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# Costs Due to Utility Fouling in China

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## ABSTRACT

This paper puts forward a method for evaluating the fouling costs of boilers and turbines in power plants. Furthermore, the Huaneng Dalian Power Plant and Changshan Power Plant are taken as examples for analyzing the costs of fouling. Based on data of on-site measurements in the above Power Plants, the costs due to fouling such as excess surface area, product loss, operating maintenance and increase of product costs are calculated. Results show that the total economical loss due to boiler and turbine fouling in China reaches 4.68 billion dollars, which covers is about 0.169% GDP of China in 2006.

## INTRODUCTION

Boilers and turbines are main facilities in power plants. Coal fired power plants have to face the fouling problems, such as ash deposit and slagging of boilers and scales and silt on the inside of condenser tubes. Because of the low thermal conductivity and partial occupation of passage of working fluid, the fouling layer would produce a large additional thermal resistance and pressure drop. As a result, the heat flux of boilers would fall, the temperature of exhaust flue gas would increase, and the boiler efficiency would go down, and power consumption would go up. For maintaining the boiler output, the fuel consumption must be increased, which could produce more ash, and leads to more serious fouling, or may cause boilers failure. On the other hand, fouling of condensers could result in the vacuum of condenser drop and make the efficiency of thermal cycle, economy and availability of unit decrease (YANG, 1993). In order to solve the fouling problems, useful work has been done. Thackery (1980) and Nostrand et al. (1981) deemed the fouling costs consisted of capital expenditure, additional fuel, maintenance charge and lost production, and estimated the fouling costs of the refinery industry in USA and the all industries in UK. Steinhagen et al. (1990), Garrett-Price et al. (1985), Pritchard (1987), Müller-Steinhagen (2000) also did useful work. The utility boilers in China usually fire poor quality coal, so the fouling problems may be more serious than that in developed countries. So far there is little information on the impacts of utility fouling on operating costs in China. The present research proposes a method for estimating the costs due to power plant fouling in China, and based on the parameters of Changshan Power Plant and Huaneng Dalian Power Plant, the pertinent fouling costs are calculated.

## COSTS DUE TO EXCESS AREA

In order to maintain the output after a heat exchanger is fouled, designers usually take more heat transfer surface area than needed to allow for the effect of fouling. The additional area is called excess heat transfer surface area. According to the Standard method of heat calculation for utility boiler (Kuenezov, 1976) used commonly in China, the excess heat transfer surface area of the boilers and condensers of 100MW and 200MW units in the Changshan Power Plant is calculated (Table 1 and 2). The fouled heat transfer surface area is the designed value in Table 1and 2. The clean heat transfer surface area is obtained by setting the fouling factor as zero or the cleanliness factor as unity. The percentage is the ratio of the excess heat transfer surface area to the total fouled heat transfer surface area. The boiler price in China is about 39474 dollars per megawatt unit. The condenser price in China is about 5263 dollars per megawatt unit. Table 1 and Table 2 show that the total excess heat transfer surface area of boilers is about 29%. The total excess heat transfer surface areas of condensers of 100MW and 200MW are about 20.0% and 12.0%, respectively. The costs due to excess heat transfer surface area are 1.22 million dollars for the 100MW boiler and turbines, and 2.42 million dollars for the 200MW boiler and turbines. The mean increased cost is approximately $12.14\times10^3$ dollars per megawatt unit. Table 3 gives the costs due to the excess heat transfer surface area of boilers and turbines used in China from 1997 to 2006.

Table 1 Excess heat transfer surface area and fouling costs of 100MW unit

| Item | Fouled $m^2$ | Clean $m^2$ | Percent % | Cost$\times10^{-4}$ \$ |
|---|---|---|---|---|
| Furnace | 1248 | 638.3 | 1.91 | 7.539 |
| Platen | 727 | 123.8 | 1.88 | 7.421 |
| Superheater 1* | 717 | 398.7 | 0.99 | 3.907 |
| Superheater 2+ | 836 | 473.6 | 1.13 | 4.460 |
| Wall superheater | 213.4 | 103.6 | 0.34 | 1.353 |
| Economizer 1* | 1172 | 761.0 | 1.28 | 5.052 |
| Air preheater 1* | 8140 | 6083.8 | 6.43 | 25.381 |
| Economizer 2+ | 2650 | 2108.6 | 1.69 | 6.671 |
| Air preheater 2+ | 16300 | 12210.4 | 12.78 | 50.447 |
| Boiler | 32003.4 | 22901.6 | 28.44 | 112.26 |
| Condenser | 6815 | 5453.8 | 20.0 | 10.526 |
| Power plants | 38818.4 | 28355.4 | 26.96 | 122.78 |

*'1' denotes the part in high temperature flue gas
+'2' denotes the part in low temperature flue gas

Table 2 Excess heat transfer surface area and fouling costs of 200MW unit

| Item | Fouled $m^2$ | Clean $m^2$ | Percent % | Cost$\times10^{-4}$ \$ |
|---|---|---|---|---|
| Furnace | 2958.4 | 1701.0 | 1.81 | 14.297 |
| Screen | 1598 | 442.1 | 1.66 | 13.142 |
| Superheater | 776.6 | 413.8 | 0.52 | 4.125 |
| Reheater 1 | 4795 | 3214.1 | 2.28 | 17.975 |
| Wall superheater | 411.9 | 219.8 | 0.28 | 2.184 |
| Attached superheater | 215 | 132.6 | 0.12 | 0.936 |
| Reheater 2 | 2298.5 | 1458.2 | 1.21 | 9.553 |
| Economizer | 9086 | 6247.7 | 4.09 | 32.272 |
| Air preheater | 47294 | 35471.3 | 17.03 | 134.42 |
| Boiler | 69433.4 | 49300.6 | 29 | 228.91 |
| Condenser | 13024.5 | 11461.6 | 12.0 | 12.631 |
| Power plants | 82457.9 | 60762.2 | 26.31 | 241.54 |

Table 3 Excess heat transfer surface area and costs in China

| Year | Capacity (MW) | Increment (MW) | Cost×10$^{-8}$ \$ /year |
|---|---|---|---|
| 1997 | 192410 | 13550 | 1.644 |
| 1998 | 209880 | 17470 | 2.121 |
| 1999 | 223430 | 13550 | 1.644 |
| 2000 | 237540 | 14110 | 1.713 |
| 2001 | 253140 | 15600 | 1.893 |
| 2002 | 265550 | 12410 | 1.506 |
| 2003 | 289770 | 24220 | 2.940 |
| 2004 | 324900 | 35130 | 4.264 |
| 2005 | 508000 | 183100 | 22.230 |
| 2006 | 585800 | 77800 | 9.444 |

## EXTRA LOST COST

### 1. Boilers

The key reason for the decrease of the boiler thermal efficiency is that the rise of the exit gas temperature causes the increase of waste heat loss. The boiler load and the excess air coefficient also influence the exit gas temperature. After eliminating the effect of boiler load and the excess air coefficient, the dependence of the waste heat loss or boiler thermal efficiency on the fouling thermal resistance is obtained. Then the additional coal consumption due to the decrease of boiler thermal efficiency could be calculated. According to the National Standard of P.R. China (1996), the waste heat loss $q_2$ is defined as:

$$q_2 = \frac{Q_{2,\mathrm{dg}} + Q_{2,\mathrm{mo}}}{Q_r} \times 100 \qquad (1)$$

The heat loss due to dry flue gas $Q_{2,\mathrm{dg}}$ and the heat loss due to moisture in the flue gas $Q_{2,\mathrm{mo}}$ are expressed respectively

$$Q_{2,\mathrm{dg}} = V_{\mathrm{dg}} c_{\mathrm{p,dg}} \left(t_{\mathrm{eg}} - t_{\mathrm{Ra}}\right) \qquad (2)$$

$$Q_{2,\mathrm{mo}} = V_{\mathrm{mo}} c_{\mathrm{p,mo}} \left(t_{\mathrm{eg}} - t_{\mathrm{Ra}}\right) \qquad (3)$$

where the exit gas temperature $t_{\mathrm{eg}}$ and reference air temperature $t_{\mathrm{Ra}}$ are measured on-line; the specific heat at constant pressure of the dry flue gas $c_{\mathrm{p,dg}}$ is taken the average value at mean temperature; and the specific heat of vapor $c_{\mathrm{p,mo}}$ is calculated on-line by a working fluid property program. The amount of dry gas $V_{\mathrm{dg}}$ and the amount of vapor in the flue gas $V_{\mathrm{mo}}$ are given by:

$$V_{\mathrm{dg}} = 1.866 \frac{\mathrm{C_{ar}} + 0.375\mathrm{S_{ar}}}{100} + (0.8\frac{\mathrm{N_{ar}}}{100} + 0.79V^0) + (\alpha_{\mathrm{eg}} - 1)V^0 \qquad (4)$$

$$V_{\mathrm{mo}} = 1.24\left(\frac{9\mathrm{H_{ar}} + \mathrm{M_{ar}}}{100} + \frac{1.043\alpha_{\mathrm{eg}} V^0 \mathrm{d_a}}{804}\right) \qquad (5)$$

The coal composition is obtained by ultimate analysis once a day, and the results ( $\mathrm{C_{ar}}$, $\mathrm{H_{ar}}$, $\mathrm{O_{ar}}$, $\mathrm{N_{ar}}$, $\mathrm{S_{ar}}$, $\mathrm{A_{ar}}$ and $\mathrm{M_{ar}}$ ) are put into the management information system (MIS). The air humidity $\mathrm{d_a}$ is taken as 10g/kg. The excess air coefficient is calculated by virtue of the measured oxygen content $O_2$ with the following equation:

$$\alpha = \frac{21}{21 - O_2} \qquad (6)$$

In order to remove the effect of the excess air coefficient on the waste heat loss, a reference value of excess air coefficient is needed. The reference value $\alpha_{\mathrm{eg,R}}$ can be obtained by the interpolation of the excess air coefficients at the loads of 100%, 75% and 50% supplied by the manufacturer. The waste heat loss due to the increase of excess air is:

$$\Delta q_{2,\mathrm{a}} = (c_{\mathrm{p,a}} + 0.0016\mathrm{d_a} c_{\mathrm{p,mo}}) \times V^0 (\alpha_{\mathrm{eg}} - \alpha_{\mathrm{eg,R}})(t_{\mathrm{eg}} - t_{\mathrm{Ra}}) \qquad (7)$$

Based on the waste heat losses at 100%, 75% and 50% load supplied by the manufacturer, interpolation gives the reference value of waste heat loss $q_{2,R}$. Since fouling has little effect on the combustible loss $q_3$, the unburned carbon loss $q_4$, the dissipation heat loss $q_5$ and the cinder loss $q_6$, the reduction of boiler efficiency is equal to the increase of waste heat loss, that is to say

$$\Delta\eta = \Delta q_2 = q_2 - q_{2,R} - \Delta q_{2,\mathrm{a}} \qquad (8)$$

Thus the cost duo to fouling $C_{\mathrm{f}}$ is

$$C_{\mathrm{f}} = \int_0^{\tau} (1000 P_{\mathrm{gen}} b_{\mathrm{s}} \frac{\Delta q_2}{\eta} Y_{\mathrm{m}}) d\tau \qquad (9)$$

### 2. Condensers

The lost products cost due to fouling consists of two parts. One is that the fouling decreases heat transfer performance of condenser, and leads the vacuum of condenser to be reduced, increase the temperature of the exhausted steam, and reduce power output. In addition, serious fouling results to plant shutdown. The later is infrequent, so this paper only calculates the former.

Changing rate of turbine power $N$ with time $\tau$ by fouling is given by:

$$\frac{\partial N}{\partial \tau} = \frac{\partial N}{\partial p_{\mathrm{c}}} \frac{\partial p_{\mathrm{c}}}{\partial t_{\mathrm{s}}} \frac{\partial t_{\mathrm{s}}}{\partial U} \frac{\partial U}{\partial R_{\mathrm{f}}} \frac{\partial R_{\mathrm{f}}}{\partial \tau} \qquad (10)$$

When the back pressure $p_{\mathrm{c}}$ is given, the changing rate of turbine power $N$ with back pressure $\partial N/\partial p_{\mathrm{c}}$ is a constant in a large range, which is given by the manufacturer. Because the condenser back pressure $p_{\mathrm{c}}$ depends on the steam condensation temperature $t_{\mathrm{s}}$, $\mathrm{d}p_{\mathrm{c}}/\mathrm{d}t_{\mathrm{s}}$ may be calculated according to steam property.

According to Fig.1, the steam condensation temperature $t_{\mathrm{s}}$ is:

$$t_{\mathrm{s}} = t_{\mathrm{wi}} + \Delta t_{\mathrm{w}} + \delta t \qquad (11)$$

where the inlet temperature of the cooling water $t_{\mathrm{wi}}$ is determined by the local climate and season, but there is a little change. The condenser terminal difference is given:

$$\delta t = \frac{\Delta t_{\mathrm{w}}}{\exp\left(\frac{UF_{\mathrm{c}}}{D_{\mathrm{w}}c_{\mathrm{w}}}\right)-1} \quad (12)$$

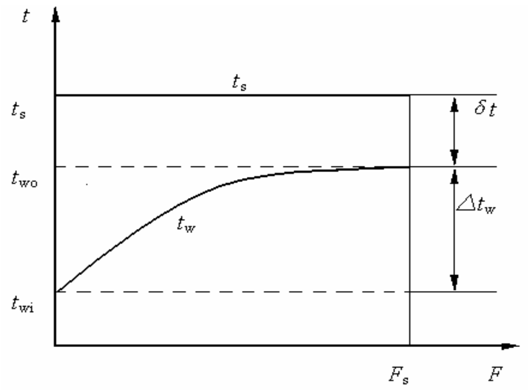


Fig.1Temperature profiles of condenser

where $F_{\mathrm{c}}$ is the condenser heat transfer area, $c_{\mathrm{w}}$ is the specific heat of cooling water, which can be calculated based on the steam property. It is known from Eq. (12):

$$\Delta t_{\mathrm{w}} = \delta t\left[\exp\left(\frac{UF_{\mathrm{c}}}{D_{\mathrm{w}}c_{\mathrm{w}}}\right)-1\right] \quad (13)$$

Substituting Eq. (13) into Eq. (11) gives

$$t_{\mathrm{s}} = t_{\mathrm{wi}} + \delta t \exp\left(\frac{UF_{\mathrm{c}}}{D_{\mathrm{w}}c_{\mathrm{w}}}\right) \quad (14)$$

The changing rate of steam condensation temperature $t_{\mathrm{s}}$ with heat transfer coefficient $U$ is:

$$\frac{\partial t_{\mathrm{s}}}{\partial U} = -\frac{\Delta t \exp\left(\frac{2UF_{\mathrm{c}}}{c_{\mathrm{w}}D_{\mathrm{w}}}\right)\frac{F_{\mathrm{c}}}{c_{\mathrm{w}}D_{\mathrm{w}}}}{\left[\exp\left(\frac{UF_{\mathrm{c}}}{c_{\mathrm{w}}D_{\mathrm{w}}}\right)-1\right]^2} + \delta t \exp\left(\frac{UF_{\mathrm{c}}}{D_{\mathrm{w}}c_{\mathrm{w}}}\right)\frac{F_{\mathrm{c}}}{c_{\mathrm{w}}D_{\mathrm{w}}} \quad (15)$$

The fouling resistance can be derived from

$$R_{\mathrm{f}} = 1/U - 1/U_{\mathrm{c}} \quad (16)$$

The overall heat transfer coefficient under the clean condition $U_{\mathrm{c}}$, is given by the Bermann equation. The coefficients $\beta$ indicating the cleanness of heat transfer is taken the upper limit during the calculation. The exhausted steam rate $D_{\mathrm{s}}$ is calculated by the Flugel equation according to last stage outlet pressure $D_{\mathrm{s}}$ the exhaust wetness of the steam turbine at a given load could be obtained by interpolation from the wetness in 100%, 75% and 50% load supplied by the manufacturer. The cooling water flow rate $D_{\mathrm{w}}$ could be calculated according to heat balance. The actual overall heat transfer coefficient of the condenser $U$ is calculated based on the cooling water flow rate, the exhausted steam temperature, the inlet and the outlet temperatures of the cooling water measured on-line. Then the fouling thermal resistance could be determined from Eq.(16), and the differential, and the derivative is :

$$\frac{\partial U}{\partial R_{\mathrm{f}}} = -\frac{{U_{\mathrm{c}}}^2}{(1+U_{\mathrm{c}}R_{\mathrm{f}})^2} \quad (17)$$

Since fouling could not be removed completely during the cleaning, the remaining fouling which is the initial fouling resistance of the next cleaning cycle $R_{\mathrm{f,i}}$ could produce loss. The loss of initial fouling resistance $\Delta N_{\mathrm{i}}$ is:

$$\Delta N_{\mathrm{i}} = \frac{\partial N}{\partial p_{\mathrm{c}}}\frac{\partial p_{\mathrm{c}}}{\partial t_{\mathrm{s}}}\frac{\partial t_{\mathrm{s}}}{\partial U}\frac{\partial U}{\partial R_{\mathrm{f}}}R_{\mathrm{f,i}} \quad (18)$$

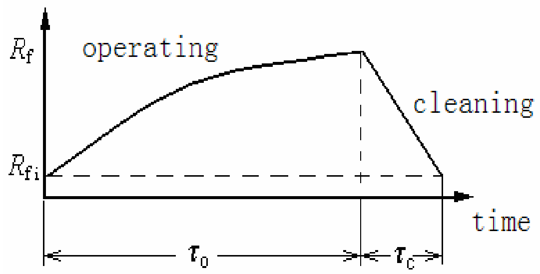


Fig.2 Fouling resistance versus time

During the operating period $\tau_0$, the reduced turbine power at time $\tau$ due to fouling is

$$\Delta N_{\mathrm{o}}(\tau) = \Delta N_{\mathrm{i}} + \int_0^{\tau}\frac{\partial N}{\partial \tau}d\tau \quad (19)$$

If the change of fouling resistance with time is linear during cleaning period, its gradient is:

$$\partial R_{\mathrm{f}} / \partial \tau = -[R_{\mathrm{f}}(\tau_{\mathrm{o}}) - R_{\mathrm{f,i}}] / \tau_{\mathrm{c}} \quad (20)$$

where $R_{\mathrm{f}}(\tau_0)$ is the initial fouling resistance before cleaning. $\partial N / \partial \tau$ can be derived from Eq. (10). At $\tau$ time of cleaning the reduced work of turbine is:

$$\Delta N_{\mathrm{c}}(\tau) = \Delta N_{\mathrm{o}}(\tau_{\mathrm{o}}) + \int_0^{\tau}\frac{\partial N}{\partial \tau}d\tau \quad (21)$$

All the additional cost due to the power reduction of the turbine in a cleaning cycle is:

$$C_{\mathrm{N}} = \int_0^{\tau_o}\Delta N_{\mathrm{o}}(\tau)d\tau\eta_{\mathrm{m}}\eta_{\mathrm{g}}y + \int_0^{\tau_c}\Delta N_{\mathrm{c}}(\tau)d\tau\eta_{\mathrm{m}}\eta_{\mathrm{g}}y \quad (22)$$

## MAINTENANCE COST

The total operating costs of a boiler due to sootblowing $C_{\mathrm{tot}}$ involves the consumed working fluid $C_{\mathrm{w}}$, the consumed power $C_{\mathrm{N}}$, maintenance and overhaul charge $C_{\mathrm{mai}}$ and depreciation charge $C_{\mathrm{dep}}$:

$$C_{\mathrm{tot}} = C_{\mathrm{w}} + C_{\mathrm{N}} + C_{\mathrm{mai}} + C_{\mathrm{dep}} \quad (23)$$

The daily steam consumption used by sootblowers is the product of the flux of a sootblower $q$, the running time $\tau_{\mathrm{s}}$ and the frequency $n$:

$$\dot{m}_d = q \times \tau_s \times n \quad (24)$$

The annual steam consumption depends on the daily steam consumption and the annual operation hours $H$:

$$\dot{m}_y = (H/24)\times \dot{m}_d \quad (25)$$

Converting to coal consumption:

$$B_1 = \dot{m}_2 / m_1 \quad (26)$$

The corresponding cost is

$$C_w = B_1 \times Y_m \quad (27)$$

The equivalent specific standard coal consumption of the consumed power $P_m$ of the sootblowing motor is:

$$B_2 = P_m \times \tau_s \times b_s (H/24) \quad (28)$$

The corresponding cost is

$$C_N = B_2 \times Y_m \quad (29)$$

Maintenance cost for a condenser $C_{mai}$ is the additional cost of condenser cleaning, including the cost of lost rubber balls used to remove fouling in the unclean tubes and the depreciation charges of the rubber balls $C_b$ , the power consumption of cleaning equipment $C_{pump}$ , the labour cost $C_p$, the depreciation charges of equipment $C_{dep}$ and miscellaneous costs $C_{mis}$

$$C_{mai} = C_{pump} + C_b + C_p + C_{dep} + C_{mis} \quad (30)$$

The cost of lost rubber balls and the depreciation charges of the rubber balls are:

$$C_b = (1-\eta_b)ny_b + ny_b\tau_c/\tau_b \quad (31)$$

The power consumption of the rubber ball cleaning system is:

$$C_{pump} = N_m \tau_c y_{el} \quad (32)$$

## CASE STUDY

The utility boiler and condenser of No.4 unit of 350MW in Huaneng Dalian Power Plant are used as examples to calculate the fouling cost. There is a performance monitoring system in Huaneng Dalian Power Plant. The system can calculate the boiler efficiency $\eta$ and specific standard coal consumption $b_s$ on-line based the measured parameters. There are 56 short sootblowers installed on the region of the waterwall of the boiler, 6 long sootblowers on the region of the platen superheater, 8 long sootblowers on the reheater, 8 long sootblowers on the economizer, and 2 rotating element sootblowers on the preheater. The long and rotating element sootblowers operate once a day, but the short sootblowers run according to the operating circumstance. All the sootblowers are controlled by a computer program, but can be changed to manual control. After the operator sets the operate mode, the sootblowers run automatically one by one. The coal fired in the power plant is the bitumenite produced in the north part of Shanxi province, whose properties are given in Table 4. Table 5 lists the operating conditions of the sootblowers. The parameters collected are the oxygen content of flue gas $O_2$, the exit gas temperature $t_{eg}$ , the boiler load $D$ and the generator power $p_{gen}$ etc. The experiment lasted 24 hours and all the sootblowers ran once during the experiment.

Table 4 Ultimate analysis of Coal used in Huaneng Dalian Power Plant

| $C_{ar}$ % | $H_{ar}$ % | $O_{ar}$ % | $N_{ar}$ % | $S_{ar}$ % | $A_{ar}$ % | $M_{ar}$ % | $Q_{ar,net}$ kJ/kg |
|---|---|---|---|---|---|---|---|
| 58.56 | 3.36 | 7.28 | 0.79 | 0.63 | 19.77 | 9.61 | 22405 |

Table 5 Parameters of soot blowing system of No.4 unit in Huaneng Dalian Power Plant

| Item | Symbol | Value | Unit |
|---|---|---|---|
| Steam pressure | $P_s$ | 1.28-1.47 | MPa |
| Steam temperature | $t$ | ≤350 | ℃ |
| Steam flux | $q$ | 4.158 | kg/s |
| Frequency | n | 1 | 1/day |
| Operating time | $\tau_s$ | 360 | s |
| Power of motor | $P_m$ | 5.4 | kW |
| Output steam per ton standard coal | $M_1$ | 10 | t/t |
| Operating hours | H | 7000 | h/year |
| Price of standard coal | $Y_m$ | 39.47 | $ /t |

The double-flow steam turbine in Huaneng Dalian Power Plant has two double-flow condensers connected with the two exhaust ports of the steam turbine. Sea water is used as cooling water, which contains large quantity of microbes, algae, barnacles, small fish, sediment and some salt. As a result of this, fouling is easily formed on the waterside of the condenser.

Fig. 3, Fig. 4 and Fig. 5 give the dependence of the parameters of the boiler operation with time. The measuring point of oxygen content is located in the economizer exit. Introducing $O_2$ into Eq. (6) yields the excess air coefficient. The calculated value plus the correction from the standard (Kuenezov, 1976) gives the excess air coefficient at the exit of the preheater. Based on Eq.(8), Fig.5 depicts the relationship between the increment of the heat loss and time. It is seen that the exit temperature increases with time between sootblowing operations. During sootblowing, the exit gas temperature goes down, the boiler efficiency goes up with time.

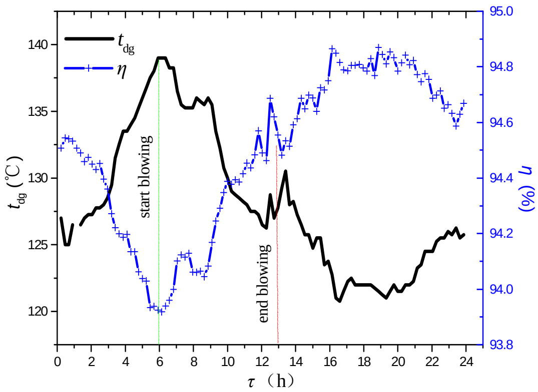


Fig. 3 Exit gas temperature and boiler efficiency

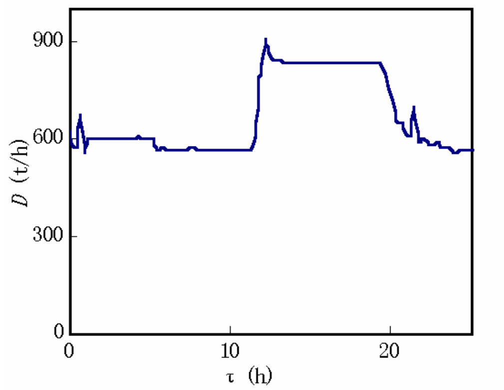


Fig. 4 Boiler load curve

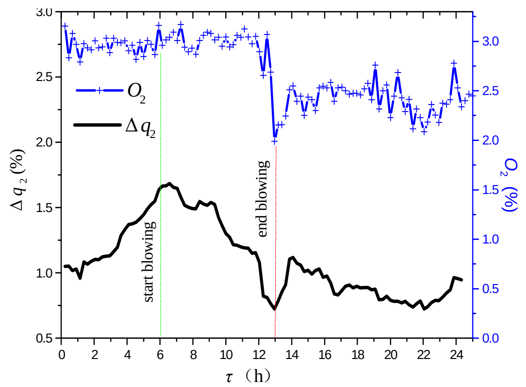


Fig. 5 Curve of oxygen content and dependence of $\Delta q_2$

The heat transfer coefficients of the condenser and the fouling resistance on the condenser (Fig.6) with time could be determined by the different ways under the operating conditions. It is known from Fig.6 that the fouling resistance increases with time, and the overall heat transfer coefficients decrease with time during the operating time. As a result, the terminal temperature difference will increase with time, the vacuum of the condenser will reduce, and the power output of the steam turbine will be low. The fouling resistance is reduced obviously during the cleaning process, the overall heat transfer coefficients go up significantly, and the terminal temperature difference decreases. It is important to mention that the load during the experimental period changed (Fig.7). The dependence of the terminal temperature difference on time shown in Fig.7 has eliminated the effect of load. This confirms that with increasing of fouling resistance the terminal temperature difference increases during operation, and the vacuum of the condenser is reduced. The effect of fouling resistance on the steam turbine power is shown in Fig.8. It is seen that with increasing fouling resistance, the lost power of the steam turbine increases. So the less fouling resistance is the better.

Based on the measured parameters, the waste heat loss $q_2$ can be calculated with Eq.(1), Eq.(7) gives the effect of the excess air coefficient on the boiler efficiency $\Delta q_{2,a}$ . Introducing $q_2$ and $\Delta q_{2,a}$ into Eq.(8) yields the change of boiler efficiency due to fouling. Using the boiler efficiency $\eta$ , the generator power $p_{gen}$ and specific standard coal consumption $b_s$ attained from the performance monitoring system, integrating numerically Eq.(9) over a running period at 10 min time interval produces the cost during the running period as 5263.16 dollars. The annual cost is 5263.16×(7000÷24)=1.535 $\times 10^6$ dollars, or 4381.58 dollars per year per megawatt unit.

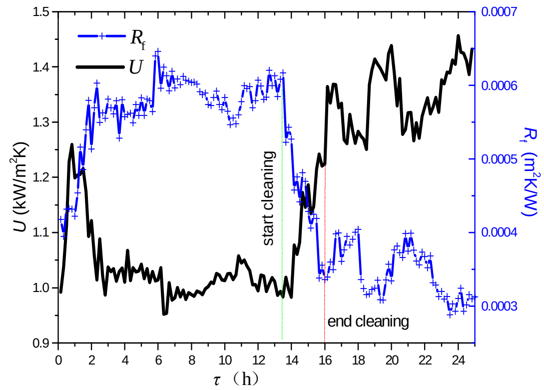


Fig. 6 Overall heat transfer coefficient profile and fouling resistance on condenser versus time

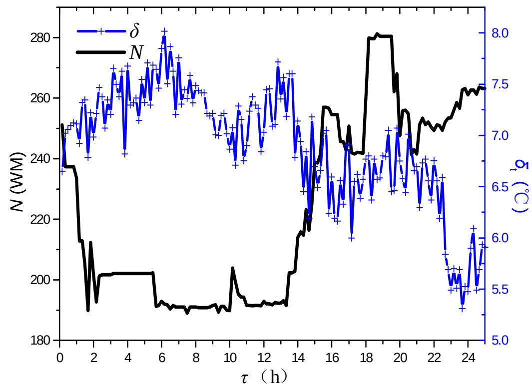


Fig. 7 Lost power of the steam turbine and terminal temperature difference of the condenser versus time

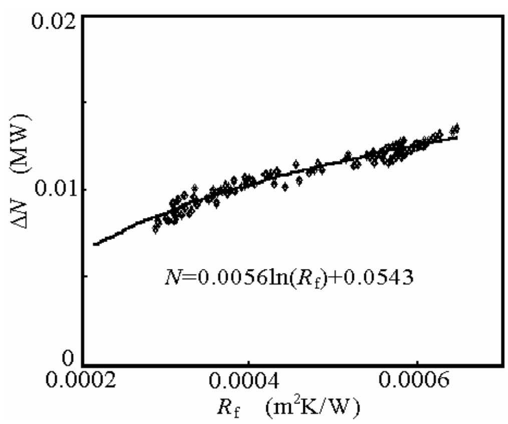


Fig. 8 Lost power of the steam turbine due to fouling resistance

Using the data in Table 3 and Table 4, from Eq.(24) the consumption of the sootblowing steam is obtained as 1497kg/day. The annual steam consumed is gained from Eq.(25) as 43.663t, is converted to standard coal consumption as 43.663t/year with Eq.(26). From Eq.(27), the annual steam expenditure is 1723.54 dollars. The annual equivalent coal consumption of the power consumed by a sootblower motor is 0.04489t. The annual motor expenditure is 1.776 dollars. The total expenditure of 80 sootblowers is (1723.54+1.776) × 80 = 138026.31 dollars. Keeping and overhauling the sootblowers. A sootblower costs 2631.58 to 7894.73 dollars in China. Taking 3947.37 dollars as its price, the service lifetime is 10 years, the depreciation charge is 80×3947.37÷10=31578.94 dollars/year. Then the costs due to sootblowing are obtained from Eq.(23) as 0.171 million dollars, or 486.84 dollars per year per megawatt unit.

The cleaning system of condenser in Huaneng Dalian Power Plant operates three hours, once a day. The cost due to lost capacity for work of the steam turbine is 1689.34 dollars in a cleaning interval by integrating Eq. (22) numerically. Maintenance cost is 70.01 dollars per day, which can be derived from Eq.(30).

The sum of three correlating factors shows that the annual fouling costs of a 350MW unit is 2.23 million dollars, averaged 6380.79 dollars per megawatt unit. The statistical data show that the total capacity of thermal power plants is 585800MW in China in 2006. The annual fouling costs due to the additional fuel and the maintenance are $585800 \times 6380.79 = 3.74 \times 10^9$ dollars. Adding the costs due to excess heat transfer surface area $0.944 \times 10^9$ dollars, the total costs are 4.68 billion dollars. The gross domestic product (GDP) of China is 2755.39 billion dollars in 2006. The costs due to utility fouling are about 0.169% of GDP of China. Obviously the evaluation does not involve the costs of transportation, installation and so on. For developed countries the fouling costs are about 0.25% of GNP (Müller-Steinhagen, 2000). Counting for other industries, for China the fouling costs may be more than that in developed countries.

## CONCLUSIONS

The costs due to fouling consist of excess heat transfer surface area, additional fuel and maintenance. The case study shows:

1. The excess heat transfer surface area of utility boilers and turbines is about 27%, the increased investment is 12144.73 dollars per megawatt unit.
2. The cost due to the additional fuel lost is about 2.04 million dollars for the 350MW unit, that is some 6065.78 dollars per year per megawatt unit.
3. The maintenance expenditure is 0.19 million dollars for the 350MW unit, that is about 493.42 dollars per year per megawatt unit.
4. The total capital cost due to power plants fouling in China is 4.68 billion dollars in 2006, which covers about 0.169% of China GDP.

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## REFERENCES

Garrett-Price, B.A. et al, 1985, Fouling of Heat Exchangers - Characteristics, Costs, Prevention, Control and Removal. Noyes Publications, Park Ridge, New Jersey.

Kuenezov, H. B., Mitor, B. B., Dubovskiy, I. E., Kalasina, Z. C., 1976, Standard method of heat calculation for utility boiler, Beijing: Machinery industry press.

Müller-Steinhagen, H., 2000, Heat Exchanger Fouling. Germany: Publico Publications.

National Standard of P.R. China GB10184-88, 1996, Performance test code for utility boiler, Beijing: Electric power press of China.

Pritchard, A.M., 1987, The Economics of Fouling. in Fouling Science and Technology, edts. Melo, L.F, Bott, T.R. and Bernardo, C.A. NATO ASl Series E, Vol. 145, KIuwer Academic Publishers.

Steinhagen, R., Müller-Steinhagen, H.M. and Maani, K., 1990, Heat Exchanger Applications, Fou1ing Problems and Fouling Costs in New Zealand Industries, Ministry of Commerce Report RD8829.

Thackery, P.A., 1980, The Cost of Fouling in Heat Exchanger Plant, Effluent and Water Treatment Journal.

Van Nostrand, W.L., Leach, Jr, S.H. and Haluska, J.L., 1981, Economic Penalties Associated with the Fouling of Refinery Heat Transfer Equipment, in "Fouling of Heat Transfer Equipment", eds, Somerscales Knudsen.

YANG Shan-rang, 1993, Steam Turbine Condensing Equipment and its Operating Administration. Beijing: Water Resource and Electric Power Press.