Development of Technologies for Improving Efficiency of Large Coal-fired Thermal Power Plants

Hajime Kimura
Takashi Sato
Christian Bergins, Dr. Eng.
Shinya Imano, Dr. Eng.
Eiji Saito, Dr. Eng.

OVERVIEW: The development of technologies for improving the efficiency of coal-fired power generation is critical to alleviating the problem of global warming. Hitachi has supplied a large number of coal-fired power plants that have featured world-leading levels of efficiency. In recent years, it has also embarked on the development of technology for 700°C-class A-USC power generation to achieve even higher efficiency. These developments are being accelerated through a global research and development infrastructure that includes not only Japan but also active involvement by Europe.

INTRODUCTION

COAL deposits are widely distributed around the world, and these reserves are cheap to extract compared with other energy sources. Use of coal for thermal power generation allows large quantities of electric power to be reliably supplied. As a result, coal-fired thermal power plants provide more than 40% of the world's electric power. Furthermore, the demand is growing steadily around the world, particularly in emerging economies such as China and India. With its proven ability to produce 1,000 MW or more from a single plant, the demand for coal-fired electric power is also growing in post-earthquake Japan as a substitute for nuclear power. Unfortunately, coal-fired power generation is also accompanied by considerable greenhouse gas emissions. Coal emits more CO_2 (carbon dioxide) than any other form of power generation, so improving its efficiency contributes directly to a reduction in CO_2 emissions. High expectations are being placed on the development of technologies that improve the efficiency of coal-fired power generation in environmentally conscious ways.

This article describes how Hitachi's development of technology for improving the efficiency of coal-fired power generation has evolved over time, and also its development of new technology.

DEVELOPMENT HISTORY OF COAL-FIRED POWER GENERATION

An important consideration in designs for improving the efficiency of coal-fired power generation is how to make use of a large amount of heat energy, with factors that contribute to increased efficiency including higher maximum pressures and temperatures in the thermal cycle. Based on the steam conditions, coal-fired power generation can be broadly divided into plants that use subcritical pressure (in which the main steam pressure is below the critical pressure of 22 MPa), supercritical pressure (pressures greater than the critical pressure of 22 MPa), and USC (ultra-supercritical) pressure (use of supercritical pressure together with a steam temperature of 593°C or more). Fig. 1 shows how the efficiencies [measured at the generator output on an LHV (lower heating value) basis] for each of these plant types have changed over time. Whereas the subcritical pressure power plants that were the predominant type used in the 1970s had a thermal efficiency of around 35%, thermal efficiency of more than 45% is now being achieved.

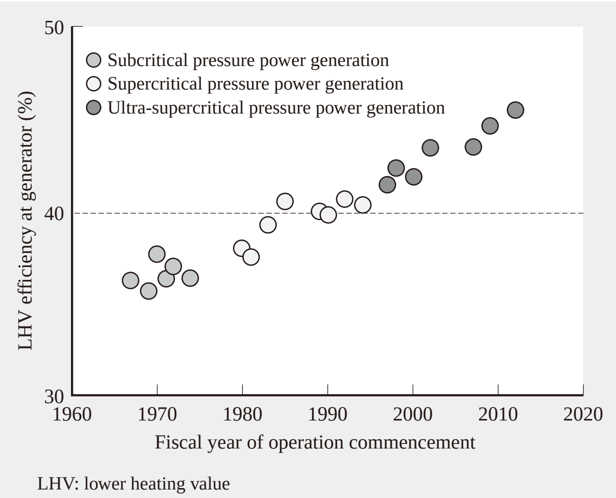


Fig. 1—Efficiency Improvement of Coal-fired Thermal Power Plants.
The efficiency of coal-fired power plants measured at the generator increased along with the maximum steam conditions used in each decade, rising from around 35% in the 1970s to more than 45% now.

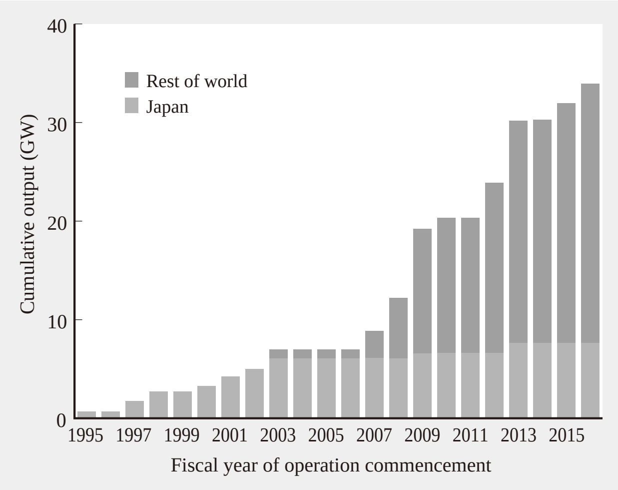


Fig. 2—Cumulative Capacity of USC Power Plant Orders Won by Hitachi.
Hitachi has won orders for a total of 38 USC coal-fired power plants to date, representing a total output of about 34 GW. Use of this technology has helped to improve the efficiency of each plant.

Fig. 3—New No. 2 Turbine Supplied to Isogo Thermal Power Plant of Electric Power Development Co., Ltd.
The turbine operates with world-leading steam conditions, with a main steam pressure of 25 MPa, main steam temperature of 600°C, and reheat steam temperature of 620°C.

Fig. 2 shows the cumulative capacity of USC plant orders won by Hitachi. Japan led the world in developing the technology for implementing USC in the 1980s, and USC plants were commercialized in Japan in the 1990s. With the aim of deploying its electric power technology more internationally, Hitachi established Hitachi Power Europe GmbH (HPE) and Hitachi Power Systems America, Ltd. (HPSA) in the 2000s, and these companies are now involved in supplying USC plants widely outside Japan.

Current Status of USC Turbines

Fig. 3 shows the new No. 2 turbine at the Isogo Thermal Power Plant of Electric Power Development Co., Ltd. (J-Power) which is an example of the latest USC turbines. The turbine operates with world-leading steam conditions, with a main steam pressure of 25 MPa, main steam temperature of 600°C, and reheat steam temperature of 620°C. It was manufactured using high-temperature materials for components such as the high- and medium-pressure turbine, main steam valves, and mixing reheat valves. One example is the HR1100 high-Cr (chromium) steel rotor material developed by Hitachi, which was used in a large number of other 600°C-class USC plants in the past. The issues associated with using a higher reheat steam temperature were resolved by adopting optimized cooling technology for the medium-pressure turbine. In addition to the higher efficiency resulting from the higher temperature and pressure of the steam, the efficiency of the turbine blades was also raised by designing them in a way that optimized the reaction force. Hitachi also succeeded in reducing the overall size of the turbine by adopting 48-inch (1219.2-mm) blades (among the longest in the world) for the low-pressure final stage.

Current Status of USC Boilers

Since the 1990s, a series of supercritical pressure power plants have been built in Japan, with technologies for higher temperatures being developed, accumulated, and passed on. Improvements in the efficiency of coal-fired power plants are made by increasing the steam temperature and pressure, and plants currently under construction have outputs in the 1,000-MW range and operate at a temperature of 600°C and pressure of 25 MPa.

Fig. 4 shows how the steam conditions used in commercial coal-fired boilers supplied by Babcock-Hitachi K.K. (BHK) have changed over time. The developments that enabled operation under these increasingly extreme conditions were made to increase plant efficiency with the aim of reducing CO_2 emissions. In 1983, the first coal-fired supercritical pressure boiler (25 MPa/543°C/541°C, 700 MW) in Japan was supplied to Unit 3 at Takehara Thermal Power Plant of Electric Power Development Co., Ltd. Subsequently, a 1,050-MW USC (25.9 MPa/605°C/613°C) coal-fired boiler was supplied to Unit 2 at Tachibanawan Thermal Power Plant which also belongs to Electric Power Development Co., Ltd. in 2000. The steam temperature and pressure conditions at the plant were the highest in Japan at the time.

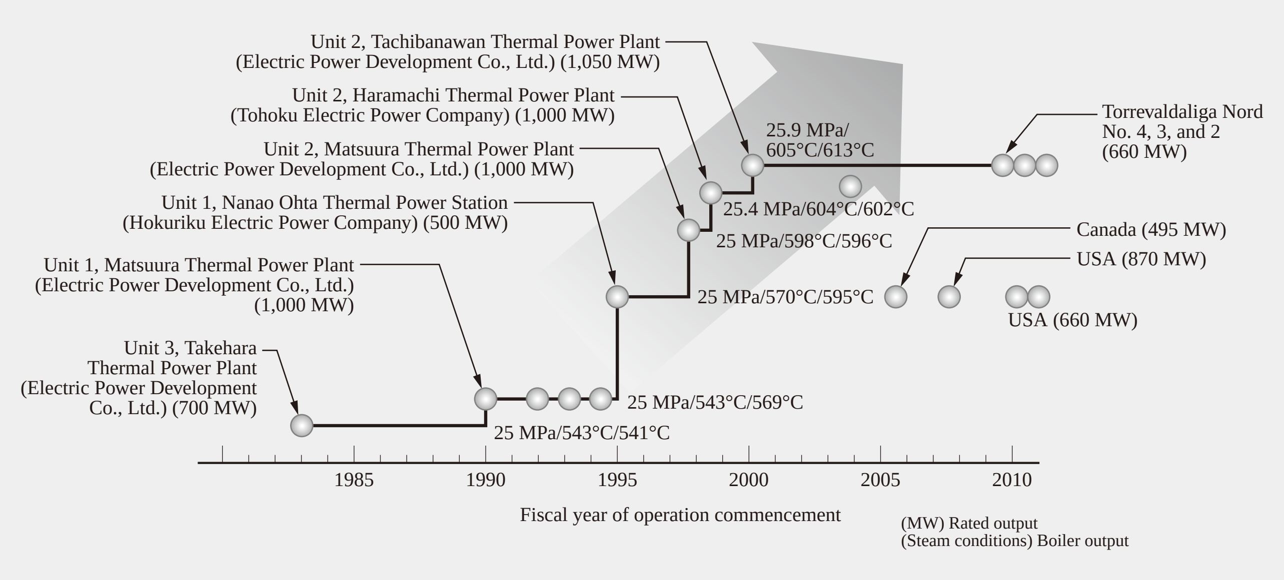


Fig. 4—Evolution of Steam Conditions of Plants Supplied by Babcock-Hitachi K.K.
Hitachi has built up experience with high-capacity plants that use supercritical or USC power generation.

This technology and experience is also highly regarded overseas, and Hitachi supplied its first 600°C-class USC coal-fired boilers (25.3 MPa/ 604°C/612°C, 660 MW) to Europe in 2010, to the Torrevaldaliga Nord Thermal Power Plant in Italy (see Fig. 5).

The Torrevaldaliga Nord Thermal Power Plant is located about 70 km north-west of Rome, and the project involved upgrading four existing oil-fired constant-pressure boilers with highly efficient coal-fired USC variable-pressure boilers. BHK was the technical leader on the project, which commenced in 2004 and was run by a consortium that included Italian boiler manufacturer Ansaldo Caldaie SPA.

BHK was responsible for the concept and basic design of all of the pressurized parts of the boiler as well as the detailed design and fabrication of the super heater, reheater, and other components associated with the high steam temperature and pressure conditions. The role of HPE was to evaluate the design of the main pressurized components to ensure that they complied with European standards. Fig. 6 shows a side elevation drawing of the boiler.

Fig. 5—Torrevaldaliga Nord Thermal Power Plant.
Babcock-Hitachi K.K. supplied its first commercial USC plant in Europe in cooperation with Hitachi Power Europe GmbH (HPE).

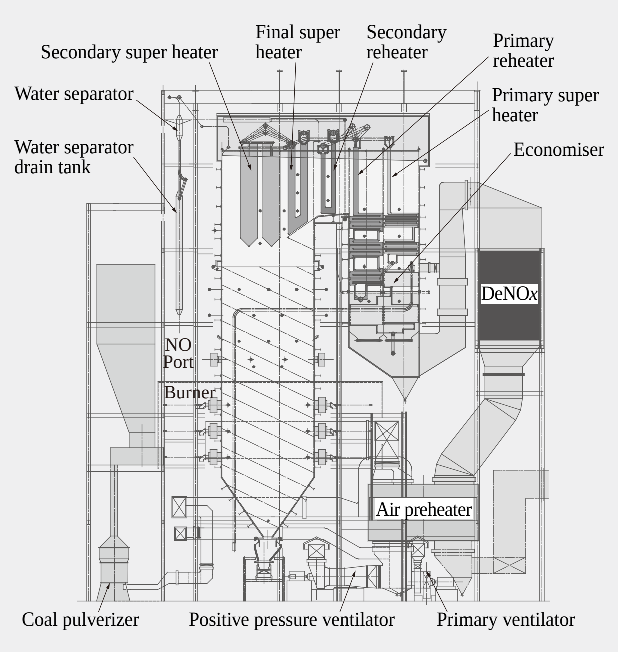


Fig. 6—Side Elevation Drawing of Torrevaldaliga Nord Boiler.
A design function evaluation of the main pressurized components was undertaken by Hitachi Power Europe GmbH to ensure compliance with European standards for boiler materials.

The success of the Torrevaldaliga Nord project was an important step toward the development of the A-USC (advanced USC) boiler described later in this article. In addition to design and fabrication technologies—including the spiral waterwall structure of the boiler, and the use of P92 (9% Cr steel) for the header and pipes and SUPER304H (18% Cr steel) for heat exchange tubes—the development of new materials able to provide adequate strength at even higher temperatures resulted in important technology and provided valuable experience for use in future A-USC boilers.

A-USC DEVELOPMENT

Recently, Hitachi has been developing A-USC technology, in which the steam temperature is raised to 700°C in order to increase the efficiency of coal-fired power generation and reduce its CO_2 emissions. While the high-Cr steel used for USC can withstand temperatures of around 600°C, this move to higher temperatures requires the adoption of materials such as austenitic steels or Ni (nickel) alloys. However, austenitic steels are subject to a significant degree of deformation at high temperatures owing to their high coefficient of linear expansion. The consequences of this deformability include manufacturing difficulties and problems with thermal strain. The problem with Ni alloys, on the other hand, is that segregation (changes in the material's internal structure) can occur in the manufacturing of large parts because the material's microstructure is sensitive to changes in temperature during in the manufacturing process. This means that, even if a high level of strength characteristics are obtained at the test piece level, ensuring that the strength satisfies the target throughout a large work piece is difficult. There is also the problem of cost, since austenitic steels and Ni alloys are more expensive than high-Cr steel.

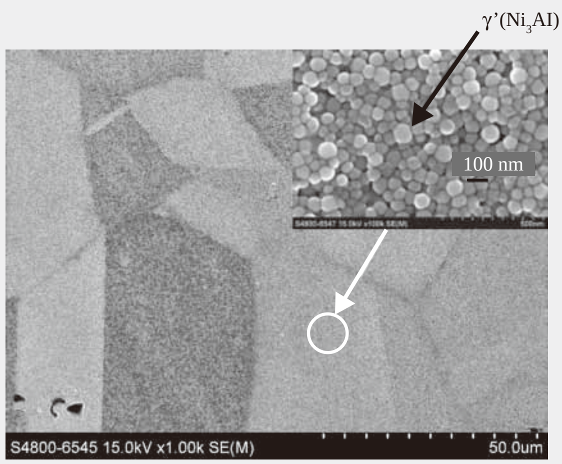
Development of A-USC aimed at resolving these issues got underway in Europe in the 1990s involving a number of materials development, trial production, and other projects. This development continues with the aim being to construct a 550-MW demonstration plant (35 MPa/700°C/720°C).

In Japan, A-USC development has been included as one of the 21 innovative energy technologies selected in an Agency for Natural Resources and Energy program because of their potential role in helping to achieve major reductions in greenhouse gas emissions by 2050. Development has been in progress since 2008, primarily by Japanese manufacturers(1).

Development of A-USC Turbine

The commercialization of 700°C-class turbines required the development of a new Ni alloy for use in the rotors, vanes, bolts, and other parts that would be subjected to 700°C temperatures. The rotor in particular needs to weigh between 10 and 30 t, and it is not possible for steam turbines to simply use the same materials as gas turbines. In addition, the use of steam as a medium means that steam turbines experience distinctive conditions, and factors such as corrosion resistance and weldability of the Ni alloy are important.

To overcome these challenges, a new Ni-Fe base superalloy, was developed by improving the composition of a base alloy (Alloy706), through the removal of Nb (niobium) and addition of Al (aluminum). Alloy706 contains a high proportion of iron and does not include high-priced elements such as Mo (molybdenum), W (tungsten), or Co (cobalt). The advantage of this is that it makes the material one of the cheaper forms of high-strength Ni alloy. Furthermore, while the Nb contained in Alloy706 plays a very important role because it is responsible for the formation of the γ" (Ni_3Nb) precipitation-hardened phase, it is also an element that segregates easily. This makes Nb an undesirable element when producing large ingots. In response, Hitachi decided to eliminate Nb from the composition of the new Ni-Fe base superalloy and added Al. Fig. 7 shows the microstructure of the new Ni-Fe base superalloy. This shows that, instead of the γ" (Ni_3Nb) precipitation-hardened phase found in Alloy706, the precipitation-hardened phase in the



Ni: nickel Al: aluminum

Fig. 7—The new Ni-Fe base superalloy Microstructure.
This photograph taken by a scanning electron microscope shows the presence of a precipitation-hardened Ni_3Al phase in the new Ni-Fe base superalloy.

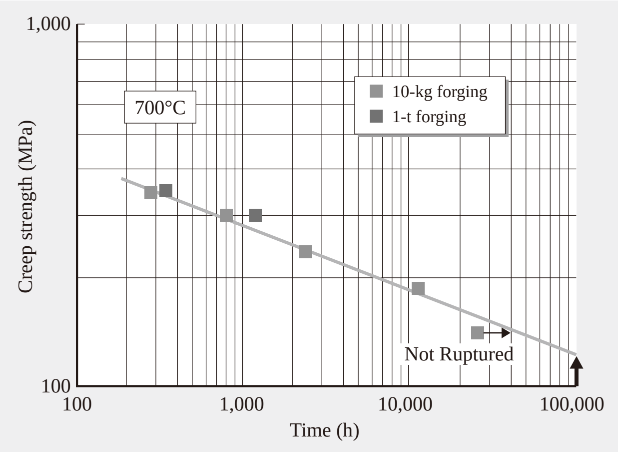


Fig. 8—Long-term Creep Testing of the New Ni-Fe Base Superalloy.
Creep testing of a 10-kg forging at 700°C has reached 45,000 hours, indicating that the target of a 100,000-hour creep strength of 100 MPa will be achieved.

new Ni-Fe base superalloy is γ' (Ni_3Al), which remains stable at temperatures of 700°C.

Fig. 8 shows a measurement of long-term creep strength in the new Ni-Fe base superalloy. Creep strength testing of the new Ni-Fe base superalloy is now up to 45,000 hours and it appears that the design strength development target of having a 100,000-hour creep strength at 700°C of more than 100 MPa will be achieved(2).

A test forging that weighs more than 10 t is currently being produced in order to verify the manufacturing characteristics of the new large Ni-Fe base superalloy components. As shown in Fig. 9, product development work has also started in preparation for the fabrication of an actual rotor. In addition to the new Ni-Fe base superalloy, Hitachi has also developed another Ni alloy able to tolerate temperatures above 700°C called Alloy141 for use in vanes, bolts, and boiler heat exchange tubes. From 2013 to 2016, these new materials are scheduled to undergo rotational testing at a temperature of 700°C to verify their suitability for use in turbines.

Fig. 9—Study of A-USC Rotor Production.
Since the Ni alloy to be used for A-USC has higher strength than previous steels, research and development of its machinability is also important.

A-USC Boiler Development at BHK

Use of Ni alloy tubing with excellent creep rupture strength is essential for the high-temperature parts of a 700°C-class A-USC boiler, and development is in progress in Europe and America using Alloy617, Alloy263, and Alloy740 as a base. By taking cost into consideration, the A-USC development project in Japan has proposed HR6W, HR35, and Alloy141 as materials that are proprietary to Japan, and is undertaking development work to ready them for practical use (see Table 1).

Fig. 10 shows where in an A-USC boiler the various materials under development are used. New Ni alloy materials like HR6W are used in the tertiary heater, final heater, secondary reheater, main steam pipes, high-temperature reheat steam pipes, and other high-temperature components.

Since Ni alloy needs to be used not only for the heat exchange tubes in the boiler furnace but also for the piping that was previously made of ferritic steel, welding techniques for thick-walled, large-diameter pipes have become the critical issue. As BHK found that the narrow-groove HST [hotwire switching TIG (tungsten inert gas)] welding it had developed itself and had been using for many years in the manufacture of 600°C-class boilers was also suitable for use with Ni alloys, it preempted the national project by

TABLE 1. Potential Ni Alloys for Use in A-USC Boilers
The A-USC projects in Europe, America, and Japan are developing and evaluating a number of Ni alloys with the potential for use in 700°C-class boilers.

	Heat exchange tube	Large-diameter pipe
HR6W*	○	○
HR35*	○	○
Alloy617	○	○
Alloy263	○	—
Alloy740	○	—
Alloy141*	○	—

○: Yes —: No

* Indicates material under development in Japan.

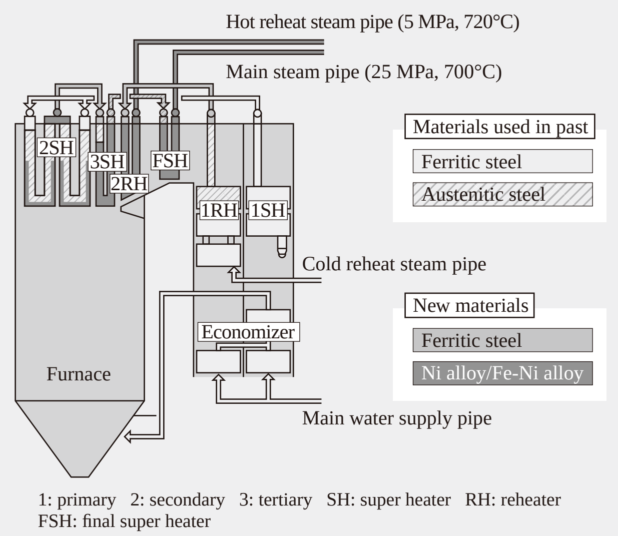


Fig. 10—Uses of A-USC Boiler Materials.
Use of Ni alloy is limited to high-temperature parts.

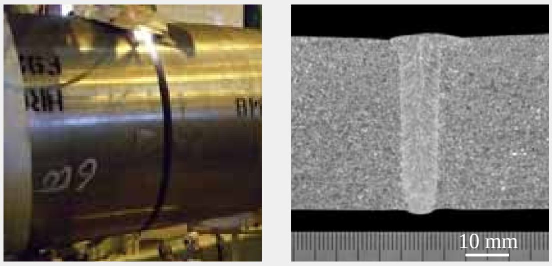


Fig. 11—Boiler Welding.
Testing involving narrow-groove HST [hotwire switching TIG (tungsten inert gas)] welding of HR6W Ni alloy has demonstrated the integrity of the welds.

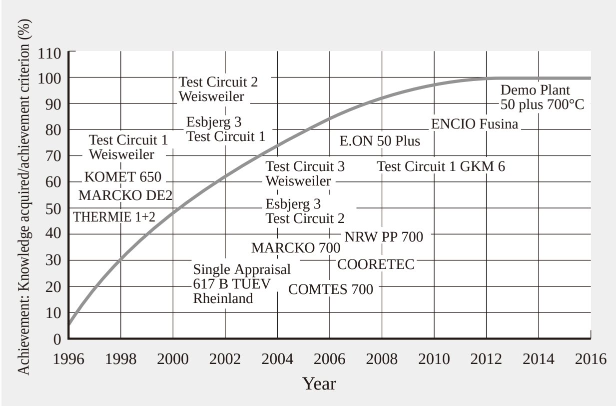


Fig. 12—European Research and Development Programs for 700°C-class Technology.
Sufficient knowledge has been acquired to construct a demonstration plant in the near future.

Fig. 13—Super Heater Panel Using Ni Alloy.
HPE is undertaking a series of technical developments required for the building of 700°C-class boilers.

conducting welding tests on promising materials and has confirmed that high-quality welds can be made efficiently. A creep rupture test of a weld is currently in progress and has passed 40,000 hours[3].

Fig. 11 shows the narrow-groove HST welding of a large-diameter pipe made of HR6W Ni alloy which is being performed by BHK as part of the A-USC development project in Japan. A reliable defect-free weld join is achieved using a narrow groove of only about 10 mm.

A-USC Boiler Development at HPE

Fig. 12 shows the key research and development programs conducted in Europe since in the mid-1990s[4]. All of the key boiler components have been systematically evaluated in Europe through numerous programs that have been funded by a mixture of public and private financing. For example, a wide range of research has been conducted on preliminary studies and basic design of 700°C-class power plants based on various different boiler types and pressure ranges. HPE has participated in the majority of the research and development projects shown in Fig. 12 and has played a leadership role in the development of Ni alloy as a manufacturing material.

As an example, Fig. 13 shows a super heater panel manufactured at HPE using Ni alloy. The panel has successfully completed 30,000 hours of testing at the COMTES700 pilot plant where it has been subjected to the 700°C steam temperatures of an actual plant. HPE also has an important role in the ENCIO Project, currently at the preparation stage, which includes a new 700°C test loop to trial solutions to the issues identified by unit testing at COMTES700. It is anticipated that this work, including practical test results and future demonstration trials, will deliver knowledge and material properties that are suitable for use in the production process. Thus, a demonstration plant can be built in the near future. Technical exchanges with BHK in fields such as welding technology are also continuing in preparation for the future construction of full-scale power plants.

CONCLUSIONS

This article has described how Hitachi’s development of technology for improving the efficiency of coal-fired power generation has evolved over time, and also its development of new technology.

In the future, Hitachi needs to be ready to supply highly efficiency coal-fired power plants as total systems, because the world has few suppliers with this total system capability. Together with improving the efficiency of coal-fired power generation, practical implementation of CO_2 capture technology is also important. Hitachi is currently working on research and development programs that relate to efficiency improvement of coal-fired power generation and CO_2 capture technology through its global research infrastructure.

Hitachi intends to continue contributing to the resolution of environmental and energy problems by commercializing A-USC plants by 2020 through ongoing technological developments in this field.

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ABOUT THE AUTHORS

Hajime Kimura

Joined Babcock-Hitachi K.K. in 1989, and now works at the Boiler Engineering Department, Thermal Power Division. He is currently engaged in the development and engineering of boiler technology for thermal power generation.

Takashi Sato

Joined Babcock-Hitachi K.K. in 1980, and now works at the Kure Research Laboratory. He is currently engaged in research into the commercialization of high-temperature heat resistant materials. Mr. Sato is a member of The Japan Society of Mechanical Engineers (JSME), The Iron and Steel Institute of Japan (ISIJ), and The Society of Materials Science, Japan.

Christian Bergins, Dr. Eng.

Joined Hitachi Power Europe GmbH in 2006, and now works at Research & Development. He is currently engaged in the research and development of oxyfuel combustion, CO_2 recovery, 700°C-class A-USC, and lignite boilers.

Shinya Imano, Dr. Eng.

Joined Hitachi, Ltd. in 1993, and now works at the Material Research Center, Hitachi Research Laboratory. He is currently engaged in the research and development of high-temperature heat resistant materials. Dr. Imano is a member of the ISIJ.

Eiji Saito, Dr. Eng.

Joined Hitachi, Ltd. in 1987, and now works at the Thermal Power Business Department, Thermal Power Systems Development & Management Division, Power Systems Company. He is currently engaged in managing the development of new technology for thermal power generation. Dr. Saito is a member of the JSME and the Turbomachinery Society of Japan.