CO_2 Reduction Technology for Thermal Power Plant Systems

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OVERVIEW: Among the international efforts to curb global warming, practical application of CO_2 removal technology and improvement of power-generation efficiency — for reducing CO_2 emission from thermal power plants (which will probably remain the prime source of power in future) — will, at the very least, become urgent issues over the next several decades. Accordingly, the Hitachi Group is aiming at further improving efficiency with the following main developments: 700°C USC coal-fired thermal power, coal-gasification power generation, a high-efficiency turbine, and a new thermal-cycle system. By performing CO_2-recovery tests on a coal-gasification power plant and developing an oxy-combustion-system coal boiler suited to CO_2 recovery, we are also actively engaged in practical application of CCS technology which incurs low energy loss.

INTRODUCTION

THE installed capacity of thermal power plants using fossil fuels like coal and natural gas around the world is expected to double by the year 2030. In the meantime, against a backdrop of increasingly severe global warming, early practical application of technology for reducing CO_2 emission is being demanded. Accordingly, the Hitachi Group is developing world-class technologies such as ultra-supercritical-pressure power generation and gas-turbine combined power generation (see Fig. 1).

In this report, activities aiming at further boosting power-generation efficiency and practically applying so-called CCS (carbon capture and storage) technology are described, and the current status of research and development on thermal power generation

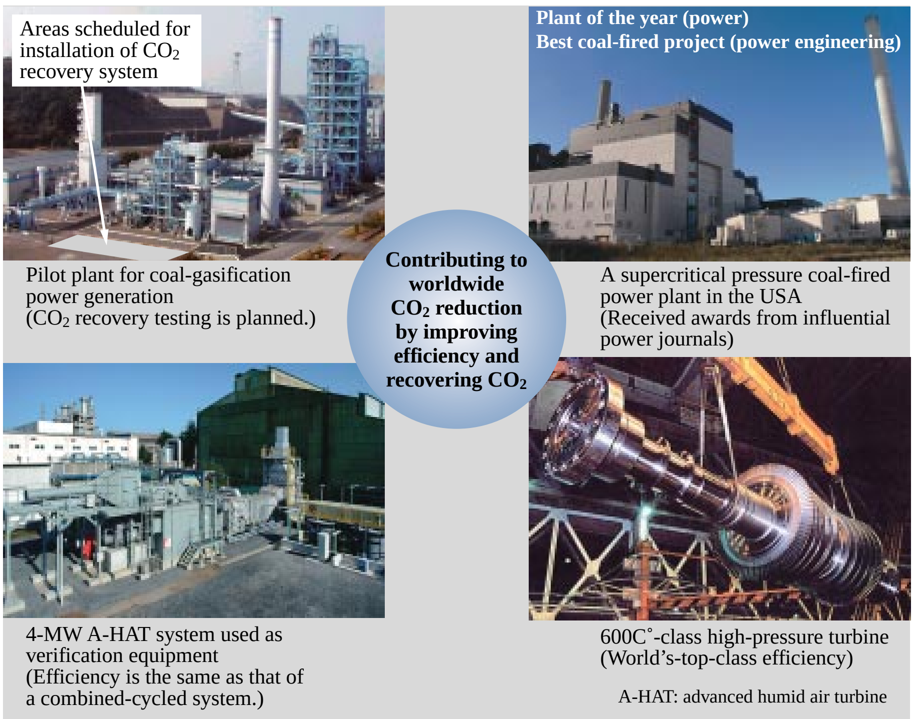

Fig. 1—Thermal-power Generation Technologies of the Hitachi Group that Contribute to Curb Global Warming.
To reduce CO_2 emissions of thermal power generation (the main force in the global power-generation field), Hitachi is engaged in practical application of coal-gasification power generation, development of ultra-supercritical-pressure power generation, improvement of gas-turbine thermal-power efficiency, and development of coal-fired-power-generation systems capable of capturing CO_2.

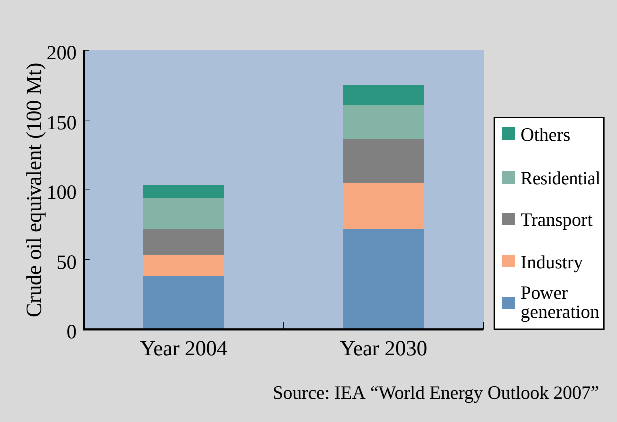

Fig. 2—Forecasted Increase in Worldwide Demand for Energy.
Global energy consumption will rise by about 1.6 times by the year 2030.

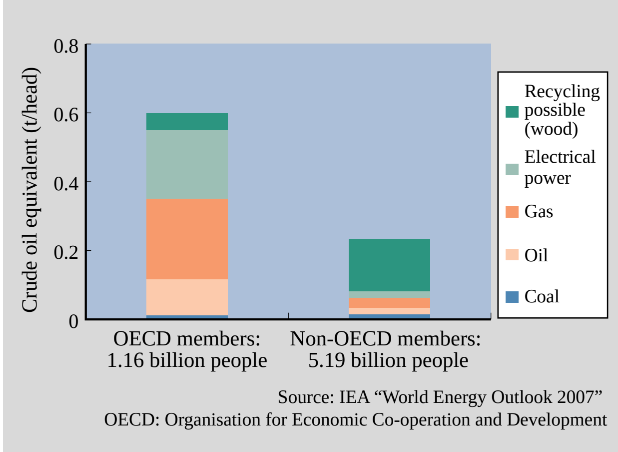

Fig. 3—Household Energy Consumption per Head.
Electrical power consumption by non-OECD members is forecast to significantly increase from now onwards.

is also explained.

SOCIAL TRENDS

At the 13th Conference of the Parties of the United Nations Framework Convention on Climate Change on the island of Bali, Indonesia in December 2007, a framework for measures addressing global warming from 2013 onwards was agreed upon. Through global cooperation, speeding up of the necessary technical developments for countering global warming and expansion of high-efficiency technologies to cover all countries are expected.

The International Energy Agency (IEA) has forecast that as a result of improved living standards and increased world population (from 6.5 billion in 2004 to 8.3 billion by the year 2030), global energy consumption will increase by 60% by 2030 (see Fig. 2). According to application of this energy, the proportion taken up by power generation is the biggest and will account for a 45% share of total global energy consumption by 2030.

Household energy consumption per capita, separated in terms of Organisation for Economic Co-operation and Development (OECD) member countries and non-OECD countries, is shown in Fig. 3. In OECD member countries, the main energy sources for everyday life are electricity and gas; in contrast, in non-OECD countries, which population accounts for more than 80% of that of the world, the main energy source (i.e. over 60% of all sources) is wood fuel used for cooking and heating.

According to the IEA, about 1.6 billion people in the world are still unable to use electricity and, from now onwards, due to economic growth in China, India, and other developing countries, electricity power grids will be upgraded and household energy consumption per head will significantly increase as living standards improve.

Although it is forecast that use of wind-generated power and solar-power generation (which contribute to controlling global warming) will increase more than tenfold by 2030 compared to 2004, their proportion will still be only 7% of total power generation. And about 70% of the sources for power generation will be still fossil fuels.

As for curbing global warming, atomic power generation is expected to make a big contribution. However, the amount of uranium resources that can be mined at present costs will only last another 80 years or so. Given that, present light-water reactors can be replaced by fast-breeder reactors, which can utilize uranium resources more than 50 times more effectively, and development of the latter is eagerly progressing. Even so, it will not be until 2050 that fast breeders become commercially available. Consequently, for some time to come, energy sources for power generation must mainly rely on fossil fuels. Therefore it is indispensable to develop technologies for suppressing CO_2 emission.

ACTIVITIES CONCERNING COAL-FIRED POWER GENERATION

Development of a 700°C-class A-USC

Coal-fired thermal power generation attains high efficiency with increasing pressure and temperature of the steam cycle. However, higher temperatures

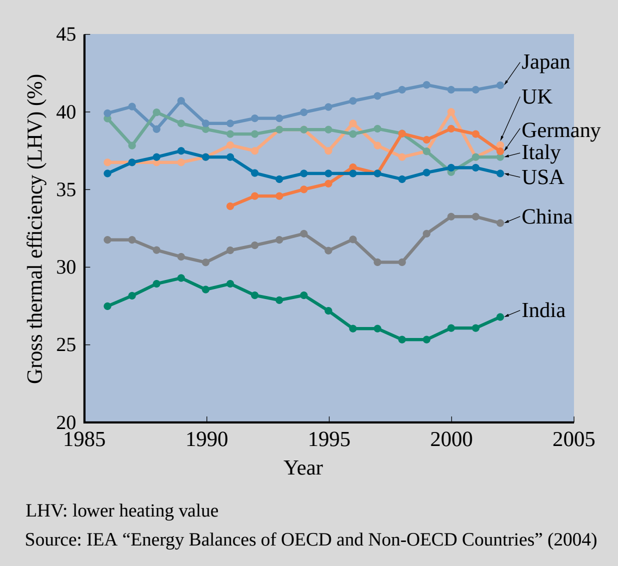

Fig. 4—Efficiency of Coal-fired Thermal-power Generation in Several Countries.
As an achievement of the 600°C-class national project, the efficiency of coal-fired thermal-power generation in Japan has been the highest in the world since 1990.

decrease creep strength and cause thermal expansion to occur, and high pressures cause efficiency loss through leakage of fluid flows and deformation of structures. As a result, accomplishing a high-temperature and high-pressure steam cycle requires significant breakthroughs in regard to material- and mechanical-design technology.

In Japan between 1980 and 2000, 600°C-class USC (ultra supercritical) pressure technology was developed(1). Through these developments, ferritic steel with high strength at low cost was developed, and design techniques for strength and heat transfer were improved up to world-class level. As a result, commercial equipment operating under steam conditions of 600°C and pressure of 25 MPa — starting with the Haramachi Thermal Power Station Unit No. 2 of Tohoku Electric Power Co., Inc. — was practically applied. The efficiencies of coal-fired power generation in several countries (reported by the IEA) are compared in Fig. 4.

Owing to the successful development of USC technology, coal-fired power generation in Japan today operates at the highest efficiency in the world, and in 2009, the No. 2 Unit of the Isogo Thermal Power Station of the Electric Power Development Co., Ltd. is due to start operation. Hitachi is applying this USC technology to state-of-the-art USC pressure power plants in North America and, in doing so, helping to reduce CO_2 emissions(2),(3).

Moreover, in Europe, the THERMIE project [to develop coal-fired thermal power plants targeting efficiency of 50% using A-USC (advanced ultra supercritical) steam-generation technology (35 MPa, 700°C or more)] was started in 1998.

As a participant in this project, Hitachi Power Europe GmbH of Germany is aiming to practically apply boilers. Presently, the application limit of ferritic steel used with USC technology is below 650°C, and withstanding steam conditions above 700°C necessitate the use of nickel-based casting alloy similar to those used in gas turbines. However, nickel-based casting alloys have a constitution that becomes unstable easily in response to temperature variations induced by the material manufacturing process, leading to the problem of segregation, which changes material constitution during manufacturing of large-scale raw materials. As gas-turbine materials, nickel-based casting alloys (which attain high strength in materials weighing several kilograms or so) cannot satisfy the design strength needed for the large-scale materials weighing several tons used in boilers and steam turbines. In Europe, while it has been ten years since nickel-based casting alloy was adopted and problems regarding fabrication were overcome, material properties of piping and valves under actual steam conditions are currently being investigated.

For the development of a 700°C-class A-USC plant, a plan is being promoted by the "Cool Earth 50" project in Japan. As part of preliminary investigations by this project, a rotor material composed of nickel-based casting alloy — called FENIX-700 — that can be applied for 700°C-class A-USC was developed (see

Fig. 5—External Appearance of a Large-scale Steel Ingot (FENIX-700).
Creep rupture strength (700°C/100,000 h) of this material exceeds 100 MPa. Presently, trial production of an 850-mm-diameter, approx.8-t-weight ingot was successful.

Fig. 5) through the "Leading Research and Development on Basic Technologies for Effective Utilization of Energy" project of the New Energy and Industrial Technology Development Organization (NEDO). FENIX-700 suffers no segregation at all and is one material that is expected to be applied practically. We will lead the A-USC project in order to achieve CO_2 reduction that exceeds the current technology.

Development of Coal-gasification Combined Power Generation with CO_2-recovery

A coal-gasification power-generation system is a promising candidate for next-generation high-efficiency power generation referred to as an IGCC (integrated coal-gasification combined cycle) system, which is a combined electricity-generation system that produces gas-turbine fuel by partially oxidizing coal and "gasifying" it and recovers heat of exhaust gas for a steam turbine.

Participating in the EAGLE project for multi-purpose coal gasification technology development since 2001, Hitachi has been engaged in operational research on coal-gasification power-generation systems(4). In a gasification furnace, oxygen gas (produced from air separator) carrying pulverized coal is fed into the furnace, where it is swirled around (see Fig. 6). The coal and oxygen are fed from the top and bottom burners, at which oxygen ratio is individually controlled. The amount of oxygen in the lower level is set so that the temperature in the furnace is higher than fluid point of ash, thereby enhancing slag melting. The amount of oxygen in the upper level is lowered so that the oxygen concentration in the entire gasification furnace is optimized. In this process, oxygen is properly distributed according to coal type, thereby assuring high-efficiency gasification.

Through running tests of the EAGLE project (with a coal feed rate of 150 t/d), world-leading performance was demonstrated (see Table 1). In order to continue

TABLE 1. Operational Performance of the EAGLE Pilot Plant
Operational performance for gasification and gas purification is shown.

	Item	Content	Operational performance
Gasification	Conversion efficiency	Cold gas efficiency	≥ 82%
		Coal-gasification efficiency	≥ 99%
	Reliability	Long-term continuous operation	1,015 h
	Operability	Multi-coal-type handling	5 coal types
Gas purification	Removal performance	H_2S and COS removal	< 1 ppm
		Dust removal	< 1 mg/Nm^3
		Halogen and NH_3 removal	< 1 ppm

EAGLE: coal energy application for gas, liquid and electricity

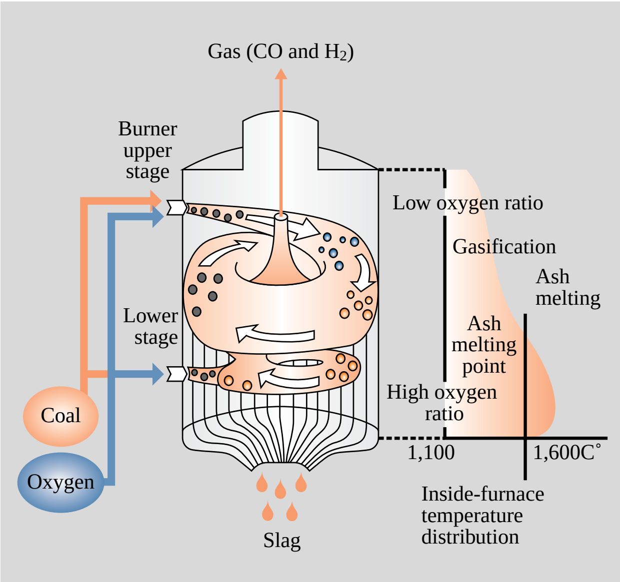

Fig. 6—Concept of Coal Gasification.
Grain dispersion in swirling flow is controlled, and appropriate oxygen delivery for all types of coal is assured.

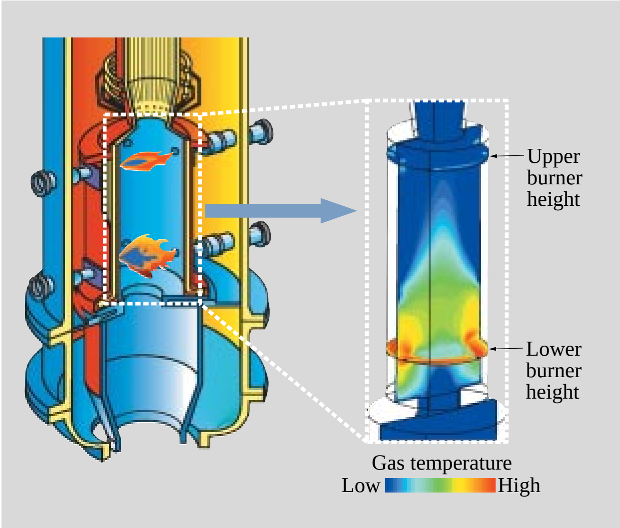

Fig. 7—Numerical Analysis on Thermal-flow Dynamics of Coal-gasification Furnace.
Accuracy of a numerical simulation technique based on data obtained from the EAGLE project is being improved, and attains high accuracy, and it is tackling design of commercial gasifier with high reliability.

technical development aiming at large-scale operation, numerical simulation for designing commercial plant is an essential part. Hitachi is thus improving accuracy (that is, gasification basic-testing results on a pressurized/normal pressure furnace are reflected in a gasification-furnace reaction simulation), identifying the issue of scalability, and confirming the reliability of commercial size plants (see Fig. 7).

IGCC technology can remove CO_2 from high-pressure syn gas before it is input into a gas turbine, therefore it is expected to achieve excellent combined efficiency for CO_2 removal. In regard to the EAGLE project, testing of the world's first cutting-edge CO_2 removal pilot plant for IGCC will start. In an existing system constructed of a gasification furnace, gas scrubbers, air separator, and gas turbines, a CO_2 absorber, regenerator equipment, and so on are installed in an area of 450 m^2 by the side of a gas scrubbers. High-pressure gas (at 2.3 MPa) is extracted from the H_2S absorber at 1,000 Nm^3/h, and CO (carbon monoxide) in the gas is converted to CO_2 by a so-called "shift reaction." Then, the gas (in which the main ingredient is CO_2 and hydrogen) is treated in the CO_2 recovery unit by chemical absorption (see Fig. 8). From now onwards, we will build up our know-how aimed at cost reduction and efficiency improvement of a commercial-class CO_2 recovery unit.

Development of Oxyfuel Coal-fired Thermal Power Plant

Conventional coal-fired power plant burns coal with air; therefore, for recovering CO_2, it is necessary to separate nitrogen and CO_2 in the flue gas. In the oxygen-combustion method, nitrogen is removed from the air before combustion, so the main components of the flue gas are H_2O (water) and CO_2. The oxygen concentration and temperature in the combustor are regulated by recycling CO_2-rich flue gas (see Fig. 9).

The system resembles practical coal-fired plants, and it is gaining attention as a "coal-fired thermal power plant with CO_2-removal" approaching practical application. In particular, in Germany, demonstration testing of oxyfuel combustion is planned, and as a key participant in European projects, Hitachi Power Europe GmbH is implementing system designs for oxyfuel combustion.

In the fundamental research field, Hitachi exchanged joint declarations on CO_2-reduction technology in thermal-power plants with the state of Nordrhein-Westfalen in Germany and started joint research with major universities. Furthermore, in collaboration with RWTH-Aachen University, it is planned to share the oxy-combustion test furnace of the university, acquire basic combustion data, and improve the numerical-analysis technology for

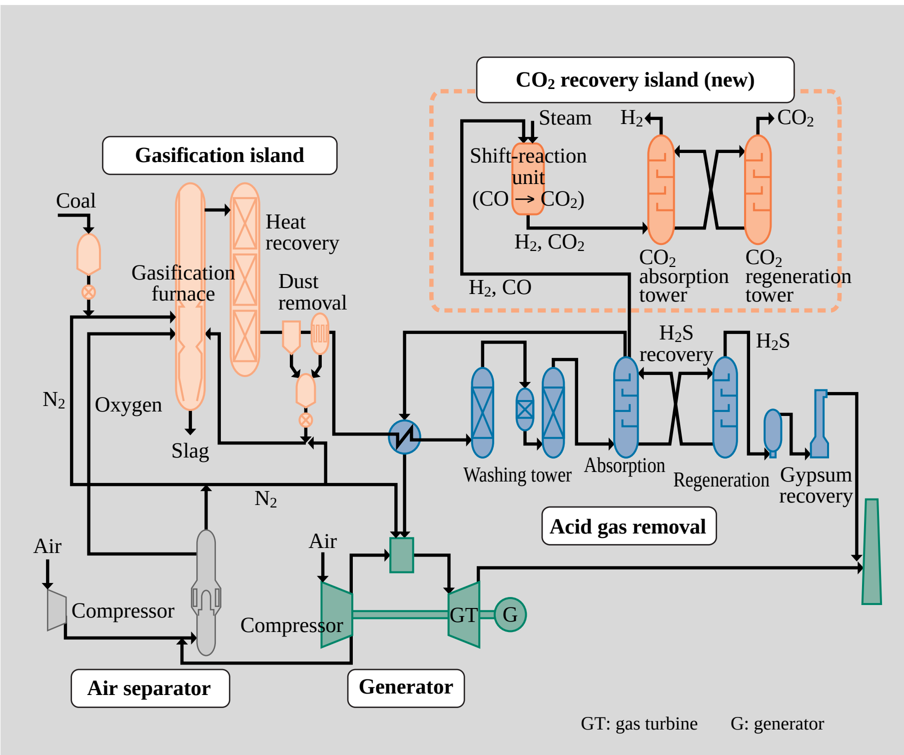

Fig. 8—System Configuration of EAGLE Pilot Plant.
Gas at 1,000 Nm^3/h is extracted from existing equipment, and CO_2 recovery performance is confirmed.

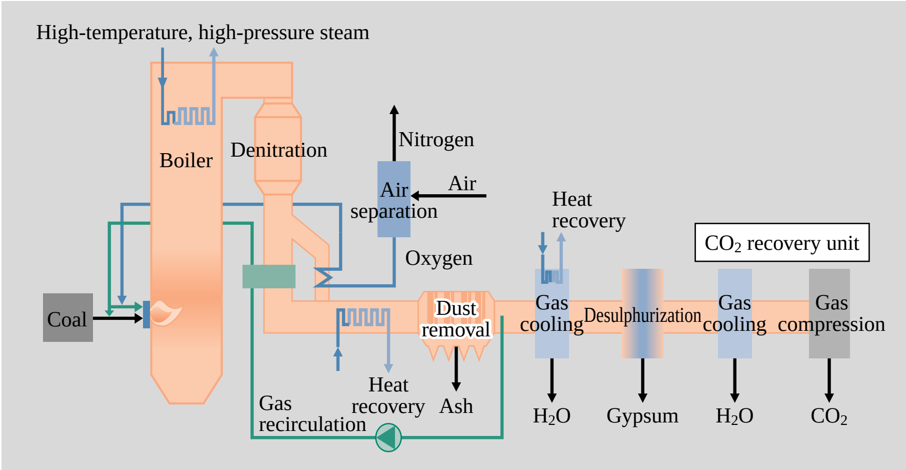

Fig. 9—Concept of System for Oxyfuel Combustion.
To validate basic performance of the oxygen-combustion boiler, a pilot test in Europe is being planned.

improving the reliability of oxy-combustion boilers(5) (see Fig. 10).

EFFORTS CONCERNING GAS-TURBINE THERMAL-POWER GENERATION

Development of A-HAT

Through innovations in the gas-turbine power-generation cycle, we are developing an A-HAT (advanced humid air turbine) as a technology for reducing CO_2 emission and attaining high efficiency(6). The system configuration of the A-HAT is shown in Fig. 11. This system accomplishes recycling by using humid air. Water atomizing cooling system set up at the compressor inlet and the main gas flow in the humidifier (fitted upstream of the regenerator) are humidified. The humidified moisture is recycled in the water-recovery system, so the amount of supplementary feed water is decreased. The same output power and efficiency as a combined-cycle system are achieved by the gas turbine itself — without having to use a

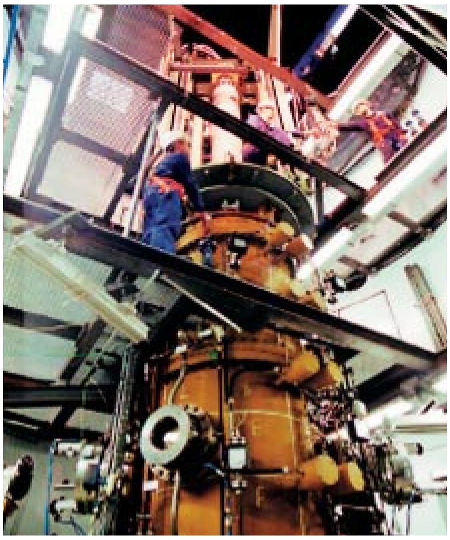

Fig. 10—Oxyfuel-combustion Testing Equipment of RWTH Aachen University.
Development of coal-combustion technology for CO_2 removal is continuing in collaboration with a German university.
(RWTH-Aachen University, Courtesy of ©Peter Winandy)

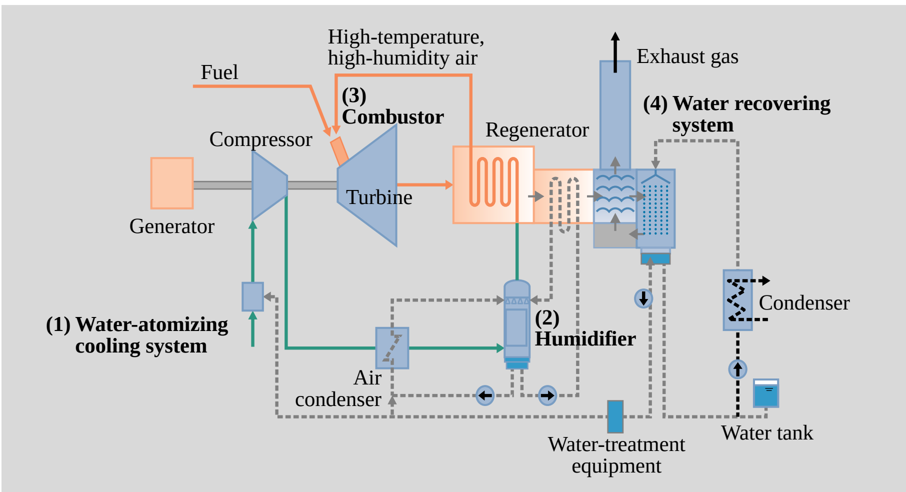

Fig. 11—Outline of A-HAT System.
A-HAT has achieved the same efficiency as combined cycle with a single gas turbine.

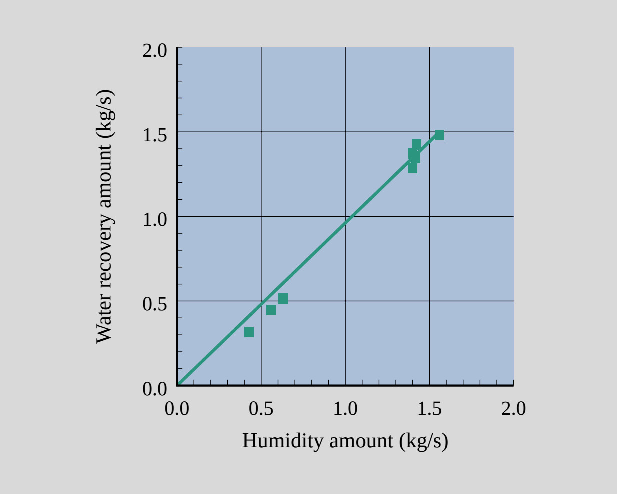

Fig. 12—Water-recovery Volume.
Almost all humidity is recovered, and amount of supplementary feed water is reduced.

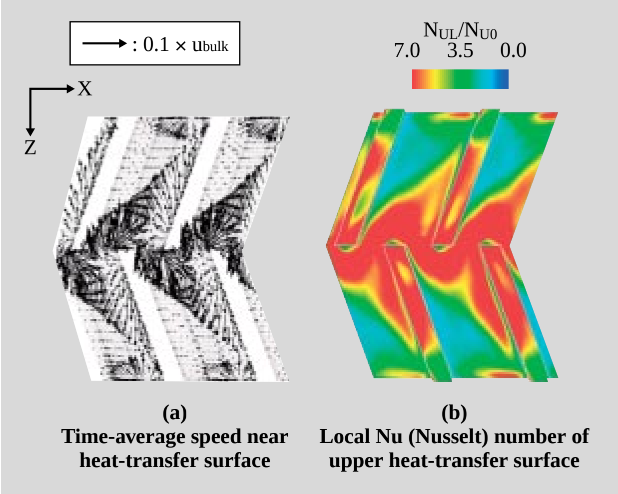

Fig. 14—Thermal-flow Analysis of Blade Cooling Passages.
Heat-transfer enhancement and cooling efficiency are improved by the turbulence-promotion ribs.

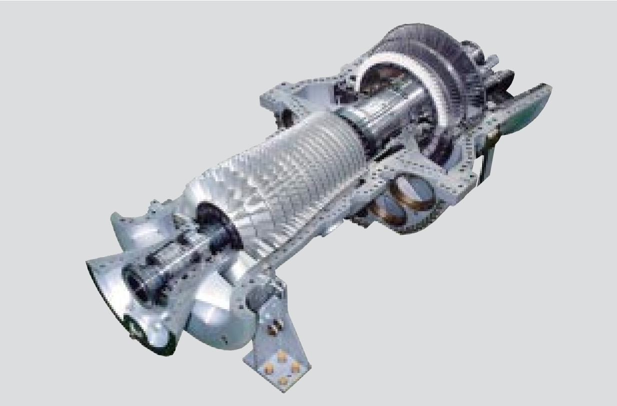

Fig. 13—H-25 Gas Turbine.
With the upper casing removed, the turbines interior parts can be seen.

steam turbine. Particular features of this system are simple plant configuration and easy operation control combined with low NO_x emission from the combustor.

Since 2004, as a grant-aided project of the Agency for Natural Resources and Energy, a compact 4-MW system-verification plant has been under development, and in March 2007, it achieved a power output of 3,985 kW. Gross thermal efficiency exceeded 40 LHV (lower heating value), and NO_x emission from the combustor was confirmed to be lower than 10 ppm. The water-recovery volume is plotted in Fig. 12. The figure shows that almost all of the humidification amount can be recovered, confirming that an A-HAT system can be established(7).

Our plan is planned to continue experimental demonstration of the A-HAT test plant from aspects such as improving performance, reliability, and economic efficiency.

Gas-turbine Elemental Technology

A cut-away view of Hitachi's H-25 gas turbine is shown in Fig. 13. Hitachi is actively engaged in elemental technological development targeting higher efficiency and lower environmental impact of the gas turbine itself(8).

(1) Turbine

To increase turbine-blade cooling efficiency and reduce coolant flow volume, the mechanism of heat-transfer enhancement is made clear by numerical analysis. Analysis results on the thermal flow on the inner surfaces of the cooling passages of the turbine by LES (large eddy simulation) are shown in Fig. 14(9). Fig. 14 (a) shows that the flow winds around the rib tips, and Fig. 14 (b) shows that a high heat-transfer ratio in center of the heat-transfer surfaces and on the upper surfaces of the ribs is attained in response to

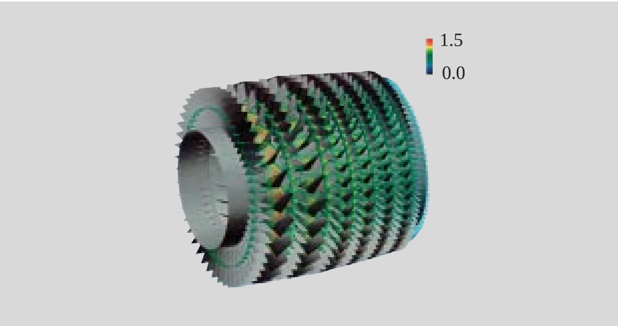

Fig. 15—Multi-stage Flow Analysis.
High performance is attained by considering matching of like blade rows.

this flow pattern. According to these analysis results, the turbulence-promotion ribs promote higher performance.

(2) Compressor

To lower cost while achieving high efficiency, it is necessary to design a high-load compressor with a reduced number of stages. As for the aerodynamic design to meet that need, a new type of compressor blade is being developed by means of a blade-design and three-dimensional-stacking method (using multiple-objective optimization). Combining multistage flow analysis with this blade-design technology has achieved high performance (see Fig. 15).

CONCLUSIONS

This report described Hitachi's efforts in achieving higher efficiency and practical application of CCS technology and explained the current status of research and development on thermal power generation.

For technology development of thermal power plants, it is necessary to address such problems as economic efficiency and verification of long-term reliability.

Drawing on our experience in development of thermal power plants accumulated up till now and making full use of cutting-edge numerical-analysis technology, the Hitachi Group will continue to develop high-efficiency thermal power plants and to commercialize CO_2-recovery technology. As a result, we are aiming to improve the reliability of developed products that will help to curb future global warming.

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