inlet concentration directly impact the amount of the pollutants in the flue gas, which will make the pollutant abatement systems in different running state to achieve the emission standard. This section analyzes the influence of unit load and pollutants inlet concentration on the energy consumption of SCR, ESP and WFGD systems because these two factors are the main factors which have a great effect on the operation of pollutants control system.

Influence of unit load

The effect of unit load on the energy consumption of SCR system, ESP system, and WFGD system is depicted in Figure 4, respectively. The increasing of unit load increases the operating power of the pollutant abatement system. In Figure 4(a), when the unit load increases from 400 to 1000 MW, the operating power of SCR system increases 7% and the real-time EPG decreases 57.2%. As discussed above, the main energy consumption system of SCR system is the flue gas system, the energy consumption of which is affected by unit load. Although the operating power of SCR system increases with the increasing of unit load, the real-time EPG, which represents the energy consumption of SCR system per unit power generation, actually decreases because the increase of power generation is much larger than the energy consumption of SCR system. The real-time EPR of SCR system basically remains about the same, which means the energy consumption per unit emission reduction will not change with unit load. The reason is that the emission reduction has positive correlation with the unit load. The increasing of the unit load will increase the amount of flue gas, while the amount of pollutants in flue gas will also increase proportionately. In Figure 4(b), when the unit load increases from 400 to 1000 MW, the operating power of ESP system increase 80% and the real-time EPR decreases 27.6%. The increase of unit load leads to more flue gas to be processed, which means the increasing of energy consumption of induced draft fan overcoming the resistance of ESP system, and what's more, the energy consumption of high-voltage system also increases because more dust particles need to be dealt with, so the total energy consumption of ESP system increases. The real-time EPR of ESP system is not calculated due to lack of the real-time inlet concentration of PM. In Figure 4(c), The effect of unit load on the energy consumption of WFGD system is depicted and the similar patterns are shown. When the unit load increases from 400 to 1000 MW, the operating power of WFGD system increase 37.6% and the real-time EPG decreases 44.5%. The influence of the unit load on the energy consumption of WFGD system is more significant. The reason is that the main energy consuming equipment in WFGD system are the booster fan and the slurry circulating pump, which are directly related to unit load. The energy consumption of the booster fan and slurry circulating pump shares the majority of the energy consumption of WFGD system.

Figure 4 here

Influence of inlet concentration of pollutants

The effect of inlet concentration of pollutants on the energy consumption is depicted in Figure 5 and 6. In order to exclude the influence of the unit load, the average real-time operating power, EPG, and EPR are analyzed when the real-time unit load is 1000MW. Figure 5 shows that the effect of NO_x inlet concentration on the energy consumption of SCR system. When the inlet concentration increases from 150 to 250 mg/Nm3, the operating power and real-time EPG increase 9% and 9.4%, respectively, while the real-time EPR decreases 32%. This reason is that the increasing of NO_x inlet concentration leads to the additional energy consumption of the ammonia producing system especially the dilution fan, which is one of the main energy consumption devices in SCR system. Besides, it can be concluded that with the increasing of NO_x inlet concentration, the real-time EPR of SCR system decreases, which can be explained by that more NO_x is converted to nitrogen at high inlet concentration without consuming too much additional energy, because ammonia supply system consumes much less energy compared with the flue gas system and a higher removal efficiency of NOx control can be achieved at a higher inlet concentration.

Figure 5 here

The effect of SO_2 inlet concentration on the energy consumption of WFGD system is depicted in Figure 6. When the inlet concentration increases from 700 to 1700 mg/Nm3, the operation power and real-time EPG increases 41.4% and 40.4%, respectively, while the real-time EPR decreases 46.5%. With the increasing of SO_2 inlet concentration, the removal efficiency of SO_2 needs to increase to ensure the emission concentration is below the emission standard, which results in the demand of more slurry circulation and more energy consumption of slurry circulating pump.

Figure 6 here

Energy-saving analysis

WFGD system

WFGD system consumes the most energy among the pollutant abatement systems. The most energy consumption equipment of WFGD system is the slurry circulation pump, accounting for 42.2 percent of total energy consumption of WFGD system. Actually, the operating power of slurry circulation pump can only be adjusted by the numbers of operating pumps. For example, if there are 4 pumps in WFGD system, there are only four variable options for operating power. In the vast majority of cases, the manager of the WFGD system keeps all the pumps operating to maintain the highest removal efficiency.

A parameter called liquid-gas ratio is used for confirming the spraying volume at specific fume volume. The design value of liquid-gas ratio makes sure that the removal efficiency of SO_2 can be achieved and the actual value of liquid-gas ratio should be a little higher that the design value. The liquid-gas ratio will increase when the SO_2 inlet concentration or the sulfur content of coal increases if the unit load is unchanged, which means the increasing of the spraying volume of slurry. The influence of inlet concentration and unit load to the operating power of total slurry circulating pumps based on the theoretical curvilinear relations is depicted in Figure 7 (a). At the condition of low inlet concentration, the emission limit can be achieved by reducing the volume of slurry spray. With the increasing of inlet concentration, the volume of slurry spray increases simultaneously. However, if the inlet concentration is in a high level, it is not an effective way that the volume of slurry spray increases to improve the desulfurization efficiency. The practical operation experience shows that when the removal efficiency of WFGD system is in a high level, the increasing of volume of slurry spray isn't a cost-effective way to improve the removal efficiency of SO_2. In Figure 7 (a), the practical theoretical relations will lead to the more increase of operating power of the total slurry circulating pumps at the high inlet concentration, compared with the low inlet concentration, which means that the volume of slurry spray should increase to achieve the same effect of reducing emission at high inlet concentration.

The practical energy consumption situation is entirely different from the theoretical energy demand because the adjustment of the slurry circulation pump is not linear and continuous, the operating power of the slurry circulation pump may exceed the actual requirement of spraying volume, as shown in Figure 7 (b). The energy consumption of slurry circulating pump with different discharge heads differs. Based on the actual operating power of each slurry circulating pump, whose operating power is about518-602, 524-619, 578-654, and 637-747 kW, respectively. The average operating power is used to simplify the analysis. When the unit load is 500 MW and the inlet concentration is lower than 1000 mg/Nm^3, the removal effect of WFGD system can meet the demand and the outlet concentration can achieve the emission standard by opening two slurry circulating pumps. But if the inlet concentration increases to about 1300 mg/Nm^3, the operating power of two slurry circulation pumps may not supply enough amount of slurry spray to reduce SO_2, then the third slurry circulation pump is turned on to increase the spraying volume. The actual operating power of total slurry circulating pumps is far more than the theoretical demand in the actual operation process, which means energy waste. It is impossible to reduce the operating power because turning off one pump can lead to the drastically reduction of the amount of slurry spray, which will weaken the removal effect and excessive emissions compared with the emission standard. For example, if the theoretical demands for the volume of slurry spray requires just about 2.5 times of rated discharge of single pump, the manger will open three pumps to ensure the removal effect, which means the half of the energy consumption of the third pump is wasted.

In most situations, the actual operating power of slurry circulation pump exceeds the theoretical demand.

In Figure 7 (b), the possible combination of different pump is depicted. When the unit load is 500 MW and the inlet concentration of SO_2 is 700 mg/Nm^3, the theoretical operating power of total slurry circulating pumps is about 760 kW, while the actual operating power is about 1114 kW with two pumps operating. The average operating power of different pump is 552, 562, 614, and 685 kW, respectively. So two pumps should be opened to provide enough slurry, although more than half of the energy consumption of the second pump is wasted. So reducing the excess energy consumption of the circulating pumps can achieve energy-saving target. One method of improving efficiency would be to have variable size fixed-rate capacity pumps or to have variable speed pumps allowing varying capacity. For example, an additional pump with smaller rated power can be combined with the original pumps. Then there are four original pumps of about 500-750 kW power and the additional pump of 350 kW power, and the modified practical situation of operating power is depicted in Figure 7 (c). When the inlet concentration is 700 mg/Nm^3 and the unit load is 500 MW, the theoretical operating power is about 760 kW, so the manager can open one original pump and the additional pump and the total operating power is 902 kW, which is less than the combination of three big pumps with the total operating power of 1114 kW. Compared with the theoretical operating power, the combination of one original and the additional pump can meet the demand of slurry spray. And the result shows that about 212 kW power is saved by the modified combination method.

Besides, adjusting the spraying slurry volume continuously can be achieved by adjusting the nozzle valve in the spray layer based on the current theoretical demand of slurry. However, there are two unsolved problems. The first problem is that adjusting the nozzle valve can only achieve the continuous adjustment of the volume of slurry but not the operating power, and the resistance brought by the valve will increase the energy consumption. The second problem is that the precise theoretical demand of the slurry at a certain operating condition must be estimated before adjusting the nozzle valve and the system running delay and response lag should also be considered. The estimation of the precise theoretical demand of slurry needs complete and systematic field test to confirm each volume of slurry spraying at different operating condition. After getting the precise theoretical volume of slurry spraying at different operating condition, the manager should consider the problem of the system running delay and response lag of the pollutant abatements system. On the one hand, the variation of unit load and inlet concentration can't affect the operating of WFGD system immediately because of flue length. On the other hand, the removal effect of the WFGD system can't respond to the operating adjustment immediately because the absorption and oxidation reaction in the desulfurization tower proceeds much slower than the operating adjustment of the slurry circulating pump. Frequent adjustment may result in the decrease of emission reduction efficiency. To ensure the emission reduction and deal with the system running delay and response lag, the actual operating power is relative higher than the theoretical minimum operating power, even many power plant will not change the operating power of the circulating pump to keep a high removal efficiency.

Another method to adjust the spraying volume and the operating power is the application of variable frequency pump. The manager can adjust the revolving speed of the motor to adjust the spraying volume of the pump. The variable frequency pump consumes less energy when the revolving speed is low, which can achieve the energy-saving effect when there is not much slurry spraying demand in the WFGD system. However, there are two issues to consider. First, the precise theoretical demand of slurry spraying and the system running delay and response lag still be the problem. Besides, the price of variable frequency pump is also an additional economic burden for the power plant.

Figure 7 here

ESP system

The design value of pressure drop of ESP system should be below 200 Pa. However, the monitoring data showed that the actual pressure drop of ESP system was between 110 Pa and 540 Pa and exceeded the design value in more than half of the operation time. The ESP system consumes much more energy because of the high pressure drop. The high pressure drop may be caused by the uneven distribution of airflow, which also has a negative effect on the dust removal efficiency of ESP system. The approach to solve this problem is the optimization of baffle distribution, which can distribute the flue gas evenly.

Besides, the dust removal area is made up with several electric fields. Each electric field has the same operating power in most cases. However, by analyzing the dust reduction effect of each electric field, the first electric field has the highest removal efficiency while the last electric field actually has a low removal efficiency. The fact is that the operating power of the last electric field remains high, which has no positive effect on the removal efficiency. As mentioned above, the high-voltage system consumed the majority of all the energy consumption of ESP system. So the improvement of the power supply can achieve the energy-saving effect. The common approach to decrease extra energy consumption without decreasing the removal effect is applying the intermittent power supply mode and replacing with high-frequency power supply (Han, 2015; Zhang, Zhang, & Zhou, 2013). The intermittent power supply mode can increase the removal efficiency of the dust with high specific resistance.

SCR system

The SCR system consumed most energy to overcome the resistance caused by the catalysts in SCR reactor. The feasible methods to reduce the resistance include the operating of soot blowing system and reducing the amount of catalyst. The former addresses the abnormal high pressure drop actual operation, while the latter focuses on the resistance of the catalyst and tries to reduce the resistance fundamentally, which also represents the reduction of the catalyst design dosage. Decreasing the inlet concentration of NO_x is an effective method to reduce the demand for catalyst because reducing the amount of catalysts properly can ensure removal effect. The common approaches to decrease the inlet concentration of NO_x are improving the operation effect of Low-NO_x combustion and the application of hybrid SNCR-SCR system. The former can decrease the inlet concentration of NO_x directly and the latter can also decrease the inlet concentration of NO_x by the pre-reaction of NO_x and NH_3 at high temperature and then the mixture continues the reaction. Both methods are feasible to reduce the amount of catalysts without decreasing the removal efficiency. However, it is difficult to improve the operation effect of Low-NO_x combustion, which means the reconstruction and upgrade of the Low-NO_x combustion system should be conducted to improve the control effect of pollutants. The application of the hybrid SNCR-SCR system also means the reconstruction of SCR system. The operation adjustment could not achieve the target of reducing the resistance without the structural change of the system or the reactor.

Conclusions

This paper conducted a survey of a 1000 MW coal-fired power unit which meets the Ultra-low emission limits, then the energy consumption characteristics of pollutant abatement systems was analyzed based on the dynamic operating parameters and system process. The results show that the energy consumption of SCR, ESP and WFGD system is 1703.7 MWh, 4626.3 MWh and 12858.6 MWh during the three months monitoring period, respectively. The total energy consumption of the pollutant abatement systems is 19188.6MWh and the auxiliary power of pollutant abatement systems is 1.27%. Besides, the influence of unit load and pollutants inlet concentration on the energy consumption of the pollutant abatement systems was also investigated in this study. With the increasing of unit load, the real-time EPG of different pollutant abatement decreases although the operating power of pollutant abatement systems increases. High inlet concentration leads to more energy consumption while the energy consumption per unit emission reduction decreases.

Based on the operation data of the system, the different feasible energy-saving strategies were analyzed. For WFGD system, the flue gas system and the absorption system consume the most energy. The energy consumption of flue gas system mainly relates to the unit load, which can only be adjusted by following the requirement of power grid. The energy-saving effect for WFGD system can be achieved by the application of variable size fixed-rate capacity pumps or the variable frequency pumps allowing varying capacity. The variable frequency pump can adjust the volume of limestone slurry by the inlet concentration and the volume of flue gas at a certain liquid to gas ratio. So the power consumption of pump can be adjusted continuously by following the requirement of the current situation without wasting energy. By contrast, the application of the combination of variable size fixed-rate capacity pumps would be relatively more feasible and simple because the additional small pumps can be integrated with existing pumps. Besides, the application of variable frequency pumps requires the precise theoretical volume of slurry spraying and the consideration of the system delay and response lag, which would be very complicated and the barrier which prevents the application. For ESP system, the high-voltage system has the greatest energy-saving potential. The application of the intermitting power supply mode is an effective method to decrease the energy consumption of ESP system without decreasing the dust removal efficiency. Besides, the high-frequency power supply can also reduce the energy consumption without decreasing the removal efficiency. The intermitting power supply mode and high-frequency power supply have been applied in some power plants and shows a good energy-saving effect. For SCR system, the main energy consumption is caused by the resistance of catalysts in the SCR reactor. The reduction of pressure drop or resistance of the SCR reactor can be achieved by reducing the catalyst dosage or the operation of the soot blowing system. Reducing the catalyst dosage means the inlet concentration of SCR system should be reduced in order to ensure the removal efficiency when the amount of catalyst is reduced. Both the improvement of the Low-NO_x combustion system and the application of the hybrid SNCR-SCR system in the power unit can achieve the reduction of inlet concentration of SCR system.

The energy consumption of the pollutant abatement systems will impact the energy efficiency of the power plant, and the implementation of the Ultra-low emission limits in China will enhance the requirement of pollution control in power sector, which will increase energy consumption of the pollutant abatement systems. In consideration of the power unit with different capacity, equipment, and design requirements, the estimation of the energy consumption should be based on the survey of the system composition and operating parameters of each unit. The results in this study provide the reference estimation for the power unit which has the similar technology route. Because of the scale effect, small capacity power unit will consume more energy per unit power generation, compared with the big capacity power unit. The detailed energy consumption analysis of the pollutant abatements system will be necessary for the manager in the power plant, and the application of different feasible energy-saving strategies will reduce the additional economic burden and improve the energy efficiency of the power plant.

Acknowledgements

This study was supported by (1) the National Key Research and Development Plan of China (No. 2016YFC0209102), (2) the Natural Science Foundation of China (No.

U1609212), and (3) the Scientific Research Projects from Department of Environmental Protection, Zhejiang Province (No. 2015A018). Authors are also grateful to Chinese Ministry of Environmental Protection. Special thanks are given to the anonymous engineers in the case coal-fired power plant for the cooperation and comments on this work.

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Table 1. The subsystems of different pollutant abatement system

Pollutant abatement system	Subsystems

SCR	Flue gas system
	SCR reactor
	Ammonia supply system
ESP	High-voltage system
	Low-voltage system
	Flue gas system
WFGD	Absorption tower
	Flue gas system
	Absorbent prepration system
	Gypsm dehydration system
	Waste disposal system
	Other devices

Implication Statement

The application of pollutant abatement technologies increases the internal energy consumption of the power plant, which will lead to an increase of power generation costs. The real-time energy consumption of the different pollutant abatement systems in a typical power unit is analyzed based on the dynamic operating data. Further, the influence of different operating parameters on the operating power of the system and the possible energy-saving potential are analyzed.

Figure 1. The workflow and abatement effect of different pollutant abatement system.

Figure 2. Emission concentration of pollutant abatement system.

Figure 3. The energy consumption of pollutant abatement system.

Figure 4. The influence of unit load to the energy consumption of (a) SCR system, (b) ESP system and (c) WFGD system.

Figure 5. The influence of NO_x inlet concentration on the energy consumption of SCR system.

Figure 6. The influence of SO_2 inlet concentration on the energy consumption of WFGD system.

Figure 7. (a) Theoretical relation, (b) Actual relation and (c) Optimized relation between operating power of slurry circulation pump to SO_2 inlet concentration and unit load.

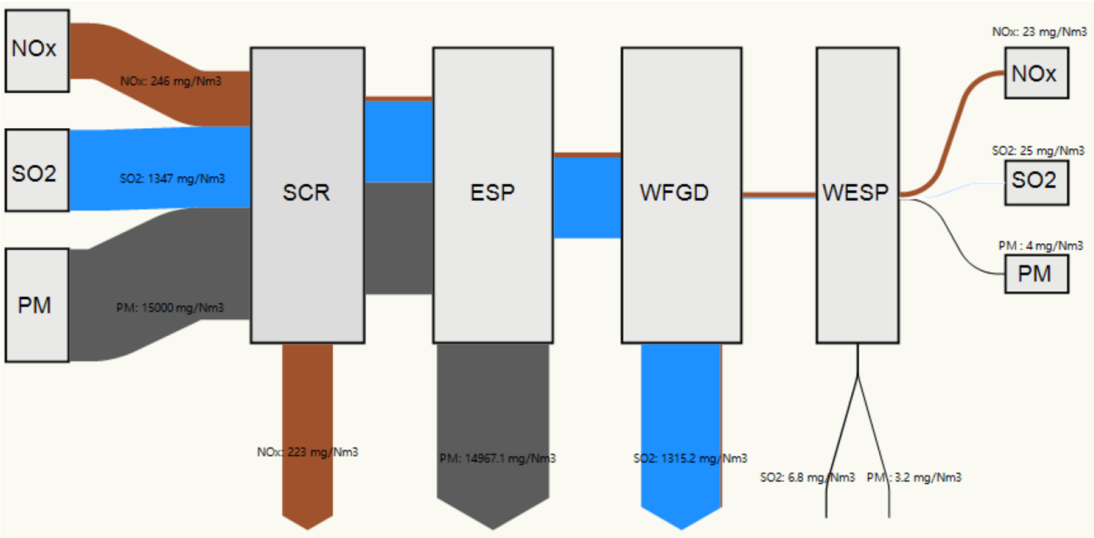

NOx
SO2
PM
NOx: 246 mg/Nm3
SO2: 1347 mg/Nm3
PM: 15000 mg/Nm3
SCR
ESP
WFGD
WESP
NOx: 23 mg/Nm3
NOx
SO2: 25 mg/Nm3
SO2
PM : 4 mg/Nm3
PM
NOx: 223 mg/Nm3
PM: 14967.1 mg/Nm3
SO2: 1315.2 mg/Nm3
SO2: 6.8 mg/Nm3
PM : 3.2 mg/Nm3

Figure1

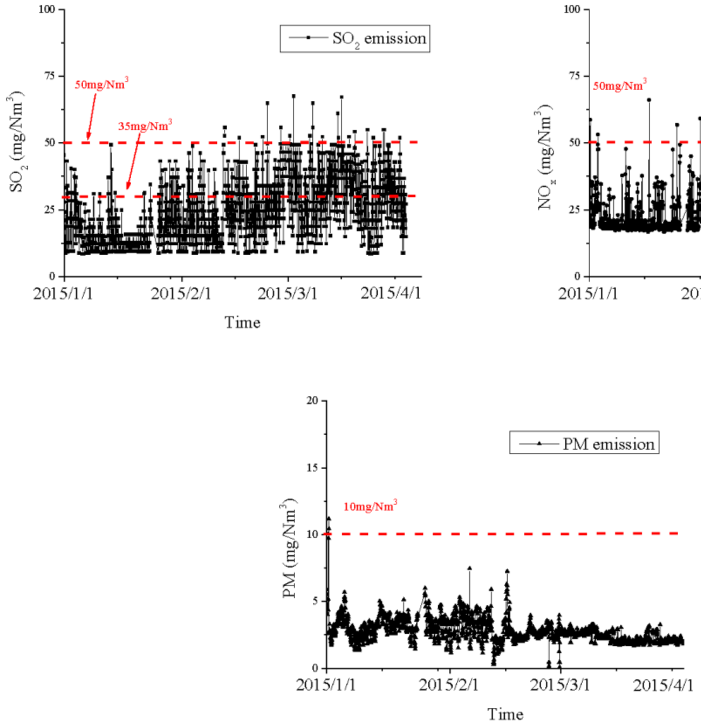

SO2 emission
50mg/Nm3
35mg/Nm3
SO2 (mg/Nm3)
Time
2015/1/1
2015/2/1
2015/3/1
2015/4/1
NOx emission
50mg/Nm3
NOx (mg/Nm3)
PM emission
10mg/Nm3
PM (mg/Nm3)

Figure2

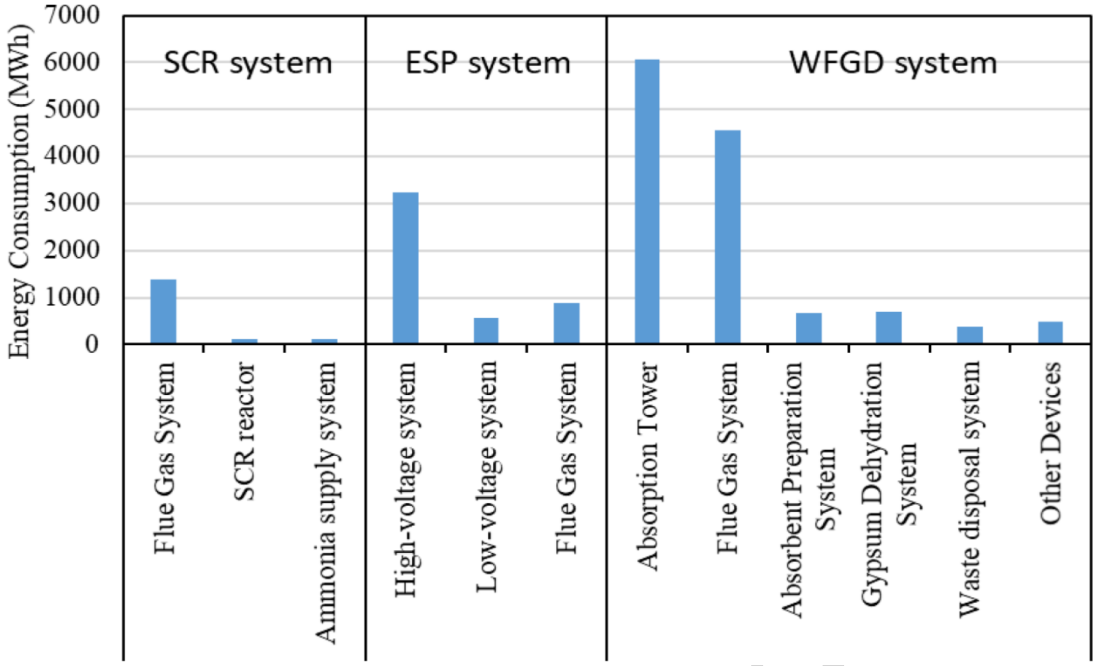
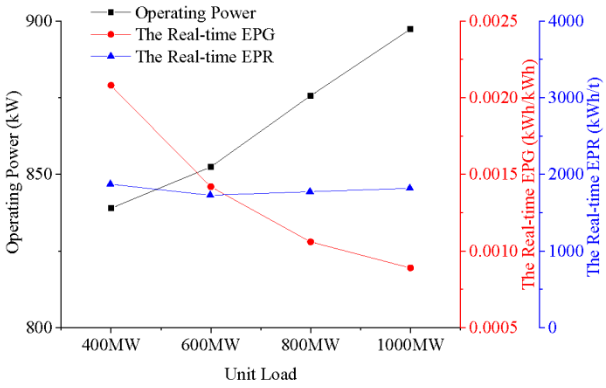
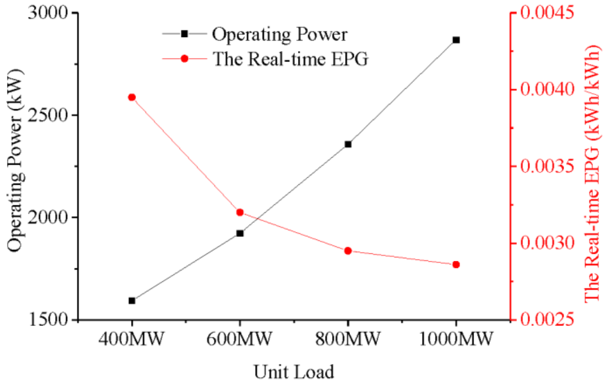

Energy Consumption (MWh)
7000
6000
5000
4000
3000
2000
1000
0
SCR system
ESP system
WFGD system
Flue Gas System
SCR reactor
Ammonia supply system
High-voltage system
Low-voltage system
Flue Gas System
Absorption Tower
Flue Gas System
Absorbent Preparation System
Gypsum Dehydration System
Waste disposal system
Other Devices

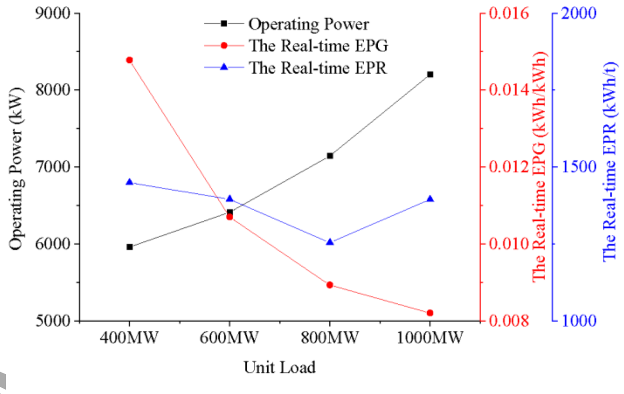
Figure 3



(a) SCR system



(b) ESP system



(c) WFGD system

Figure 4

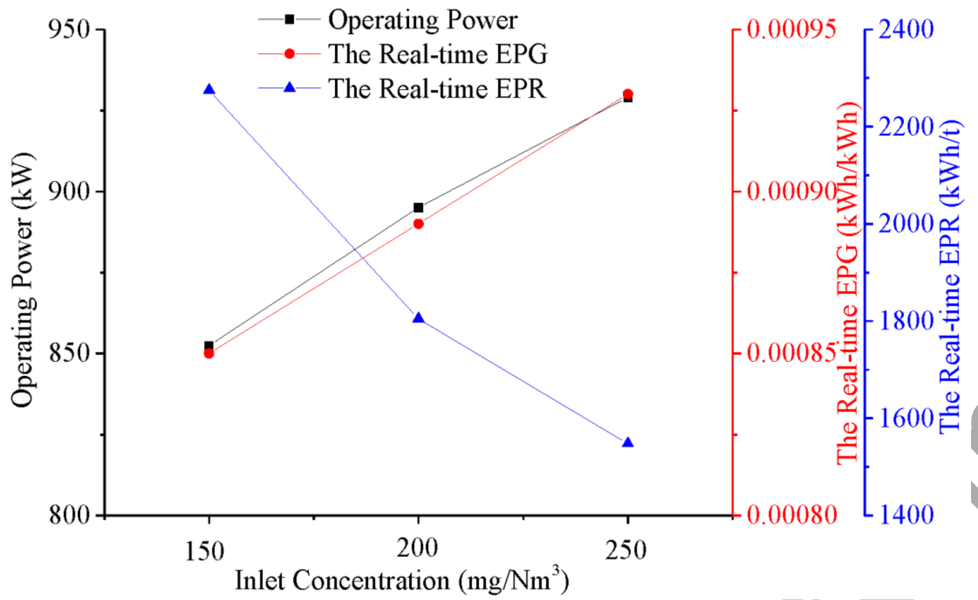
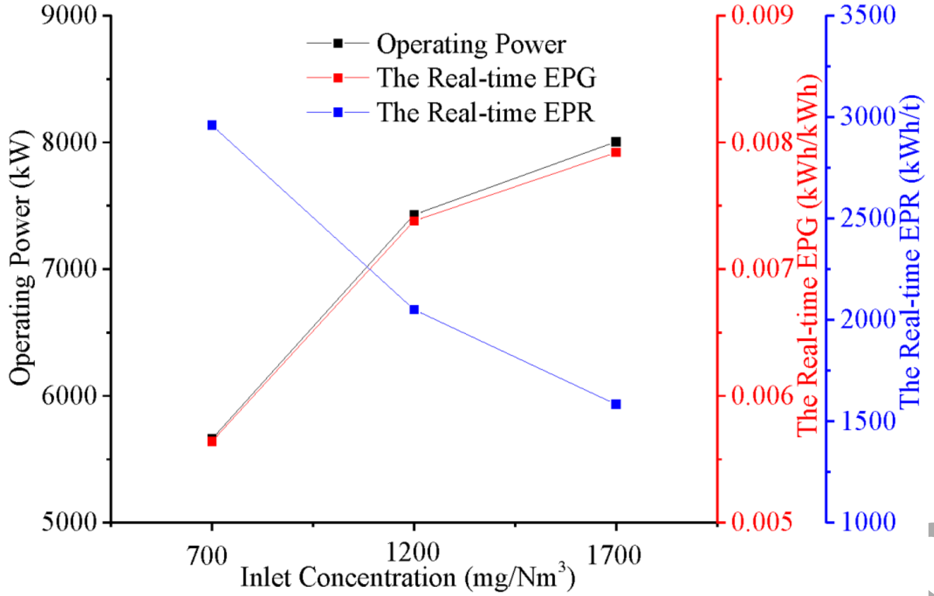
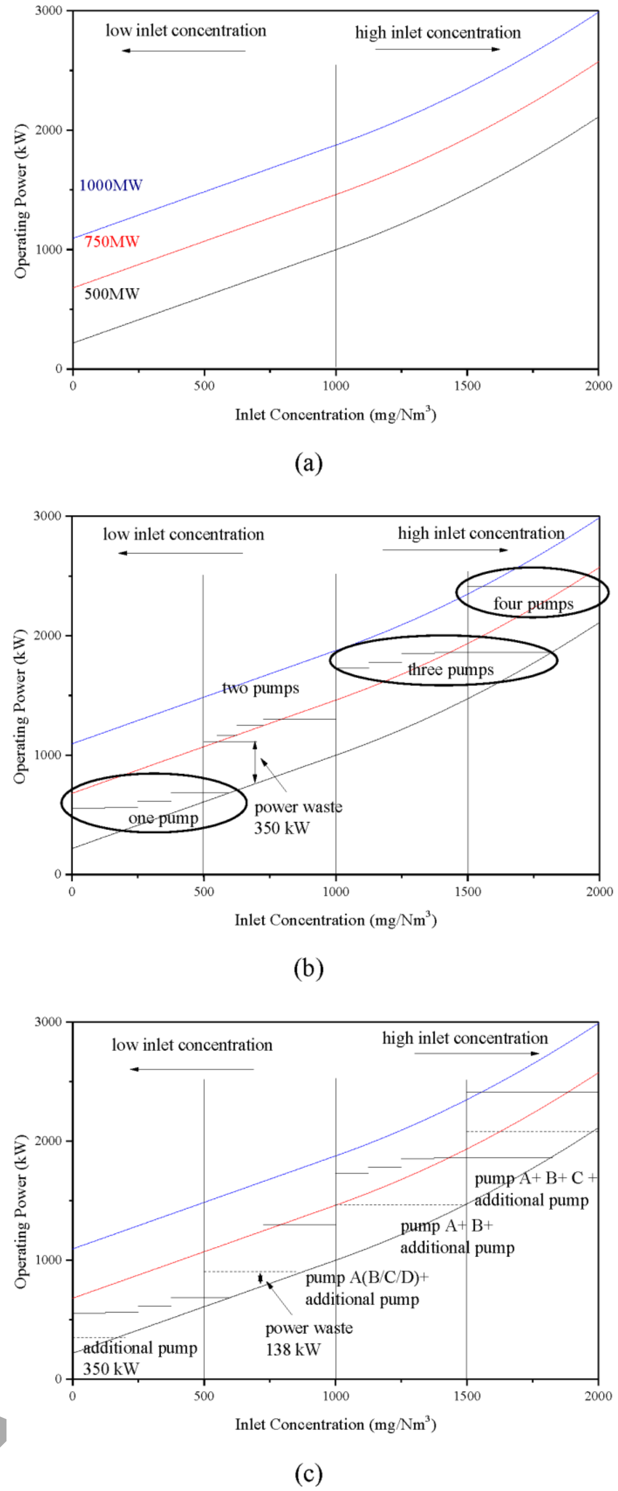

Operating Power
The Real-time EPG
The Real-time EPR
950
900
850
800
Operating Power (kW)
150
200
250
Inlet Concentration (mg/Nm3)
0.00095
0.00090
0.00085
0.00080
The Real-time EPG (kWh/kWh)
2400
2200
2000
1800
1600
1400
The Real-time EPR (kWh/t)

Figure 5



Operating Power
The Real-time EPG
The Real-time EPR
Operating Power (kW)
9000
8000
7000
6000
5000
700
1200
1700
Inlet Concentration (mg/Nm3)
The Real-time EPG (kWh/kWh)
0.009
0.008
0.007
0.006
0.005
The Real-time EPR (kWh/t)
3500
3000
2500
2000
1500
1000

Figure 6



low inlet concentration
high inlet concentration
1000MW
750MW
500MW
Operating Power (kW)
Inlet Concentration (mg/Nm3)
(a)
two pumps
four pumps
three pumps
one pump
power waste
350 kW
(b)
pump A+ B+ C +
additional pump
pump A+ B+
additional pump
pump A(B/C/D)+
additional pump
power waste
138 kW
additional pump
350 kW
(c)

Figure 7