Annual Research Report

2006

(Research Results related to EERN)
Contents

Promotive Subjects

Harmonization of energy and environment
[Effective utilization of biomass energy]
- Development of Hot Gas Purification System for Multi Impurities
  - Proposal of Mercury Absorbent and Halide Sorbent

Base Research Subjects

Energy Services for Customer
[Energy conservation and comfortable environment design]

Fossil Fuel Power Generation
[Diversification and clean utilization of fossil fuels]
- Development of a Supporting System for Optimal Gasifier Operation

[Improving the efficiency of thermal power generation]
- Development of Coating Technology for Preventing Sulfide Corrosion on Boiler Tubes in Coal Fired Power Plant
- Development of Lifetime Estimation Method for MCFC Stack

[Establishment of advanced pulverized coal combustion technology]
- Development of Reduction Technology of Unburned Carbon on Pulverized Coal Combustion
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Development of Hot Gas Purification System for Multi Impurities
—Proposal of Mercury Absorbent and Halide Sorbent—

Background
To use biomass or wastes for high efficiency power generation, CRIEPI is investigating a high temperature dry gas cleaning system (Fig.1) which removes impurities such as heavy metals (Hg etc.), halides (HCl, HF) and sulfur compounds (H₂S etc.) in biomass/waste derived gas. Although high temperature dry gas cleaning system has superior purified potential applicable to the molten carbonate fuel cell, technological developments of high performance removal sorbent represent an important issue in realization of this system. Although activated carbons are utilized as Hg absorbent at waste incinerator and LNG plant, Hg removal efficiency of activated carbons in biomass/waste derived gas at driving temperature of bag filter (120-160°C) is not clarified. And the sodium aluminate (NaAlO₂) sorbent, which was developed for halide removal material, needs to balance property between halides removability and strength characteristics for industrial-scale reactor application.

Objectives
To reveal a Hg removal efficiency of activated carbons and to develop molded halide sorbent combined removability and strength characteristics as applications of sorbent to the high temperature dry gas cleaning system for biomass/waste derived gas.

Principal Results
1. Evaluation of Hg removal efficiency of activated carbon
Impregnated activated carbon was most effective for removing Hg in simulated biomass derived gas at 160°C among eight kinds of commercially produced activated carbons for Hg, acid gas, dioxin and deodorizing treatments. Although Hg absorption capacity was reduced by increased coexisting H₂S concentration, using at low temperature around 120°C improved Hg absorption capacity (Fig.2). It was clarified that the mercury removal process with impregnated activated carbon could be applied to the high temperature dry gas cleaning system.

2. Investigation of molded halide sorbent
Pellet formed halide sorbents were prepared with different methods in NaAlO₂ formation processes, additive types and molding methods. The halides reactivity in simulated biomass derived gas and strength characteristics for molded sorbents were evaluated. As a result, the extruded sodium aluminate sorbent with activated alumina additives offers an excellent compromise between HCl and HF concurrent removability (Fig.3) and practical strength to applicable potential for high temperature dry gas cleanup systems.

This work was carried out under joint research with New Energy Industrial Technology Development Organization (NEDO).

Future Developments
We will demonstrate the performance of Hg removal activated carbon and molded halide sorbent for the fuel gas produced by the biomass/waste gasifier with high temperature dry gas cleaning facilities installed in 2006 (gas quantity: 200m³/h).

Main Researchers: Makoto Nunokawa, Hiroyuki Akiho,
Research Scientist, Fuel and Combustion Engineering Sector, Energy Engineering Research Laboratory

References

* 2: Japanese Patent No. 3571219
* 3: Carbonaceous adsorbents which have chemicals finely distributed on their internal surface.
The fuel gas produced in biomass gasifier is treated with 1) halides (roughly), 2) dust, 3) heavy metals, 4) halides (closely), 5) sulfur compounds removing units.

Hg absorption capacity was improved by using at low temperature (120ºC) although it was reduced by increased coexisting H₂S concentration.

*1: Amount of Hg that IAC absorbed until Hg outlet concentration reach 5% of Hg inlet concentration.
*2: Hg absorption capacity in 100 hours (Hg outlet concentration was kept 0µg/m³ N for 100 hours).

The molded halide sorbent could reduce HCl and HF in simulated biomass derived gas below 1ppm concurrently.

**Fig. 1** High temperature dry gas cleaning system proposed CRIEPI

**Fig. 2** Relationship between Hg absorption capacity and coexisting gas concentration and reaction temperature

**Fig. 3** HCl/HF breakthrough curves of molded halide sorbent
Principal Research Results


Background
Heat pump water heater technology using CO₂ as a refrigerant (ECO CUTE technology) is attracting attention for its ability to save energy and reduce greenhouse gas emissions. The government support program has been introduced with a target to increase total installation to 5.2 million by 2010. There are several problems to hinder progress toward the goal, for example large footprint, degradation of COP in cold regions and so on. To overcome these problems, technical development projects have been conducted since 2005 on the initiative of NEDO (development subjects include downsizing and improving performance in cold regions). There is no appropriate evaluation method for new developed heat pump water heaters, so it is essential to study new evaluation methods of heat pump water heaters.

Objectives
In order to establish a performance evaluation method for a standard family for new CO₂ heat pump water heater, the following subjects were carried out; (1) reviewing existing performance evaluation methods, (2) extracting necessary evaluation items according to development subjects, (3) investigating testing facilities necessary for the performance evaluation, and (4) studying test procedures for extracted evaluation items.

Principal Results
1. Reviewing existing performance evaluation methods
   Table 1 shows the characteristics of existing performance evaluation methods. It is found that JRA 4050:2005 that is voluntary standard of JRAIA *1, is de facto standard.

2. Extraction of necessary evaluation item according to development subjects
   It is found that “two-axis evaluation” is necessary to evaluate the new heat pump water heater appropriately. Two axes are “performance” and “function and ability that should be secured” (hereinafter abbreviated to “F&A”). Table 2 shows necessary evaluation items organized according to development subjects and the two-axis. For “performance”, it is necessary to evaluate “performance of a heat pump” *2 that has been conventionally evaluated, in addition, we proposed that “annual performance of heat pump system with supplying standard hot water tapping profile *4**3 (hereinafter abbreviated to “annual system performance”) should be evaluated because it is comprehensible to users. For “F&A”, we also proposed it is necessary to evaluate and we extracted items in consideration of new equipment's usability and of technologies that would be applied, for example, using small storage tank and large compressor for downsizing.

3. Investigation of test facilities necessary for the performance evaluation
   In order to carry out the evaluation, a testing chamber in the artificial environment room that keeps all temperature conditions (hereinafter abbreviated to “TC”) for a long time, hot water load equipment that can control time-dependent load minutely and a high accuracy measurement system that ensures traceability are required.

4. Studying test procedures for extracted evaluation items
   Performance evaluation methods were built based on JRA4050. New tapping and heating profiles, testing procedures and so on were proposed in this report for additional evaluation items not included in JRA4050. “F&A” evaluation methods were newly built. New quantitative testing procedures were proposed in this report (Table 3).

Future Developments
It is necessary to keep observation on the movement of other performance evaluation methods and hot water supplying mode (modified M1 mode *10 etc.) and to improve continually the proposed procedure and method.

Main Researcher: Katsumi Hashimoto,
Research Scientist, Energy Conversion Engineering Sector, Energy Engineering Research Laboratory

Reference
3. Energy services for customer - Energy conservation and comfortable environment design

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Characteristics of the existing evaluation methods for heat pump water heater</th>
</tr>
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<tbody>
<tr>
<td><strong>Standards</strong></td>
<td><strong>Heat pump efficiency</strong></td>
</tr>
<tr>
<td></td>
<td>- Procedures for measuring performance under intermediate, summer and winter TCs (Remarks: measuring COP need to be over 90% of one on brochure)</td>
</tr>
<tr>
<td></td>
<td>- Procedures for measuring availability of de-frosting operation and cold winter with low temperature TC.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>IEA HPP Annex 28** in EU, US and Japan (9 countries)</td>
<td>Discussion about proposals from European (EN255-3), US (ARI470) and Japan (JRA4050).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Extracted evaluation items according to development subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Development Subjects</strong></td>
<td><strong>Performance (heating capacity, power consumption and COP)</strong></td>
</tr>
<tr>
<td>“Downsizing”</td>
<td>- Heat pump performance (under intermediate, summer winter and defrosting TCs)</td>
</tr>
<tr>
<td></td>
<td>- Annual system performance for warm regions</td>
</tr>
<tr>
<td>“Improving performance in Cold region”</td>
<td>- Heat pump performance (under intermediate, summer, winter, defrosting, cold winter with high temperature heating TCs)</td>
</tr>
<tr>
<td></td>
<td>- Annual system performance for cold regions</td>
</tr>
<tr>
<td></td>
<td>- Annual combined (hot water tapping and floor heating) system performance for cold regions</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Newly proposed evaluation items, tables and test procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TEST NAME</strong></td>
<td><strong>Proposed items</strong></td>
</tr>
<tr>
<td>Heat pump performance</td>
<td>- CO₂ heat pump water heaters classification</td>
</tr>
<tr>
<td>- Testing procedures are given**</td>
<td>- Out-going temperature from heat pump according to classification (New TC array)</td>
</tr>
<tr>
<td>- New TCs</td>
<td>- Measuring items under new TCs (for example, COP under defrosting and cold winter with high temperature output TCs)</td>
</tr>
<tr>
<td>Annual system performance</td>
<td>- Discussion about auto defrosting operation</td>
</tr>
<tr>
<td>- Testing procedures are almost given**</td>
<td>- Waiting time for stable state and measuring time</td>
</tr>
<tr>
<td>- New TCs</td>
<td>- TC and heating-load-days for estimating annual system performance for cold regions</td>
</tr>
<tr>
<td></td>
<td>- New heating-load-days for cold regions</td>
</tr>
<tr>
<td>Newly proposed testing method for F&amp;A</td>
<td>- Testing procedure for continuous hot water tapping capacity</td>
</tr>
<tr>
<td></td>
<td>- Testing procedure for maximum hot water tapping capacity</td>
</tr>
<tr>
<td></td>
<td>- Testing procedure for re-heating to hot water in bath</td>
</tr>
<tr>
<td></td>
<td>- Testing procedure for black-out durability in cold regions</td>
</tr>
<tr>
<td></td>
<td>- Intermittent hot tapping profile</td>
</tr>
</tbody>
</table>

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*1: Japan Refrigeration and Air Conditioning Industry Association.
*2: Heating capacity (capacity of water supplying), power consumption and COP (coefficient of performance) which measured under each TC *5.
*3: Hot water supplying system includes heat pump and storage tank. Each seasons’ system performance is measured under summer, winter and intermediate TCs *5 in artificial environmental room with meeting standard tapping profile *4 (IBEC-L mode). Annual system performance is calculated as a heating-load-days *6 weighted average.
*4: It includes start time of tapping, tapping duration, tapping temperature and tapping flow rate. There is IBEC-L mode in the typical one.
*5: TC is a kind of array which include seasonal average ambient dry-bulb temperature, wet-bulb temperature, tapping temperature and out-going temperature from heat pump.
*6: It is deemed running days of each TCs.
*7: Better Living Foundation
*10: New hot water tapping profile proposed by the book “Design guideline to independence circulation type house” (IBEC supervision).
*11: Testing procedure is “given” in JRA 4050:2005
Principal Research Results

Development of a Supporting System for Optimal Gasifier Operation

Background
For highly efficient and stable operation of a coal gasifier in practical use of IGCC, it is important to establish methods for operating plant in appropriate conditions. In CRIEPI, a system which oversees online data and slag flow and optimizes the operating conditions automatically has been examined.

Objectives
The purpose of this study is to develop technique which analyzes online data involving instantaneous fluctuations and builds gasifier performance evaluation functions (PEFs) simultaneously during the operation. In addition, it is intended to confirm the utility of the technique being applied to data based on the test results of the FRONTIA (3 t/d coal gasifier) of CRIEPI.

Principal Results
1. Development of technique for real-time analysis of online data and building of gasifier performance evaluation functions

   In the Supporting System for Optimal Gasifier Operation” (Fig.1) which was proposed in the previous work, technique for real-time analysis of online data and generation of gasifier performance evaluation functions (PEF) is examined.

   (1) As a result of statistical analysis of online data, it is found that the trend of combustor temperature can be expressed by the function of air ratio and coal feeding ratio, and that of calorific value of syngas and char production rate can be expressed by the function of air ratio. Time averaging of the data in a certain interval which depends on the individual gasifier is effective to generate such functions accurately.

   (2) It is also found that the fluctuations of the combustor temperature, calorific value of syngas and char production rate obtained by the experiment can be expressed accurately by the normal distribution. This proves that, for example, the probability (risk ratio) that the calorific value decreases below the lower limitation due to the stable combustion in the gas turbine combustor can be defined mathematically. Therefore the gasifier can be operated in the condition which suppresses the risk of exceeding the constraint of the gasifier's operation (Fig.2).

   (3) The gasifier PEF and risk ratio obtained from the experiment of RUN1 (Fig.2) can be applied to the prediction of the gasification performance and fluctuations of online data in the experiment of RUN2 (Fig.3). In the range of air ratio in RUN1 and RUN2, the gasifier PEFs generated once can be utilized for the optimization calculation in other operating conditions.

2. Optimization calculation for actual gasifier test conditions

   The technique for real-time generation of the gasifier PEF mentioned earlier is introduced into the optimization code and the optimization calculation is performed to investigate the optimal operating condition for FRONTIA with Coal DT (Table 1). In addition, for the actual experiment condition, the two calculations are performed in conditions of constant combustor temperature and air ratio to investigate the high performance and stable operation conditions respectively.

   Therefore, it was confirmed that the presented technique was effective for the optimization of the gasifier operating condition.

Future Developments
The presented technique will be applied to actual gasifier operation and validity will be explicitly demonstrated. In addition, online video processing for molten slag flows will be investigated to develop technique of evaluation of slag fluidity.

Main Researcher: Hiroaki Watanabe,
Research Scientist, Thermal Engineering Sector, Energy Engineering Research Laboratory

Reference

*3: Ratio of coal fed into the reductor with coal fed into the combustor.
*4: RUN1: high air ratio condition, RUN2: low air ratio condition.
6. Fossil Fuel Power Generation - Diversification and clean utilization of fossil fuels

It was confirmed that the presented technique was effective for the optimization of the gasifier operating condition.

Fig. 1 Flow chart of the supporting system for optimum coal gasifier operation

Fig. 2 (a) Experimental data and PEF of calorific value of syngas in RUN1 and relation between risk ratio and optimization. (b) Relation between frequency of occurrence and difference from PEF

Fluctuations (difference from PEF) can be expressed accurately by the normal distribution. Therefore the risk ratio which is defined as the probability of exceeding the constraint rules of operating the gasifier can be defined mathematically and the solution which suppresses the risk ratio in a certain range is calculated by the optimization calculation.

Table 1 Optimization calculation results

<table>
<thead>
<tr>
<th>Items</th>
<th>Const. rule</th>
<th>Solution</th>
<th>Base</th>
<th>Const. com. temp.</th>
<th>Const. air ratio</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air ratio</td>
<td>-</td>
<td>0.467</td>
<td>0.505</td>
<td>0.467</td>
<td>(0.505)</td>
<td>- 0.038</td>
</tr>
<tr>
<td>Combustor temperature K</td>
<td>&gt; 1570</td>
<td>1625</td>
<td>1630</td>
<td>(1630)</td>
<td>1645</td>
<td>+ 15 K</td>
</tr>
<tr>
<td>Calorific value of syngas MJ/m³N</td>
<td>-</td>
<td>3.05</td>
<td>2.92</td>
<td>3.05</td>
<td>(2.92)</td>
<td>+ 0.13 MJ/m³N</td>
</tr>
<tr>
<td>Char production rate kg/h</td>
<td>&lt; 30</td>
<td>25.8</td>
<td>12.9</td>
<td>25.8</td>
<td>21.3</td>
<td>-</td>
</tr>
<tr>
<td>Coal feeding ratio</td>
<td>0.5 to 0.6</td>
<td>0.56</td>
<td>0.59</td>
<td>0.54</td>
<td>0.53</td>
<td>-</td>
</tr>
</tbody>
</table>

Solution on the left hand side in Table 1 shows the maximum performance using the FRONTIA with Coal DT. Solutions on the right hand side shows that air ratio of 0.038 can be reduced in the same combustor temperature condition and combustor temperature of 15 K can be increased in the same air ratio condition from the base which is the actual experimental condition.

Note: constraint rules of optimization calculation in this paper
  Combustor temperature: Temperature at slag viscosity of 15 Pa*s of Coal DT.
  Char production rate: The value is based on the experience of the FRONTIA of CRIEPI.
Development of Coating Technology for Preventing Sulfide Corrosion on Boiler Tubes in Coal Fired Power Plant

Background
In coal fired power plant, operating that controls the amount of NOx generation is promoted. Due to the low NOx firing combustion, a reducing atmosphere becomes strong in the burner area. Therefore, the concentration of H2S becomes higher and the boiler tubes are damaged due to sulfide corrosion. The damaged tube should be repaired by buildup welding or thermal spraying. If the damage by the sulfide corrosion is large, the boiler tubes need to be replaced. These repairs cost is from tens to hundreds of million yen. Therefore, an effective and economical technique of coating on the hot parts is demanded in order to increase efficiency and improve equipment reliability. Therefore we have developed an economical and straight forward technique of coating for preventing sulfide corrosion.

Objectives
In order to develop economical and straight forward technique of coating for preventing sulfide corrosion, the performance of TiO2 film is evaluated and the coating method is developed.

Principal Results
1. Function of mitigating sulfide corrosion by TiO2 film
TiO2 was selected as a film material to evaluate by using three methods (thermal spraying, physical vapor deposition, spraying the liquid solution). The coating cost of thermal spraying and physical vapor deposition is much higher than that of spraying the liquid solution. On base metal specimens of STBA24 coated with TiO2 by thermal spraying and physical vapor deposition, the iron sulfide layer and chromium oxide layer are not observed (Fig.1 (b), (c)). TiO2 film proves to have the function of mitigating sulfide corrosion. However, specimens coated with TiO2 by spraying the liquid solution are not effective in protecting the surface from sulfide corrosion (Fig.(d)). This is caused by micro cracks generating on the film during the coating process.

2. Development of film consisting of TiO2 film and carbon film
In order to decrease the influence of micro cracks that decreased the function of environmental interception, we have contrived a new type of film consisting of TiO2 film and carbon film (Fig.2). As a result of the sulfide corrosion test performed, the growth of iron sulfide layer and chromium oxide layer on the specimen coated with this film is much less than that on the original specimen (Fig.1 (e)). Moreover, these layers don't peel off. Thus, the developed film proved to have superior corrosion resistant to the conventional TiO2 film.

3. Durability evaluation of developed film in the simulated environment of coal thermal power boiler.
Base metal tubes of STBA24 coated with and without developed film were tested in the simulated environment of coal fired power plant boiler (MARINE boiler). On the part without developed film, the corrosion layer is thick and some pieces peeled off. On the other hand, the corrosion layer on tube coated with developed film was not observed clearly (Fig.3, Fig.4). The developed film proved to have superior corrosion resistance.

Future Developments
In order to prove reliability of developed film, the long term corrosion test and the various gas composition tests will be performed in the simulated coal fired power plant boiler (MARINE boiler) and bench scale test stands. After that we will try to apply the result to real coal fired power plant boiler.

Main Researcher: Makoto Kawase, Ph. D.,
Research Scientist, Energy Conversion Engineering Sector, Energy Engineering Research Laboratory

Reference
6. Fossil Fuel Power Generation - Improving the efficiency of thermal power generation

<table>
<thead>
<tr>
<th>Before the test</th>
<th>After the test</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) No coating</td>
<td>(b) TiO₂ thermal spraying</td>
</tr>
<tr>
<td>(c) TiCN by PVD</td>
<td>(d) Spraying TiO₂ solution</td>
</tr>
<tr>
<td>(e) Spraying TiO₂ solution + carbon solution</td>
<td></td>
</tr>
</tbody>
</table>

**Fig.1** Comparison of sulfide corrosion before and after the tests (Base metal: STBA24)

Testing time: 200hr, Temperature: 500°C, Gas composition: N₂/H₂/CO/CO₂/H₂O = 73.1/2.7/6.8/8.8/8.6, H₂S: 290ppm

A new type of film consisting of TiO₂ film and carbon film is coated by the spray method using the liquid solution. The developed film proved to have superior corrosion resistance to the conventional TiO₂ film.

**Fig.2** Schematic diagram of developed film consisting of TiO₂ film and carbon film

The influence of the micro crack that decreased the function of environmental barrier was controlled by alternately accumulating TiO₂ film and carbon film. Therefore, the growth of the sulfide corrosion layer is prevented.

**Fig.3** Photo of sample tube before and after exposure test in MARINE boiler

**Fig.4** Cross-sectional SEM images after exposure test

As a result of tests in the simulated environment of coal fired power plant boiler (MARINE boiler), the developed film proved to have superior corrosion resistance.
Development of Lifetime Estimation Method for MCFC Stack

**Background**
Cell voltage of molten carbonate fuel cell (MCFC) decreases with operating time since the electrolyte in the cell is consumed by mainly corrosion of cell components. Since MCFC power plants are operated for long time, lifetime estimation of MCFC stack would be a strong tool to improve stack performance and to optimize the plant operation. Lifetime estimation method for single cells has been already developed. Application of lifetime estimation method to the stacks is desired.

**Objectives**
Stack lifetime estimation method is developed for stack performance improvement, estimation of stack lifetime and optimal plant operation.

**Principal Results**
(1) For application of lifetime estimation method to stacks, an electrolyte content equation for the stack as shown in Table 1 is essential. Especially, parameters $e_0$ and $Scor$ in step 1 in Table 1 have to be determined. For single cells, $e_0$ and $Scor$ can be determined using measured internal resistance (IR). However, measurement of IR for stacks is difficult because of large cell area. Therefore, $e_0$ and $Scor$ were determined using measured cell voltages of 0.4 m$^2$ and 1m$^2$ stacks. As shown in Table 2 and Fig.1, $e_0$ for 0.4 m$^2$ stack was in the range from 2.95 to 3.3. $e_0$ for 1m$^2$ stack was in the range from 2.35 to 3.3. $Scor$ was 6.3 for both 0.4 m$^2$ and 1m$^2$ stacks. Finally stack lifetime estimation method has been developed as shown in Table1. For verification of the method, measured and estimated electrolyte contents after 10,000 hours were compared in Fig.2. Estimated electrolyte content agrees with measured electrolyte content. Precision of the method was confirmed.

(2) Each cell voltage of a stack was analyzed. A low initial electrolyte content cell had low cell voltage. It was confirmed that difference in cell voltages of a stack originates from initial electrolyte content as shown in Table 2. In addition, $e_0$ for a stack with larger cell area is lower than that for a stack with smaller cell area. Low $e_0$ for a stack with larger cell area would be caused by non-uniformity of stack tightening pressure in electrolyte impregnation process. Stack tightening pressure becomes non-uniform since stack height decreases by impregnation of the electrolyte into the matrix. Pre-impregnation process has to be adopted to avoid stack height change. In addition, since $Scor$ depends on metal surface area of a separator plate, reduction of the metal surface area by improvement of the separator design is important.

(3) Using the stack lifetime estimation method, cell voltage change up to 40,000 hours was estimated. Estimated cell voltages were shown as base line in Fig.3. Base line means cell voltages were estimated with center temperature of the stack at 638˚C. A high initial electrolyte content cell in a 1m$^2$ stack is able to keep 90% of initial cell voltage after 40,000 hours. Therefore, a high initial electrolyte content cell would achieve lifetime target of 40,000 hours. Subsequently, effect of center temperature of the stack on cell voltage was investigated as shown in Fig.3. Lower center temperature of the stack has made lifetime longer.

Consequently, MCFC lifetime estimation method has been developed by a compilation of CRIEPI’s MCFC development activities, even though a lifetime estimation method for other fuel cells has not been achieved. By the stack lifetime estimation method, optimal MCFC plant operation has been achieved.

**Main Researcher:** Yoshihiro Mugikura, Ph. D.,
Senior Research Scientist, Advanced Power Engineering Section, Energy Engineering Research Laboratory

**References**
6. Fossil Fuel Power Generation - Improving the efficiency of thermal power generation

Table 1: Stack lifetime estimation method based on reaction resistance model

| 1 | Electrolyte content at certain time (e) | \( e = e_0 - \left(90.43 + 9.02S_{c0} \right)e^{0.5} + 30.48 + 2.029S_{c0} \times \exp\left(-10170/T-1/923\right) \) |
| 2 | Reaction area (S0, S1, S2) | \( S_{H1} = 0.318e \times S_{H2} = 1.75S_{H2} \) |
| 3 | Parameters (A1, A2) | \( A_1 = R T_0 n / F^2 \times \eta_{H1} D_{H1} S_{H1} \times A_2 = R T_0^{2} / F^2 n^2 \kappa_{H1} A S_{H1} \) |
| 4 | Reaction resistance (R0) | \( R_{H1} = (A_1 + A_2 \sigma_{H1}) p_{H1} \) |
| 5 | Cell voltage (V) | \( V = e - \eta_{N1} - j(R_{H1} - R_{0} - R_{g}) \) |

- e: Electrolyte content, e0: Initial electrolyte content, Scor: Coefficient of corrosion area, t: Time,
- T: Temperature, S: Reaction area, A: Coefficient of anode reaction resistance, D: Diffusion constant,
- R: Gas constant, K: Henry constant, F: Faraday constant, n: Electron number, \( \delta \): Diffusion distance,
- P: Pressure, E: Open circuit voltage, j: Current density, \( \eta_{N1} \): Nernst loss, Ra: Anode reaction resistance,
- Rc: Cathode reaction resistance, Rg: Internal resistance, g: Gas phase

Table 2: Summary of e0 and Scor

<table>
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<tr>
<th>Cell area</th>
<th>Cell voltage e0</th>
<th>Scor</th>
</tr>
</thead>
<tbody>
<tr>
<td>High 0.4m²</td>
<td>3.3 (According to Separator configurations of 0.4m² and 1m² stacks are same)</td>
<td>6.3</td>
</tr>
<tr>
<td>Low 1m²</td>
<td>2.95</td>
<td>2.35</td>
</tr>
</tbody>
</table>

- Cell voltage depends strongly on e0.

Fig. 1: Comparison between measured and estimated cell voltages of 0.4 m² stack

Fig. 2: Comparison between measured and estimated electrolyte contents after operations

Fig. 3: A result of estimated lifetime of 1m² stack

Target of lifetime (40,000 h) would be achieved.
Principal Research Results

Development of Reduction Technology of Unburned Carbon on Pulverized Coal Combustion
- Blended Combustion of Sub-bituminous Coal with Bituminous Coal -

Background
Coal is an important energy resource for meeting the increasing demand for electricity because there are more abundant reserves than other fossil fuels. However, considering the security of fuel supply and fuel cost, it is desirable to use lower rank coal. Although sub-bituminous coal with moisture content higher than 20% is mined in large amounts throughout the world, ignitability of sub-bituminous coal is worse because of the latent heat of vaporized moisture. If sub-bituminous coal is fired in the conventional boilers designed for bituminous coal combustion, it must be utilized for blended combustion with bituminous coal. We have already clarified that unburned carbon concentration in fly ash during blended combustion is higher than that in non-blended combustion. This reason is that the increase of latent heat of vaporized moisture from sub-bituminous coal tends to reduce the combustion efficiency of bituminous coal. And, fly ash is mainly utilized as cement material. However, such utilization entails considerable treatment cost. To reduce the treatment cost, fly ash has to be utilized as useful material such as cement or concrete admixtures. In the utilization of fly ash as these admixtures, the unburned carbon concentration in fly ash must be reduced to less than 3%.

Objectives
Reduction technology of unburned carbon concentration in fly ash without the increase of NOx concentration at the exit of furnace is developed during the blended combustion of sub-bituminous coal in the blended ratio of 30%. Fuel ratio of tested bituminous coal is about 1.5 and moisture content of sub-bituminous coal is about 20%.

Principal Results
1. Optimization of combustion air injection condition
   (1) Air injection condition from burner
   When the primary air velocity is reduced to the minimum value, which prevents the sedimentation of pulverized coal in primary air nozzle, oxygen consumption progressed efficiently around the burner outlet. Then, unburned carbon concentration in fly ash decreases, although NOx emission at the exit of furnace increases (Fig.1). Additionally, the optimization of swirl vane angle of secondary air, shape of combustion flame is modified and NOx reduction area before injection point of multi staged air is expanded. These optimizations are able to reduce both NOx emission at the exit of furnace and unburned carbon concentration in fly ash (Fig.2).
   (2) Injection condition for multi staged air
   The temperature in the furnace during blended combustion of sub-bituminous coal is lower than that on bituminous coal combustion. Therefore, air injection ratio of first stage should be increased to reduce unburned carbon concentration in fly ash (Fig.3). But, NOx concentration after air injection point of first stage becomes high. When air injection point of second stage is shifted toward the exit of furnace, NOx reduction area becomes wide and NOx emission at the exit of furnace is decreased (Fig.4).

2. Optimization of structure of primary air nozzle
   The cross section area of primary air is modified wider in order to reduce primary air velocity at the burner outlet without the decrease of primary air flow rate. And the optimization of structure design where pulverized coal is concentrated by swirl force at the burner outlet is proposed to improve oxygen consumption (Fig.5). In these optimizations, NOx is decomposed efficiently before air injection point of first stage. So, both NOx emission at the exit of furnace and unburned carbon concentration in fly ash are reduced to almost the same value as those in bituminous coal combustion (Fig.6).

As a result, by optimizing air injection condition from burner and that for multi staged air, it is clarified that unburned carbon concentration in fly ash is reduced to less than 3% at 100 ppm of NOx emission at the exit of furnace.

Future Developments
Advanced combustion technology for controlling ash quality (diameter and density, etc.) will be further developed during bituminous coal and blended combustion of sub-bituminous coal with bituminous coal.

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Reference
6. Fossil Fuel Power Generation - Establishment of advanced pulverized coal combustion technology

**Fig.1** Influence of Air/Coal on NOx emission and unburned carbon concentration in fly ash

As Air/Coal decreases, although NOx emission at the exit of furnace is increased, unburned carbon concentration in fly ash is reduced.

**Fig.3** Influence of air injection ratio of first stage on NOx emission and unburned carbon concentration in fly ash

The increase of air injection ratio of first stage makes unburned carbon concentration in fly ash reduce.

**Fig.2** Influence of swirl vane angle of secondary air on NOx emission and unburned carbon concentration in fly ash

The decrease of swirl vane angle makes both NOx emission at the exit of furnace and unburned carbon concentration in fly ash reduce.

**Fig.4** Influence of air injection point of second stage on NOx emission and unburned carbon concentration in fly ash

As air injection position of second stage shifts to downstream, NOx reduction area is expanded and NOx emission at the exit of furnace is reduced.

**Fig.5** Optimization of structure of primary air nozzle

Cross section area expands and pulverized coal is concentrated by swirler.

**Fig.6** Effect of optimization of structure of primary air nozzle on NOx emission and unburned carbon concentration in fly ash

The optimizing structure of primary air nozzle makes NOx emission at the exit of furnace reduce without the increase of unburned carbon concentration in fly ash.

Pulverized coal is concentrated by swirler.