Eco-friendly Regenerative Burner Heating System Technology Application and Its Future Prospects

Shinichiro Fukushima*, Yutaka Suzukawa**,
Toshikazu Akiyama***, Yuzo Kato****, Akio Fujibayashi***** and Takeshi Tada******

* Principal Engineer of Energy, Environmental Control and Energy Dept., Steel Technology Center
** Manager, Environmental Control and Energy Dept., Steel Technology Center
*** Manager, Environmental Control and Energy Dept., Keihin Works
**** Group Manager, Environmental Control and Energy Dept., Fukuyama Works
***** Team Manager, Rolling & Processing Research Dept., Materials & Processing Research Center
****** Director, Nippon Furnace Kogyo Kaisha Ltd.

The environmental friendly, ceramic honeycomb regenerative burner system is worth noting as innovative technology, for its effect of low energy consumption and NOx emission. It is recognized as one of concrete measures to prevent global warming and to solve environmental problems. NKK and Nippon Furnace Kogyo have jointly developed the system and succeeded in starting its practical operation. In NKK, this technology has been already applied to eleven furnaces. NKK has achieved over 30% energy saving effect and over 50% NOx reductions. This system ensures to provide the world with an effective countermeasure for the global greenhouse effect and the acid rain.

1. Introduction

The Toronto Congress was held in 1988, fifteen years after the First Oil Crisis, and was the first official meeting to declare the need for action in terms of global warming issues. Since then, another fifteen years have passed. During this time, the World Environmental Technology Development Congress adopted the United Nations Framework Convention on Climate Change in 1992. This was enforced in March 1994. In addition, the Kyoto Protocol, which was adopted at COP3 (the Kyoto Protocol to the United Nations Framework Convention on Climate Change) in 1997 to determine the detailed targets associated with the reduction of CO_2 emissions for individual developed countries by 2010. These were determined on the basis of 1990 levels and have been successfully adopted by developed countries by 2002 except for the U.S.A. In Japan during the thirty years since the Oil Crisis, there have been many energy saving actions and efforts against global warming (i.e. reducing CO_2 emissions). This trend is likely to continue and these actions to be enhanced.

Throughout the period, NKK has been promoting company-wide efforts on the basis of energy saving actions by all employees at both the Keihin and Fukuyama Works. This includes employees in the Research and Development Sections. As a result, NKK has successfully attained energy savings of more than 30% (saved amount) at both works. The actions have included many significant technologies including:

1) enhancing operational maintenance of individual iron manufacturing process facilities;
2) improving energy control of processes such as combustion control including adjustment of the air-to-fuel ratio of the heating furnace, heating control such as heat pattern control, and production yield improvements by reducing facility defects;
3) establishing an energy center with control systems for planning, implementation, and outcomes, as well as a remote control system for energy facilities;
4) establishing a waste heat recovery system linking electricity, fuel, and steam lines to each other;
5) recovering heat from hot coke (cogeneration power recovery of this kind accounts for a maximum of 35 MW per unit);
6) recovering blast furnace top gas pressure energy through power generation (power generation recovery of this kind produces a maximum of 24 MW per unit);
7) large-scale waste energy recovery including recovering waste heat produced by sintering plants and coolers (medium to low pressure steam recovery);
8) recovering latent heat from converter waste heat (gas

was recovered at 100 m^3/t or larger volume), as well as sensible heat recovery, and
9) saving energy such as by continuous casting and annealing achieved by eliminating process steps and by achieving continuous process operation.
As a result, all possible measures had been taken and completed by the late 1980's.

As for environmental issues, the measures needed to respond to the Air Pollution Control Law and the Water Pollution Control Law, which were enforced in 1970, have apparently been completed for the first stage of the works. After that, methods have been successively introduced to deal with the newly emerged problems of global warming (CO_2 emission), increases in NOx (nitric oxides) emissions from urban mobile sources, the issues of SPM, waste, dioxins, and endocrine disrupters. The Life Cycle Analysis evaluation method was finally introduced for these issues where one countermeasure leads to the need for further countermeasures. For further action associated with energy saving and global warming to be undertaken under such circumstances, it is vital that new subjects be explored and new technology developed through a comprehensive approach to the challenges of environmental problems. Based on this concept, NKK has shifted its focus on new energy saving activities to improving the quality of efficiency in terms of increasing the quantity of energy saving. For instance, NKK has promoted exclusive technology development that concentrates on the method of supplying quality energy (i.e. calorific value, temperature, etc.) by responding to each energy use level in terms of heat recovery method without degrading the energy quality, as well as the environmental problems.

NKK has developed an eco-friendly regenerative burner heating system in partnership with NFK(Nippon Furnace Kogyo Kaisha) Ltd. This technology has been successful in solving issues related to energy and the environment, or ultimate heat recovery and reduction of NOx emissions. These issues could not be achieved simultaneously through conventional technologies[1]. This paper describes the development, practical applications, and technological outlook for this eco-friendly regenerative burner system. This technology was adopted as a base technology by the National Project, "High Performance Industrial Furnace Project", which ran from 1993 to 2000. The project addressed the national policy for improving energy saving, and has been recognized as a base technology in terms of developmental results from Japanese-based technologies.

2. Characteristics of eco-friendly regenerative burner heating system technology

2.1 Innovative technology in the heating furnace sector[2),3)]

Heating furnaces have improved in terms of heating quality as well as energy saving. As for quality improvement, the conveyance method has been changed from pusher to walking beam, and a heating control model has been introduced to achieve improvements in surface defects and skid marks, as well as the soaking performance assurance. In terms of energy saving, unit fuel consumption has decreased through hardware improvements such as the change from radiation heat exchanger to convection heat exchanger, strengthening furnace insulation and furnace seals, and utilizing ceramic fibers in furnace walls, as well as operational improvements such as optimizing furnace pressure controls, air-to-fuel ratios, and preventing overheating. Almost all heating furnaces have already adopted these discrete technologies as the proven form of technology. The industries concerned have accepted that it is impossible to make further improvements.

The eco-friendly regenerative burner heating system is an innovative technology that achieves, to be the first in the world, further energy savings at large-scale continuous slab heating furnaces as well as significant reductions in NOx concentrations in flue gases at the same time. The recovery of heat from the heating furnace by using regenerative burners is conducted by heat exchange between flue gases and combustion air in each regenerator installed in a burner. This is illustrated in **Fig.1**.

Using a ceramic honeycomb regenerator, which has strong endurance for high temperature, brings the temperature of preheated air to a level close to the temperature of furnace gases, thus resulting in an extremely efficient recovery of heat when compared with the performance of a conventional heat exchanger.

In conventional furnaces, if the temperature of preheated air exceeds 1200 K, the concentration of NOx in flue gases increases rapidly. As a result conventional furnaces operating at high temperatures were not practical in terms of emission regulation. In this regard, the eco-friendly regenerative burner heating system has proved, to be the first in the world, to significantly reduce NOx concentration in flue gases by developing a highly preheated air combustion technology which conducts mild reactions between high temperature preheated air, at 1500 K or above, and fuel in the furnace while at the same time diluting the fuel in the air.

The technology was examined in detail by the National Project, and as a result a new sector was created, termed "highly preheated air combustion", in the field of combustion science. The introduction of dispersed heat recovery technology and highly preheated air combustion technology to the industrial heating furnace technology, which was thought to have matured, has led to the eco-friendly regenerative burner heating system. This is an innovative technology in the heating furnace sector that achieves 30% energy savings and 50% reduction in NOx emissions.

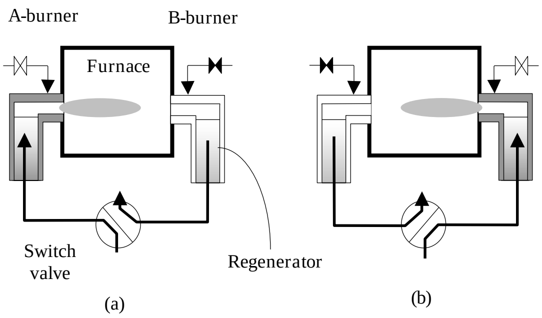

Fig.1 Regenerative burner system

2.2 Ultimate heat recovery (Regenerator optimization)[4)-6)]

Developing a regenerative burner entailed the potentially conflicting issues of maximizing heat recovery capacity within the regenerator, and compact design. The honeycomb regenerator has solved the problem. The honeycomb regenerator is the optimal heat exchanger when compared with other heat exchangers such as balls, owing to the geometrically large specific surface area contained within a honeycomb design. The honeycomb regenerator is superior also in terms of pressure drops and the preheated air temperatures. The relationship between the combustion capacity of the burner and the necessary weight of the honeycomb regenerator is calculated based on the energy balance. For example, **Fig.2** shows the relationship between the calculated weight of the regenerator (solid line) and the actual weight of the regenerator for a burner in a continuous slab-heating furnace at the Fukuyama Works' hot-rolling mill.

Compared with the weight of ball regenerators discussed in other papers, the honeycomb regenerator is significantly lighter. Furthermore, compact designs are available for the burner body. A regenerative burner using a honeycomb regenerator will attain a maximum preheated air temperature of 1570 K (50 K lower than the furnace temperature). The preheated air temperature obtained by using ball regenerators is expected to be about 150 K lower than the furnace temperature, based on experimental data. In case of conventional metal-tube heat exchangers, the preheated air temperature is about 900 K.

Achievable heat recovery obtained by the regenerative burner is in the range 70 to 90% (depending on fuel type). That obtained by metal-tube heat exchanger is in the range 40 to 50%. Energy saving is attained by increasing the preheated air temperature by recovering sensible heat from the flue gases.

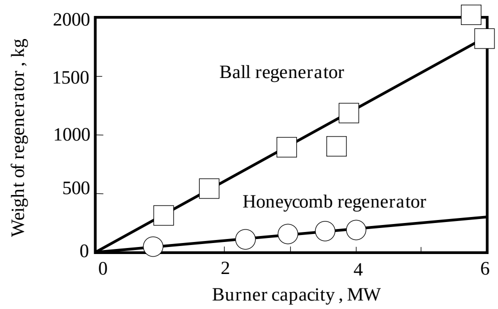

Fig.2 Relationship between weight of regenerator and burner capacity

2.3 Ultra low NOx emissions (Discovery of "highly preheated air combustion")

Developing industrial burner that use highly preheated air emphasizes the suppression of NOx emissions generated by oxidation of nitrogen in the air, (thermal NOx). Zeldovich et al. studied the generation of thermal NOx and found that the generation of thermal NOx is determined by a function of temperature, oxygen concentration, and residence time. Accordingly, achieving low NOx combustion should result from: (1) the suppression of maximum flame temperature, and (2) the prevention of excess amounts of oxygen. To do this, NKK adopted a 2-stage fuel burner, which was brought into practical use by NFK, after modification for highly preheated air combustion use (as shown in **Fig.3**).

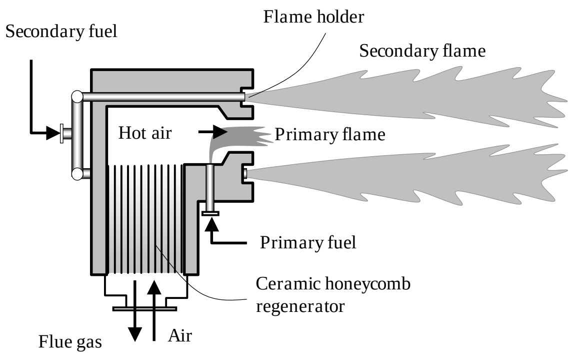

Fig.3 Schematic diagram of the newly developed regenerative burner

Fig.4 shows examples of experimental data from the developed burner in terms of flame temperature distribution, oxygen concentration distribution, and NOx concentration distribution observed during the combustion of by-product gases of steel works. **Fig.4**(a) shows the case the primary fuel ratio is 20%, and **Fig.4**(b) shows the case of 5%. The combustion load was 1.2 MW. This is equivalent to the capacity of a commercial burner. When primary fuel ratio was 20%, heat spots appeared in the temperature distribution. Oxygen concentrations in the heat spot were high, thus inducing the Zeldovich reaction, which resulted in a rapid increase in thermal NOx.

When primary fuel ratio was 5%, no heat spots appeared in the temperature distribution, and oxygen concentration decreased rapidly. In this case, raw NOx concentration was as low as 80 ppm (or 40 ppm converted to 11% O_2). The low NOx concentration presumably comes from the diffusion combustion of secondary fuel and highly preheated air being diluted by the intrafurnace combustion flue gases. Accordingly, the suppression of thermal NOx generation during combustion using highly preheated air can be attained by adequate diffusion and controlling the mixing of fuel with combustion air. To do this, an optimum design of burner is required. This would include the positioning of the fuel and air nozzles, the jet velocity of the fuel and air, and the secondary fuel ratio.

This technology was adopted as a core technology in the National Project of "Development of High Performance Industrial Furnaces", and was verified by many researchers including those in universities. In particular, the experimental results given by Hasegawa et al., shown in **Fig.5**, have been repeatedly cited as the data representing the essence of this technology. As a result of this figure, the academic sector has accepted the reality of low NOx combustion at low oxygen concentrations using highly preheated air. This new combustion is termed "Highly preheated air combustion". The essence of the combustion technology presented already in **Fig.4** equals one described in **Fig.5**.

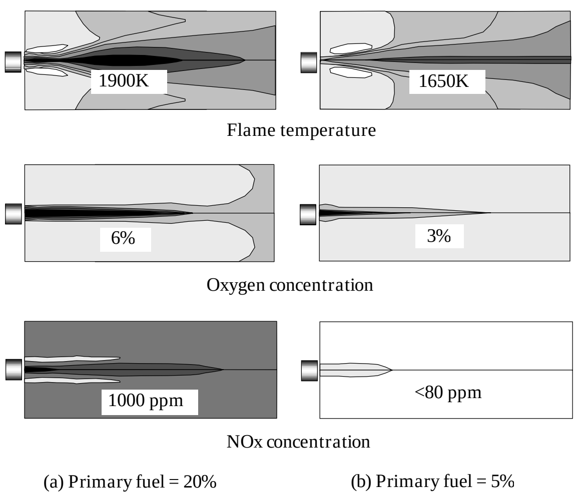

Fig.4 Comparison of flame structure of fuel staged combustion

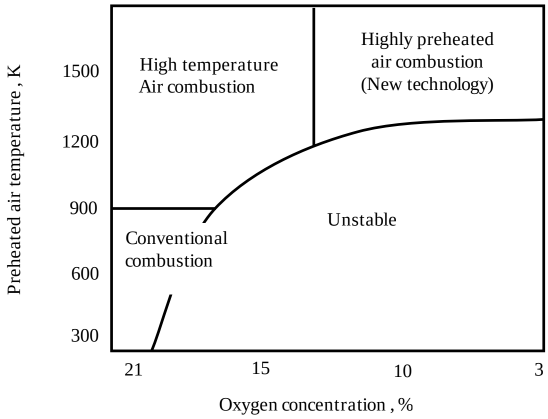

Fig.5 Combustion map by Hasegawa et al[6]

2.4 Various types of fuel applications

The highly preheated air combustion resulting from steel works byproduct gas and natural gas, is an established technology. This technology is readily applicable to oil combustion. **Figs.6** and **7** compare the distribution of heat flux emitted from flames, NOx in flue gases, etc. observed in combustion experiments using various types of fuel. As shown in these figures, low NOx combustion is attained independent of fuel type. The distribution of heat flux produced differences between fuel types. The oil combustion that gives off a luminous flame produced a larger amount of heat flux thus producing a higher heating efficiency. When A-fuel oil is combusted, a highly preheated air combustion condition can be established without soot being generated by conducting appropriate fuel nozzle purging when combustion method is changed.

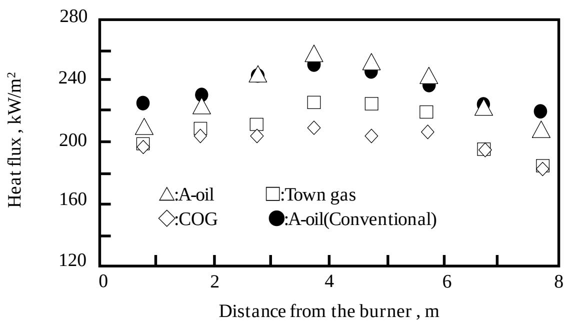

Fig.6 Comparison of heat flux for various fuels

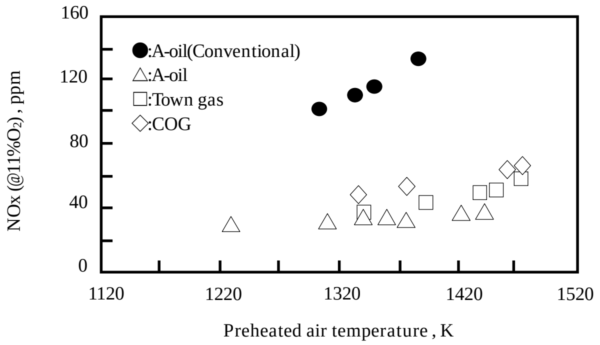

Fig.7 Comparison of NOx emission for various fuels

3. Application to iron and steel making processes

3.1 History of applying regenerative burners in iron and steel making processes

The first time regenerative burners were used in the iron and steel making processes was presumably in Europe during the 1980's as an energy saving technology. After that, the regenerative burner technology, using balls and nuggets as the regenerator, was introduced to Japan. In 1994, this technology was applied to a part of continuous slab reheating furnace at Mizushima Works to obtain energy savings. However, this technology had problems such that reduction of NOx emission remains small and the volume of the regenerator was still large.

3.2 Full-scale application to large continuous furnaces

The No.3 reheating furnace, a large-scale continuous slab reheating furnace, at NKK's Fukuyama Works' No.1 hot-rolling mill started operation in 1996, and totally applied the eco-friendly regenerative burner. For the first time in the world, both low NOx combustion and energy savings were achieved in the furnace. The No.3 reheating furnace attained the impressive result of a 25% reduction in energy consumption and a 80% reduction in NOx emissions when compared with conventional heating furnaces. Furthermore, the No.2 reheating furnace, which started operation in 2001, attained similar results to the No.3 reheating furnace, thus establishing the effectiveness of this technology.

Fig.8 compares unit fuel consumption between furnaces. Since the start of operations, the No.3 reheating furnace has sustained a lower unit fuel consumption than that of reheating furnaces Nos.4 and 5, which are renewed furnaces of a conventional type producing a preheated air temperature of 900 K. The difference in unit fuel consumption between these furnaces has stayed at about 80 MJ/t since operations began. The fluctuation in unit fuel consumption is caused by variations in production conditions, as well as by deterioration in the heat recovery rate resulting from the degradation of regenerator and increased leakage from the switching valves. Design standardization was conducted by applying measures to each of the causes. The No.2 reheating furnace, which started operation in January 2001, meets the standard design level of unit fuel consumption, producing a lower level (by about 80 MJ/t or more) than the levels of heating furnaces Nos.4 and 5. Thus, it is confirmed that the designed heat recovery rate is attained by adequate design and control of the regenerator and switching valves, as well as those of the furnace body.

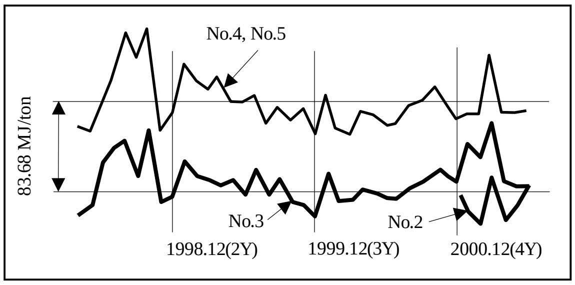

Fig.8 Comparison of unit energy consumption between conventional (No.4, No.5) furnaces and regenerative (No.2, No.3) furnaces

Also in terms of the amount of NOx generated, the No.2 reheating furnace has achieved significant reductions, as much as 80%, owing to the synergistic effect of reductions in NOx concentrations in flue gases and reductions in flue gas amounts resulting from fuel saving. Furthermore, as a secondary effect, skid marks were reduced by more than 30%. As a result of these effects, the eco-friendly regenerative burner heating system that has been developed (see **Fig.9**), has proved to be an extremely effective technology in energy saving as well as environmental conservation aspects.

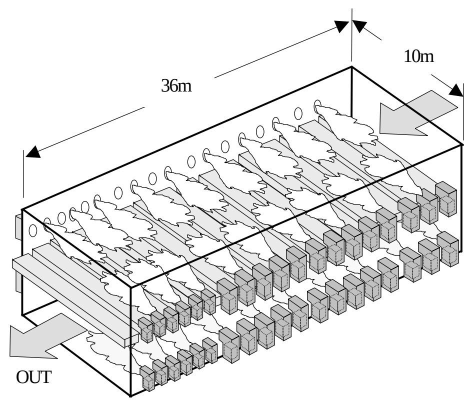

Fig.9 Slab reheating furnace with eco-friendly regenerative burner heating system

3.3 Partial application to large, continuous furnaces

The regenerative burner can be readily introduced to existing large, continuous slab heating furnaces. The method of introduction differs in terms of the intended use.

3.3.1 Increasing heating capacity through an additional regenerative burner

The plate mill at NKK's Keihin Works is intended to integrate two reheating furnaces into one by increasing the heating capacity of one of the reheating furnaces. This has been achieved by modifying the furnace by adding regenerative burners to the charge side of the furnace. Since the modification did not mean replacement of the existing burners, the recuperator could be used as part of the modification. Also in terms of the control system, the system for additional burners only, was added. By modifying the plant in this way, single-furnace operation became possible instead of a conventional two-furnace operation, thus improving the unit fuel consumption of the heating furnace by 13%. Furthermore, the furnace successfully keeps NOx generation below the regulated level while attaining increases in heating capacity. Since the environmental regulations are likely to become more severe in the future, heating furnaces will be forced to adopt the eco-friendly regenerative burner.

3.3.2 Attaining energy saving by replacing conventional type burners with regenerative burners

NKK's Fukuyama Works' plate mill has conducted modifications of continuous reheating furnaces by replacing the conventional type burners in the heating zone, whose burners consumed about 50% of the total heating furnace fuel, with regenerative burners, for energy saving purpose. In other words, the conventional burners were removed, and the regenerative burners were mounted in their place. Since the regenerative burner, which has a built-in honeycomb regenerator, is a compact burner, the regenerative burners could be mounted without changing the burner pitch. Through modification, the recuperator capacity should be decreased since the existing burners in the heating zone were removed. As for the control system, the existed control system was used while only the switching control for the regenerative burners was added. After modification, unit fuel consumption of the reheating furnace was improved by 9%. Furthermore, the adoption of the eco-friendly regenerative burner decreased NOx generation by more than 40%.

3.4 Conclusion

The eco-friendly regenerative burner can be applied to any type of heating facility by simply adjusting the number of burners responding to the required heating capacity.

Up until now, NKK has installed the eco-friendly regenerative burner heating system in eleven heating facilities. **Table 1** shows the energy savings and NOx reduction effects in these eleven facilities. Energy savings have reached an average of 30%, accounting for as much as 1212 TJ/y. NOx generation has significantly decreased by an average of 50%.

As a result, the eco-friendly regenerative burner heating system was awarded the Ministry of International Trade and Industry Excellent Energy Saving Cases Minister's Prize in FY 1998 and FY 1999. It has also been awarded the Okochi Memorial Prize in FY 1999 and in FY 2000, the National Invention Honor.

Table 1 List of regenerative burner applications in NKK

Name	Year	Application	Burner units	Fuel cut ▲%	Fuel cut ▲TJ/y	NOx cut ▲%
Fukuyama 1HOT No.3 Continuous Slab Reheating Furnace	1996	Full	76	25	294	80
Keihin Electric Furnace Ladle Heater	1996	Full	2	56	29	-
Keihin Seamless Pipe Continuous Reheating Furnace	1997	Full	60	49	56	52
Fukuyama Plate Mill No.1 Batch-type Reheating Furnace	1998	Full	12	40	111	60
Fukuyama No.3 CAL-RT	1999	Full	176	32	21	35
Keihin Plate Mill No.1 Continuous Slab Reheating Furnace	1999	Partial	16	13	212	31
Fukuyama 1HOT No.2 Continuous Slab Reheating Furnace	2000	Full	76	25	294	80
Fukuyama Plate Mill No.3 Batch-type Reheating Furnace	2000	Partial	6	37	51	53
Keihin Ingot Soaking Furnace	2000	Full	4	23	14	62
Fukuyama Plate Mill No.1 Continuous Slab Reheating Furnace	2001	Partial	30	9	65	44
Fukuyama Plate Mill No.2 Continuous Slab Reheating Furnace	2001	Partial	30	9	6	44

4. Future prospects

4.1 Effects on industrial furnaces and applications to other fields

Since the sales of the eco-friendly regenerative burner began in 1992, NFK has led the sales activity mainly in the industrial furnace field, selling 1532 pairs to 263 facilities. About 50% of customers are from the iron and steel sector, 40% from the automobile and non-ferrous sectors, and 10% from the ceramics and other sectors. As described earlier, the National Project, "High Performance Industrial Furnace Project", which was promoted during the period 1998 to 2000, studied the increase in and clarification mechanism of performance in various industrial furnaces, such as, heat treatment furnace, and melting furnace, applying highly preheated air combustion technology using the eco-friendly regenerative burner heating system as well as adopting the optimal heating furnace design. As a result, the possibility of energy saving (by 30%), significant reduction of NOx (by 50%), reduction in noise, and compact design (by 20%) has been confirmed in reality as well as from a theoretical point of view. Following these studies, a field test project (FT Project) was planned to conduct verification tests at commercial furnaces using various types of industrial furnace, and to widely distribute this technology. These FT Projects have been conducted on 167 furnace units over the three years from 1998 to 2000. The test data has been accumulated for each furnace throughout the four years of continuous testing. At the point of proposing the testing of these 167 units, the expected effect was 160 thousand kl/y of reduction in fuel converted to oil.

In the view that such superior technology should also be applied to other combustion facilities, the five-year plan High Temperature Air Combustion Technology Project (HICOT Project) began in 1999. The target facilities for research and development are: (1) pulverized coal-fired boilers; (2) waste incineration furnaces, and (3) high temperature chemical reaction furnaces. Since the direct application of highly preheated air combustion technology to these facilities is not possible, individual issues resulting from practical application have been studied. NKK has studied the waste incineration furnace. In March 2002, NKK optimized the addition of hot air, thus attaining both lean air combustion, reducing the conventional air ratio of 1.7 to between 1.2 to 1.3, and the detoxification of flue gases, thus achieving energy savings of more than 30% and NOx reduction of more than 30%[7].

The application of highly preheated air combustion is not limited to the above fields. For instance, tests for wider application fields are underway by substituting hot air with a hot fluid and by substituting combustion with a chemical reaction[8]. A hot fluid generator using a honeycomb regenerator supplying hot fluid to the reactor, achieves a high temperature fluid at 1579 K with 87% heat efficiency and 100 m/s velocity.

4.2 Domestic measures and overseas development activities

Since the COP7 Marrakech Congress held in 2001 prepared the conditions for ratification, (3.9% for absorption measures from sources such as forests, application of Kyoto Mechanism, etc.), the Japanese government has reviewed the Law Concerning the Rational Use of Energy as well as the Fundamental Principles on Global Warming until 2002. The Japanese Cabinet decided to adopt the reviewed results. The review includes the introduction of outline measures to reduce CO_2 by 6% by 2010 from 1990 levels. This was determined as a policy at COP3. The review expects energy saving from oil of 400 thousand kl/y as a result of the measures taken at high performance industrial furnaces. If the preceding effect of FT projects is taken into account, the measures to modify more than 400 facilities will be required. This is about 2.5 times the number of facilities adopted in the FT projects. Based on this calculation, if about 50% of the value derived by a survey on industrial furnaces in Japan is assumed as a practical target (about 20 thousand units), and, if the required number (400 facilities) is added to the conventional result, the percentage of high performance industrial furnaces to the target is still below 5%. Accordingly, it is expected that this technology will include more applications in other fields as a necessary means of achieving the target energy savings (47 million kl/y as oil) as a countermeasure to global warming during and after 2010.

The eco-friendly ceramic honeycomb regenerative burner heating system emphasizes the highly preheated air combustion technology. This establishes energy savings resulting from the high heat recovery rate and ultimately low NOx emissions. The system has attracted the attention of overseas industries as well as domestic ones, particularly those in Europe who are particularly concerned about environmental issues. This method of achieving ultimately low NOx emissions has become increasingly important both from the point of forest conservation as an absorption source of CO_2, etc., and as a countermeasure to the acidification of lakes and marshes. In this regard, the performance verification tests of the NFK-made ceramic honeycomb regenerative burner are planned for France, Sweden, and Holland from 2001 to 2002. The test results will be evaluated within one to two years. In addition, Asian countries and developing countries, including Korea, China, Taiwan, Indonesia, Thailand, and Malaysia; South American countries such as Brazil, and countries in Eastern Europe are showing keen interest in this technology. Consequently, the eco-friendly ceramic honeycomb regenerative burner heating system is expected to find wider practical applications in waste incineration, reactors and other fields as a countermeasure to global warming (due to CO_2 emission) and acid rain.

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Shinichiro Fukushima
Environmental Control and Energy Dept., Steel Technology Center
Tel : (81) 3-3217-3388
e-mail : Shinichiro_Fukushima@ntsgw.tokyo.nkk.co.jp