Economical Study of a Boiler Fueled with DME

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Abstract. In this paper, the cost-based function has been used to study the economy of a DME boiler (operating costs). The contribution of the emissions of major pollutants (CO₂, NOₓ, and CO) to the external costs are calculated. About 88% external costs is produced by CO₂ emission. In addition, the internal costs and external costs and total operating costs are calculated. Subsequently, the operating costs of DME are used to compared with fuel oil. Clearly, not only the internal costs but the external costs of fuel oil are higher than that of DME. Importantly, the emissions of SO₂ and SO₃ are produced when boiler fueled with fuel oil. The use of DME leads to annual saving 299375.68 US$ (saving efficiency about 41%) comparing with fuel oil.

1. Introduction
In China, the energy structure is dominated by coal and coal accounts for about 70% total energy consumption. Annually, millions of tons’ pollutions which come from coal combustion are released into atmosphere. It resulted in serious environmental issue, such as acid rain, haze etc. Accordingly, developing clean coal utilization has (such as hydrocarbons, alcohol and ethers etc.) become the focus of research. As the simplest ether, DME is a potential clean alternative fuel which can be obtained from coal gasification process [1]. Therefore, the coal-derived DME is very significant for the environmental protection or national energy security of China [2].

Recently, the performances of DME have been developed [3-12], including ignition [3, 4], emission [5, 6] and efficiency over the traditional fuels [7-12]. Clearly, these properties indicate that DME is an important alternative energy which substitute for the LPG, diesel and LNG [13, 14]. As the alternative fuel, DME was already applied to the internal-combustion engines [15, 16], gas turbines [17-19], domestic cooking [20]. More recently, DME has also been used in industrial boiler [21-27]. All of studies in DME boiler focuses on the flame characteristics, however, the boiler operating costs are neglected.

For boilers, the operation costs include two parts: the price of fuels (internal cost) and the price of the environmental impacts of the pollutants (external cost). In order to calculate the operating costs of a boiler, a multi-objective function which includes internal and external costs has been established and used to optimize the boilers [28-32]. Kaewboonsong et al. has investigated the minimizing fuel and external cost for a 350 MW fuel oil boiler with the cost-based function, the result indicates that boiler total costs reducing and minimum soot formation depend on identified compromise excess air [28].
Subsequently, the cost-based function has been used to optimize the combustion of different fuels, the result implies the costs reduce observably at a specific excess air [29]. The load dispatch of a load-variable co-fired power plant has been optimized by the cost-based function, the result shows there is a quasi-linear relationship between the total costs of the boiler unit and the unit load [30]. Clearly, the cost-based function is also the most important factor to decide the economic and environmental feasibility of different fuels.

In this paper, the cost-based function has been employed to study the economy of boiler fueled with DME. The annual boiler total cost has been quantified and the external costs have been used to compared with fuel oil boiler in Ref. [28] to analyze the feasibility of using the DME in the boiler.

2. Economical model and parameters input
For a steam boiler fueled with fuel oil/gas, the internal costs \( (C_{\text{int}}) \) and external costs \( (C_{\text{ext}}) \) can be defined as [28]

\[
C_{\text{int}} = P_{\text{fuel}} \dot{m}_{\text{fuel}}; \\
C_{\text{ext}} = P_{\text{NO}_x} \dot{m}_{\text{NO}_x} + P_{\text{SO}_2} \dot{m}_{\text{SO}_2} + P_{\text{SO}_3} \dot{m}_{\text{SO}_3} + P_{\text{CO}_2} \dot{m}_{\text{CO}_2} + P_{\text{PM}} \dot{m}_{\text{PM}}
\]

Where \( P \) and \( \dot{m} \) are the price (US$/kg) and mass flow (or emission) rates (kg/s). The subscript is used to describe the fuel and the various pollutants emitted from the boiler.

For various pollutants, the emission rates can be expressed as functions of fuel consumption (\( \dot{m}_{\text{fuel}} \)) and the measured emission concentrations in dry flue gas (in ppm) and its volume (\( V_{\text{dg}} \)) at sampling point:

\[
\dot{m}_{\text{NO}_x} = 2.05 \times 10^{-6} \dot{m}_{\text{fuel}} C_{\text{NO}_x} V_{\text{dg}} \\
\dot{m}_{\text{SO}_2} = 2.93 \times 10^{-6} \dot{m}_{\text{fuel}} C_{\text{SO}_2} V_{\text{dg}} \\
\dot{m}_{\text{SO}_3} = 3.57 \times 10^{-6} \dot{m}_{\text{fuel}} C_{\text{SO}_3} V_{\text{dg}} \\
\dot{m}_{\text{CO}} = 1.25 \times 10^{-6} \dot{m}_{\text{fuel}} C_{\text{CO}} V_{\text{dg}}
\]

It is known that \( V_{\text{dg}} \) can be related to the theoretical volume of air (\( V^0 \)) and excess air ratio at sampling point (\( \alpha_{\text{sp}} \)) [33] and can be expressed as

\[
V_{\text{dg}} \approx \alpha_{\text{sp}} V^0
\]

For the emission rate of CO, it can be predicted with the fuel-carbon content, \( C' \) (%), and fuel flow rate [34]:

\[
\dot{m}_{\text{CO}} = 0.03667 \dot{m}_{\text{fuel}} C'
\]

The DME boiler with the model WNS1-1.0-Y.Q has been selected for this investigation. The boiler produces 1000kg/h saturated vapor at 130°C and 4 bar (100% load) with the DME consumption 90.14kg/h. At sampling point, the “Testo-350” gas analyzer has been installed to measure the concentrations of major pollutants and \( O_2 \). The lower heating value (LHV) and fuel carbon of DME are 36MJ/kg and \( C' = 52\% \). The level of emissions of major pollutants for DME boiler which are obtained from the sampling point are shown in Table 1.

| Emissions(ppm) | CO  | NOx | SO2 | SO3 | \( \alpha_{\text{sp}} \) |
|----------------|-----|-----|-----|-----|-----------------|
| DME            | 38  | 163 | 0   | 0   | 1.0554          |
For analyzing the feasibility of DME replacing fuel oil, the total cost and external costs of two fuels are compared. According to Ref. [28], the level of emissions of major pollutants for fuel oil as the fuel oil consumption 19.6kg/s are shown in Table 2. In addition, \( \alpha_{sp} = 1.0554 \) can be obtained by Eqs. (10) and (11) in Ref. [28] Table 2.

| Emissions(ppm) | CO | NO\(_x\) | SO\(_2\) | SO\(_3\) | \( \alpha_{sp} \) |
|----------------|----|----------|----------|----------|--------------|
| Fuel oil       | 84.5 | 250      | 880      | 18       | 1.0554       |

Note that, the value of \( P_{PM} \) is very low in fuel oil/gas boiler, the last term of \( C_{ext} \) in Eq. (1) can be omitted.

### 3. Results and discussion

According to Eq. (1), both \( C_{int} \) and \( C_{ext} \) are related to the fuel price and the emissions price, respectively. The prices of DME and fuel oil (LHV about 41MJ/kg) are 0.62US$/kg and 1.18US$/kg, respectively. Besides, the costs of damage done to the environment and humans by unit mass of a particular airborne pollutant, were assumed by \([35, 36]\): \( P_{NOx} = 2.4 \) US$/kg, \( P_{SO3} = 3.0 \) US$/kg, \( P_{SO2} = 1.72 \) US$/kg, \( P_{CO2} = 0.03 \) US$/kg and \( P_{CO} = 0.99 \) US$/kg.

The internal costs of DME boiler can be calculated by Eq. (1), \( C_{int} = 391207.6 \) US$/year and the external costs of DME boiler can be obtained from the emissions of major pollutants throughout 1 years (7000h/year), as shown in Table 3. From Table 3, one can know that the cost of CO\(_2\) is the most contributing factor for the external costs of DME and it covers about 88% of the total external costs. In addition, the cost of CO can be reduced to 0 though adjusting the excess air ratio. Therefore, the total external costs can decrease 273.37 US$/year, because the difference of price between CO\(_2\) and CO.

**Table 3. The external costs of DME boiler**

| External cost elements (US$/year) | CO\(_2\) | CO  | NO\(_x\) | Total external costs(US$/year) |
|-----------------------------------|--------|-----|----------|--------------------------------|
| DME                              | 36159.81 | 282.24 | 4813.2  | 41255.25                      |

The cost of NO\(_x\) is another most contributing factor. For DME fuel, the formation of NO is formed through thermal and prompt two different mechanisms. It is well known that the high temperature of combustion and oxygen content are the major factors which triggers the highly endothermic reactions for two mechanisms. Therefore, controlling the temperature of the combustion and optimizing the excess air ratio can reduce the value of NO producing.

In addition, the internal and external costs of fuel oil boiler in Ref. [28] are used to compare with that of DME boil under the same thermal load. Here, the consumption of fuel oil is equal to 79.14kg/h. Thus, the internal costs of fuel oil boiler can be also calculated by Eq. (1), \( C_{int} = 653696.4 \) US$/year and the external costs of fuel oil boiler can be obtained from the emissions of major pollutants throughout 1 years (7000h/year), as shown in Table 4.

**Table 4. The external costs of fuel oil boiler**

| External cost elements (US$/year) | CO\(_2\) | CO  | NO\(_x\) | SO\(_2\) | SO\(_3\) | Total external costs(US$/year) |
|-----------------------------------|--------|-----|----------|----------|----------|--------------------------------|
| Fuel oil                          | 52722.08 | 643.58 | 7461.77  | 16110.64 | 1204.06  | 78142.13                      |
Clearly, the costs of CO$_2$ and SO$_2$ are the most contributing two factors for the external costs of fuel oil and they cover about 88% of the total external costs. The operation costs of DME and fuel oil are illustrated in Figure 1. All of costs of fuel oil are higher than that of DME. Specially, sulfur oxides are produced owing to fuel oil containing sulfur. The result indicates that the DME is leaner alternative fuel comparing with fuel oil. The potential saving total operation costs of about 299375.68 US$/year (the saving efficiency about 41%) when we used DME replace fuel oil.

4. Conclusions
In this paper, the cost-based optimization method included experimental data has been successfully applied in the study of the operation costs for the boiler fueled with DME. The major pollutants for DME boiler are CO$_2$, NO$_x$ and CO, and the NO$_x$ and CO emissions were 163 ppm and 38 ppm, respectively, which were obtained at the sampling point. The emission rate of CO2 depends on Cr and $\dot{m}_{fuel}$.

The internal and external costs were 391207.6 US$/year and 41255.25 US$/year for 100% DME boiler load, respectively. Clearly, the external cost of CO$_2$ is the highest and it covers about 88% of the total external costs.

Finally, the operation costs of DME boiler were used to compared with that of fuel oil boiler. The results imply that all operation costs of fuel oil boiler are higher than that of DME boiler. Note that SO$_2$ and SO$_3$ emissions will produce in the fuel oil boiler. Importantly, the operation costs will reduce 299375.68 US$/year (saving efficiency about 41%) when boiler fueled with DME.

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