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A Survey of State-of-the-Art Development of Coal-Fired Steam Turbine Power Plant Based on Advanced Ultrasupercritical Steam Technology

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Abstract

This paper surveys the development of coal-fired power plant technology based on steam turbine generator units. It is shown that, over recent decades as well as in the immediate future, development efforts in this area were and will be focused on improving thermal efficiency of the plant by boosting initial parameters of its working medium: main steam pressure and temperature as well as reheat steam temperature. Ultrasupercritical steam (with pressures ranging between 28 and 32 MPa and temperatures of 600 to 620°C) can be considered as a mature steam turbine generator technology, with plant efficiency factors of 45…46%. The transition to advanced ultrasupercritical steam (700 to 760°C, 35 to 40 MPa) is the next step in the development of coal-fired steam turbine power plant technology, one that makes efficiency of 50% attainable. This direction in the development of coal-fired power plant technology appears to be the most promising at present. State-of-the art developments in steam turbine power plant technology employing advanced ultrasupercritical (A-USC) steam with efficiency factors about 50% have been analyzed for the European Union, US, Japan and China. Covered in the paper are work programs and findings pertaining to development and studies of materials and structural members of high-temperature boiler sections and steam turbines, power plant designs with unit capacities up to 1100 MW, as well as economic and environmental aspects of A-USC steam power plant development. Information on project participants is provided.

Keywords: ultrasupercritical steam, coal-fired power plant, clean coal technology, heat-resistant alloys, nickel alloys, steam turbine units, steam lines

1 Introduction

Even allowing for most optimistic growth projections of clean and renewable energy technologies, organic fuel-fired power plant is set to dominate the power utilities landscape for the foreseeable future. It is highly likely that coal, despite all the complexities involved in its combustion and in the treatment/disposal of its combustion products, will continue as a major fuel for thermal power plant thanks to its abundance and relatively low market price.

Expected growth of electricity consumption coupled with cost pressure, depletability and severe environmental stress posed by fuel resources have prompted global community’s efforts on improving the efficiency of power utilities and reducing their environmental impact. While utilities operating on gaseous fuels have long settled on combined gas-and-steam cycle as a mainstream efficiency improvement technique [1, 10, 11] coal-fired power plant technology engineers, apart from relying on solid fuel gasification processes, place emphasis on improving thermodynamic parameters of the turbine cycle, that is, increasing steam temperature and pressure.

Known techniques of emissions reduction and treatment/disposal/landfilling of combustion products are extremely capital-intensive and power-consuming, often nearly doubling plant construction costs and drawing off about 10% of plant's output power. This makes improvement of electricity generation efficiency a matter of vital importance for coal-fired power plant technology. Such an improvement alone would lead to a reduction of hazardous emissions as a consequence of burning less fuel.

State-of-the art steam-turbine power plant already operates with ultrasupercritical (USC) steam: main steam temperature to 610°C at a pressure of 29 MPa, reheat steam temperature up to 620°C at a pressure of 5.6 MPa. The attainable efficiency ratio for these units is about 45.6% [2, 6, 7].

As becomes evident from multiple computations summarized on Fig. 1, surmounting the 50% efficiency barrier requires main steam temperatures greater than 700°C and pressures in excess of 35 MPa [17, 18].

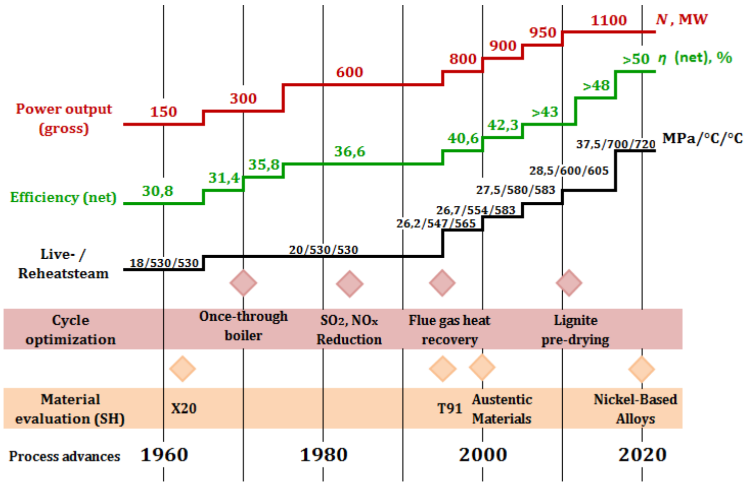

Fig. 1: The evolution of steam turbine unit operating parameters

Such steam parameters are known as advanced ultrasupercritical (A-USC). A-USC steam power plant design is now the object of extensive studies by researchers from the EU, US, Japan and China, as well as South Korea and India seeking to improve electricity generation efficiency while reducing CO_2 emissions.

2 Common problems

Materials and their processing techniques comprise the most formidable engineering issue when the matter of A-USC power plant is concerned: at the present stage, designers' efforts are focused on choosing the correct materials and devising appropriate manufacturing and testing technology both for materials as such and the respective final articles – boiler equipment components, turbines and valves. As even greater temperatures and pressures are sought, it becomes necessary to study the properties of materials, whether well-established or new to the steam turbine technology, including protective and thermal barrier coatings possessing sufficient long-term strength in A-USC conditions, withstanding exposure to corrosive combustion products at high temperatures, resistant to oxidation by superheated steam and withstanding erosive wear. These materials would require perfecting numerous processes including casting, welding of thick-walled parts, forging, pressure treatment, machining, heat treatment, and coating.

When transitioning from USC to A-USC, as shown in Fig. 2, the range of usable structural materials begins to be dominated by heat-resistant, high-melting-point steels with significant nickel content [8] whose thermophysical properties relevant to their application in power plant fall short of martensitic steels used in USC conditions. Their relatively low heat conductivity and a high thermal expansion factor retard temperature equalization in structural members, bringing about higher thermal stresses prompting changes in crystal structure and the development of cracks. As the emergence of renewable power sources requires greater controllability from thermal power stations, these properties of austenitic steels will have to be compensated for by additional structural and technology measures and the application of nickel alloys.

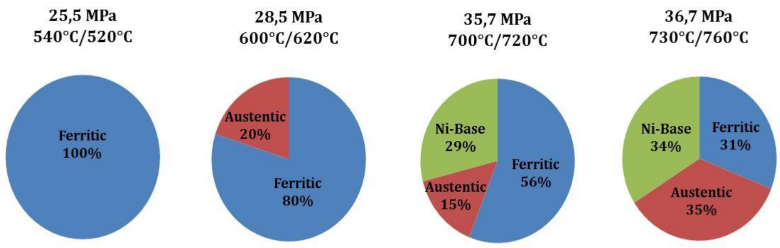

Fig. 2: Different steel properties necessary depending on steam turbine unit parameters

As ever stronger steam is demanded, technical issues become increasingly compounded by a cost aspect: while the relationship between temperature and efficiency is largely linear, the cost of heat-resistant nickel-alloy structurals rises exponentially with increasing heat strength [4] so that they cost more than 10 times more than chromium-molybdenum steels applied in modern USC boilers. For example, in absolute terms, the cost of a heat-resistant nickel alloy pipe ranges between $55 and $110 for kilogram [16]. In order to meet A-USC pressure/temperature ratings, parts made of these alloys will have to be thick-walled, thus consuming significant amounts of costly materials. Therefore, the optimization of material choice must take into account both technical and economic aspects. Considering that wall thickness may be brought down by employing higher-quality (albeit more expensive) materials, this may be the preferred option both on grounds of material economy as well as technical properties: reduced temperature gradients and less sophisticated welding/pressure treatment processes. Fig. 3 [15, 16], Fig. 4 [13] and Fig. 5 [19] show properties and applications of several alloys suitable for A-UCS conditions.

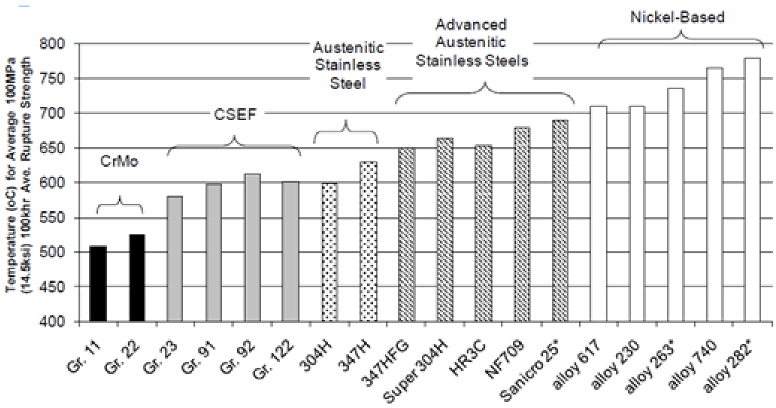

Fig. 3: Heat strength properties of various steels

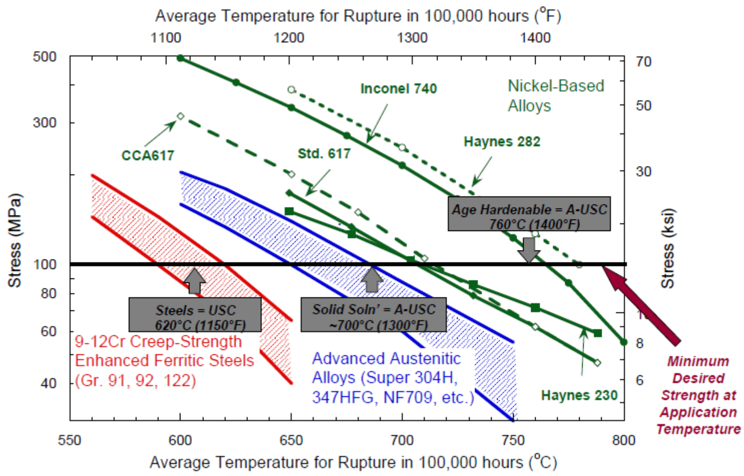

Fig. 4: Application ranges for various steels

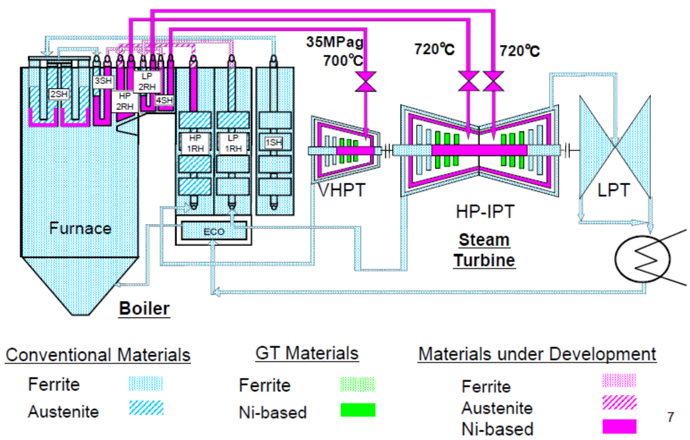

Fig. 5: Choice of steels for A-USC steam-turbine generator units

3 Current Global Research Activities in Coal-Fired A-USC Steam Turbine Power Plant technology

A brief summary of research programs in the field of innovative coal-fired A-USC steam-turbine power plant technology is provided in the Table below; the summary chart in Fig. 6 reflects the progress of projects in this area.

Table 1: Research programs in the field of innovative coal-fired A-USC steam-turbine power plant technology

Country	Technology stage	Targets	Programs
EU	> 57 GW coal-fired thermal power plant operating or under construction (2004)	t = 700…720°C, p = 35…39 MPa, efficiency ≥ 50%, N = 400…1000 MW, CO_2 emissions reduction	1. Set Plan – projects FT7: NextGenPower, MACPLUS 2. AD700 program projects: COMTES 700, COMTES+ including ENCIO, HWT II
US	> 30% (~100 GW) TPPs using SC steam pressure; ~ 50% plant in construction with USC steam at SC pressure	t = 760°C, p = 35 MPa, Efficiency (net) = 45…47%, N = 400…1000 MW, CO_2 emissions reduction by 15…22%	Advanced Ultra Supercritical Power Plant, a program run by DOE and OCDO
Japan	~ 50% (~ 17 GW) coal-fired TPPs with USC steam (600°C, 25 MPa)	t = 700/720°C, p = 35 MPa, Efficiency (net) = 46…48%, N = 1000 MW, CO_2 emissions reduction by 15%	A-USC Technology Development Project, a program run by CEIETP
China	> 70 GW coal-fired TPPs with USC steam (44x600 MW units and 73x1000 MW units commissioned or under construction); orders placed for 317 GW in total of TPP of this type (>85% of all orders)	t = 700/720°C, p = 35 MPa, efficiency ≥ 50%, CO_2 emissions reduction	1. Ministry of Energy program National 700°C USC Coal-Fired Power Generation technology Innovation Consortium 2. “Production of Mission-Critical Pipes for 700°C A-USC Units”, a project sponsored by the Ministry of Science and Technology 3. Research funded by national research foundations (9 assignments)

Note: All countries pursue a common goal of creating proof-of-concept A-USC steam turbine power plant by 2020–2025.

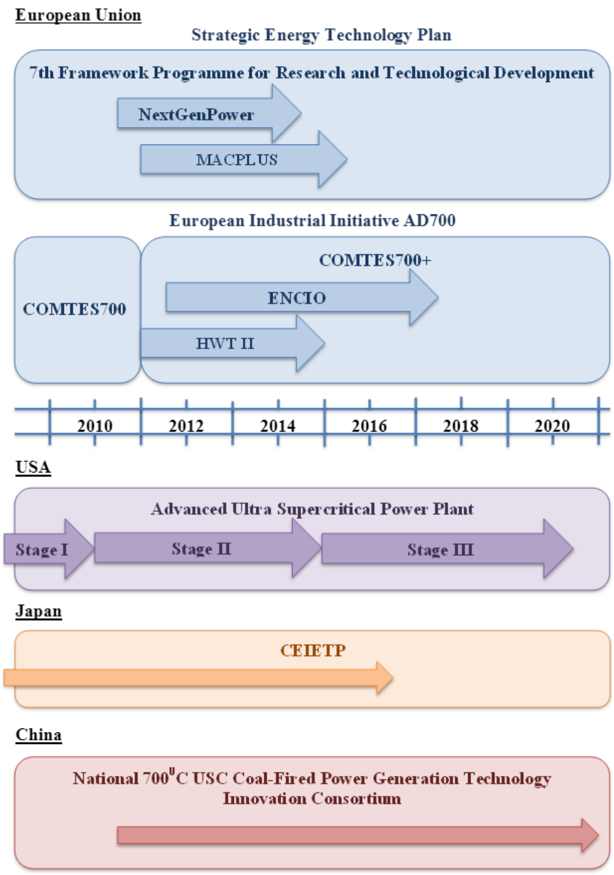

Fig. 6: Timeline of coal-fired steam turbine power plant project execution

3.1 European Union

A total of 57 GW in A-USC steam power plant is in operation or under construction in EU countries. Current research in the EU focuses on improving efficiency beyond 50% by upgrading main steam to 700…720°C and 35…39 MPa.

3.1.1 Strategic Energy Technology Plan – SET Plan

Authorized under Commission's Strategic Energy Technology Plan (SET Plan) [19] aimed at speeding up research and implementation of greenhouse gas emissions reduction technologies, the FT7 program ("EU Framework Research Program 7"), is funded by the European Investment Bank and participant countries. The Program calls for proof-of-concept demonstrations of zero-emission power plant by 2015 and industrial-stage maturity of technology designs by 2020. Program's objectives are to be met by optimizing the efficiency of coal-fired power plant as a result of stronger steam made possible by improved materials. CO_2 emissions reduction options considered in the Program include increasing the share of biomass co-fired with coal.

Two A-USC technology design projects are funded under the FT7 program: NextGenPower and MACPLUS.

The NextGenPower project is concerned with optimum choice of materials and manufacturing processes for constructing high-efficiency pulverized coal power plant with a CCS (carbon dioxide capture and storage) capacity. Studies are focused on: (a) identifying properties of innovative alloys and coatings for boilers, turbines and pipelines suitable for use in A-USC steam conditions and enabling generator units to be designed with net efficiencies above 45%; (b) increasing the fraction of biomass when co-fired with coal; (c) developing technology for the production of nickel-based alloys and coatings for coal-fired power plant with co-firing of biomass.

The project, launched on May 1st 2010 and scheduled to run for 4 years, has a budget of 10.3 million EUR including an appropriation of 6 million EUR from the EU and 4.3 million EUR contributed by participant countries.

The project steering consortium brings together research and design institutions, power utilities and equipment manufacturers from 6 European countries: KEMA и E.ON Benelux from the Netherlands, The Institut fur Werkstoffkunde (IfW) together with Technische Universtat Darmstadt (TUD) and Saarschmiede GmbH Freiformschmiede from Germany, Doosan Babcock (DB), Cranfield University, Goodwin Steel Castings Ltd. and Monitor Coatings Ltd. from the UK, Aubert & Duval (A&D) from France, VTT Technical Research Centre of Finland, Skoda Power from Czech Republice, and VUZ Welding Research Institute from Slovakia.

The dual strategy of cost-efficient efficiency improvement and carbon dioxide emissions reduction pursued by the MACPLUS (Material-Component Performance-driven Solutions for Long-Term Efficiency Increase in Ultra Supercritical Power Plants) project offers two main courses for the development of coal-fired power plant:

- Increasing working steam pressure and temperature (up to 37.7 MPa 700°C at minimum), matched by more rigorous design of internal boiler structurals.
- Adopting clean coal firing technologies such as burning in oxygen atmosphere and co-firing other fuel with coal, including biomass in particular.

Goals raised by the project are expected to be met by improving both performance and durability of heat-resistant materials for mission-critical power plant components such as boiler combustion chamber (especially when the oxygen-atmosphere firing method is used), manifolds and pipelines, steam reheaters, and boiler pipes with protective metal cladding. In addition the project calls for increasing useful life of mission-critical components by upgrading their manufacturing and repair processes.

18.2 million EUR has been budgeted for this project including contributions of 10.7 million EUR by the EU and 7.5 million by project participants. The project has been launched to run for 4.5 years on January 1st 2011.

The project includes 24 primary contractors and 7 assistant contractors from 10 European countries: RWE Power (RWE), TUV Rheinland Werkstoffprufung GmbH (TUV), Fraunhofer Institute of Freiburg (IWM), Research Centre Juelich

(JUELICH) and MPA Stuttgart (USTUTT) from Germany, EON New Build & Technology Ltd (EON), Doosan Babcock (DB), National Physical Laboratories (NPL), Loughborough University (LBORO), Imperial College (IC), Alstom Ltd (ALSUK) and Goodwin Steel Castings Ltd (GOO) from the UK, Graz University of Technology (TUG) from Austria, Royal Technical University (KTH) from Sweden, Centro Sviluppo Materiali SpA (CSM) and Cogne Acciai Speciali S.p.a. (CAS) from Italy, Foster Wheeler Energia Oy (FWE) and Technical Research Centre of Finland (VTT) from Finland, Technical University of Denmark (DTU) from Denmark, Tubacex S.A. (TUX), Endesa (END) and Fundacion Ciudad de la Energia (CIUDEN) from Spain, Flame Spray Hungary Kft (FLAME) from Hungary, Welding Research Institute (VUZ) from Slovakia.

3.1.2 Component Test Facility for 700°C Power Plant Flagship Project

Dating back to early 1990s, the AD700 European Technology Initiative is concerned with the development of innovative materials enabling steam temperature in pulverized-coal boilers to be raised to 700°C and beyond. AD700 Phase 3 (COMTES 700, Component Test Facility for 700°C power Plant Flagship Project, launched in 2003) is a project for designing a test facility to ensure functionality of power plant components at temperatures as high as 700°C. Its stated goal is designing, manufacturing and operating test benches for experimental studies and tests of heat-resistant materials and coatings and components based on them for a future A-USC power plant rated for 700°C and 35,7 MPa with efficiency above 50%. Project participants include VGB PowerTech, E.ON, EDF, Electrabel, EnBW, ENEL, DONG, PPC, RWE, Vattenfall, Alstom, HPE (Hitachi Power Europe GmbH), B&W (Babcock&Wilcox), and Siemens. The project's budget of 15.2 million EUR has been contributed by participants, with 6.1 million EUR donated by the EU Research Fund for Coal and Steel (RFCS).

After a successful completion in 2011, COMTES 700 has evolved into COMTES 700+ to include the ENCIO project (European Network for Component Integration and Optimization). The project is focused on applied research seeking improved agility, weldability, serviceability and durability of thick-walled parts, and studies of materials subjected to static and cyclical (start/stop) loads. The ultimate goal is transitioning from experimental technology to a trial plant as the final step toward a 700°C power plant.

The ENCIO experiment/research program pursues the following goals:

- Acquiring data on the behavior of parts and materials in thick-walled structures in real operating conditions.
- Addressing miscellaneous problems identified during comprehensive studies under the COMTES 700 project.
- Testing newly-designed materials and manufacturing processes (including weld-seam annealing) to improve reliability of welded parts based on nickel alloys.
- Devising a lifecycle monitoring system for pipelines based on nickel alloys.
- Expanding the choice of materials and processes that meet cost reduction and

controllability requirements raised by A-UCS applications.

- Devising technical standards for attaining high efficiency.

Trial equipment contributed by ENCIO will be installed at Unit #4 of Andrea Palladio, a 320 MW power plant operated by ENEL at Fusina, Italy. Designed for superheated steam temperature of 540°C and pressure of 18 MPa, the T-shaped boiler of the generating unit is equipped with tangential burners and has a hourly firing capacity of 1050 tons of coal with added solid waste.

Leading contractors for the project include VGB PowerTech (as the coordinator), CSM (Centro Sviluppo Materiali S.p.A.), ENEL IIN (ENEL Ingegneria e Innovazione S.p.A), ENEL GEM (ENEL Produzione S.p.A) and HPE (Hitachi Power Europe GmbH).

Work on the project has begun on July 1st 2011 and is expected to continue for 6 years. Project's budget of 24 million EUR is funded by RFCS (10 million EUR) and other industry and government foundations, as well as contributions by generating companies: CEZ a.s., EDF, EnBW Kraftwerke AG, ENEL, E.ON New Building & Technology GmbH, Eskom Generation Business Engineering, Evonik Energy Services GmbH, EVN AG, GDF Suez, GKM, RWE Power AG, Vattenfall Europe Generation AG (Germany) and Vattenfall A/S (Sweden) and equipment/materials manufacturers: Bohler Schweißtechnik, Holter Regelarmaturen GmbH & Co. KG, Sandvik AB, Sempell AG, Siemens, Sumitomo, ThyssenKrupp VDM GmbH, V&M (Vallourec & Mannesmann Tubes), Voestalpine Giessen Traisen GmbH.

Closely related to ENCIO and sharing a common goal of designing technologies fit for A-USC steam power plant is the HWT II project financed by the German Ministry of Economy and Technology (BMWi) with support from industrial enterprises.

As a part of this project, trial equipment will be installed at the GKM electric power plant at Mannheim, Germany for a research experiment concerned with modeling the behavior of materials and structurals. Findings from this modeling experiment will then be recomputed using a specially devised technique. A series of planned activities will be concerned with modeling start/stop cycles that produce combined fatigue and creep effects in materials. These studies will inform the researchers on the nature of structural damage at power plant operating in cycling mode.

The HWT II project steering consortium includes research institutes, manufacturers of materials/equipment and utility companies: BASF, EnBW, ENT, GKM, MVV, VGB, CEZ, EDF, ENEL, Eskom, Evonik, EVN, GDF Suez, RWE, Vattenfall, ABB, BBS, BGH, BHR, Bopp & Reuther (B&R), Bohler, EagleBurgmann, IfW, IWM, KAM, KSB, Lisega, MPA Stuttgart, RWTH Aachen, Saarschmiede, SLV, SMST, TUV, ThyssenKrupp VDM, V&M, Wrede & Niedecken (W&N), Welland & Tuxhorn (W&T).

The work on HWT II, launched in January 2011, is scheduled for 4 years.

3.1.3 Findings from completed projects

The European projects, NextGenPower and MACPLUS COMTES 700, COMTES 700+, ENCIO and HWT II, involved the following activities:

- Development and optimization of high-temperature materials and thermal barrier coatings enabling identification of nickel alloy microstructure are demonstration of production capabilities for materials suitable for exposure to A-UCS steam conditions (700°C, 35 MPa): Alloy 263, Alloy 740, Alloy 740H, Alloy 617, Alloy 617B, Sanicro25, Alloy 316, Super304H, TP347HFG, Ni50Cr, NiCrAIY, HastalloyC276, "ERS", 10CrMo, FeCr, NanosteelSYS8000 (Fe based 22Cr) Alloy 625, A59, 15Mo3, 10Cr9.10, TPAA1, FeCrAl, NiCrAlY, HCM12, HR3C, DMV310N, Super 304H, T11, T24, T92, P92, VM12).
- High-temperature corrosion tests of materials, coatings and structurals: lab tests with significant ash deposition at 575…50°C and bench tests at 600…850°C, including tests with oxygen-atmosphere firing, as well as full-scale tests in boilers of operating power plant at 475…800°C and pressures up to 400 MPa.
- Mechanical creep tests and stress relaxation surveys at temperatures up to 800°C and pressures up to 40 MPa.
- Tests of materials, parts and components of high-temperature gate valves, safety valves and relief valves.
- Development of rotor forging and welding technology and large-size casting processes.

The above-named activities have yielded positive findings and recommendations for design, manufacturing, operation and repair techniques, particularly pertaining to optimization of high-temperature valve design, choice of thermal annealing processes for thick-walled parts and repair welding technology. In addition, issues to be addressed in subsequent studies have been identified.

Based on these findings, research activities are now underway in the following fields:

- Further testing of materials and structurals for long-term strength and external impact resistance, including tests of full-size high-pressure valves at 725°C.
- High-temperature corrosion tests at 575…850°C.
- Gaining experience with welding processes, including repair welding.
- Simulating co-firiing of coal and biomass in oxygen atmosphere with the objective of increasing MTBF ratings of A-UCS steam boiler reheaters.
- Designing a coal-fired generator unit capable of capturing up to 90% CO_2 with a net efficiency of 45%.

Further objectives pursued by European projects include the following:

- Completing process trials and tests of materials and full-size structurals by 2020 for building a proof-of-concept 550 MW generator unit operating at 705/720°C, 40 MPa (E.ON50+Kraftwerk project) as well as future A-UCS units with output power of 400 to 1000 MW.
- Developing a serviceability concept.
- Working out issues that prevent deeper controllability of operating duty (15–100%).
- Obtaining necessary data for construction and operation of an A-UCS generator unit, including economic aspects.

It is expected that EU projects will yield the following results:

- Minimizing technical risks involved in the construction of a 700°C generator unit.
- Bringing down generator unit equipment costs relative to current estimates.

- Increased controllability of generator units to adjust for increasing share of renewable sources in the grid.
- Creating proof-of-concept power plant by 2020–2025.

3.2 United States

More than 30% (about 100 GW) of coal-fired power plant capacity in the USA is presently comprised by units operating at SC steam pressure, and about 50% of plant under construction is designed to operate with USC steam at SC pressure.

Compared to the European program, its counterpart run by the US Department of Energy (DOE) and Ohio Coal Department Office (OCDO) as Advanced Ultra Supercritical Power Plant targets hotter main steam at 760°C and 35 MPa, net[1] efficiency factor of 45…47%, CO_2 emissions reduction by 15…22%, oxygen-atmosphere combustion in trial mode, as well as additional measures for ensuring corrosion resistance of materials exposed to combustion products specific to coals fired by US utilities. This program includes development and testing of new materials and technologies, researching opportunities for repurposing already-known materials with the objective of boosting power plant efficiency while cutting emissions sharply. Combined, these measures are expected to bring about improved economy as well. The ultimate goal of the Program is designing 400-1000 MW generator units operating with A-USC steam [16].

The program is supported by research performed by ORNL (Oak Ridge National Laboratory), NELT (National Energy Technology Laboratory), EIO (Energy Industries of Ohio), EPRI (Electric Power Research Institute); boilers are turbines are designed by Alstom, B&W (Babcock&Wilcox), FW (Foster Wheeler), RP (Riley Power), GE (General Electric Energy) with additional involvement of Toshiba.

The project is funded by DOE and OCDO as well as directly by participants.

Activities completed between 2000 and 2009 (Phase I) include the development, research and certification of materials and casting/welding technologies, testing of steam circuit components in A-USC steam conditions, generator unit preliminary design studies, designing a 400 WM turbine, and constructing test benches.

The researchers have surveyed a number of alloys: Alloy740, Alloy617, Alloy230, Alloy282, Super304H, HR6W, HR3S, HR120, SAVE12, T91/92, Alloy 263, Sanicro 25, Alloy625, as well as coatings: EN33, EN622, Armstar [9].

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[1] US calculations of efficiency factors are based on highest combustion heat, leading to higher values compared to European estimates which are normally based on lowest combustion heat.

Activities planned in the program for 2010 to 2014 (Phase II) include evaluating stability of materials constantly exposed to external effects such as oxygen-atmosphere combustion, developing manufacturing/machining technologies for structurals (welding, casting, forging, pressure treatment, long-term stability testing of full-size parts and structurals).

The final stage of the project (2015 to 2020) will be concerned with designing process equipment, test benches, and a proof-of-concept power plant.

3.3 Japan

The advanced ultrasupercritical steam technology employing 600°C steam has been designed in Japan in 1980s and 1990s by Electric Power Development Company (J-Power) and sufficiently put into practice thanks to the development of low-chromium (9…12%) steels in 2001. A quarter of total electricity production in Japan (about 17 GW) is presently contributed by coal-fired plant operating with USC steam (t = 600°C, p = 25 MPa). At the same time, older stations built in 1970s and early 1980s face retirement, therefore it would be quite appropriate for them to be replaced with USC and A-USC plant of 700°C class. Large-scale work on A-USC technology has commenced in 2008 as a part of A-USC Technology Development Project overseen by the Ministry of Economy, Trade and Industry, universities and foundries throughout Japan. The project is a part of CEIETP (Cool Earth – Innovative Energy Technology Program) and is planned to run for 9 years (up to 2016) [3].

Problems faced by project participants, ABB Bailey Japan, Babcock-Hitachi, CRIEPI (Central Research Institute of Electric Power Industry), Fuji electric, Hitachi, IHICorporation, MHI (Mitsubishi Heavy Industries), NIMS (National Institute for Materials Science), Okano Valve, Sumitomo Metals, Toa Valves, and Toshiba, include creating materials and designing processes for manufacturing structural members of A-USC steam coal-fired power plant; devising manufacturing techniques for boilers, turbines and valves, including production of heat-resistant materials and welding/forging/casting processes; and researching technologies for co-firing of biomass with CO2.

The project provides for identification of opportunities for retrofitting of old coal-fired power plant (538-566°C) with new USC/A-USC grade equipment (700°C).

The ultimate goal is achieving steam temperatures of 700/720°C and pressures of 35 MPa with net efficiency of 46 to 48%, and bringing down CO_2 emissions by 15% by proposing a 1000 MW generator unit design.

As of now, alloys based on Fe-Ni (HR6W) and Ni (HR35, Alloy 617, Alloy 263, Alloy 740, Alloy 141) have been chosen for boiler structurals operating at temperatures above 650°C, while high-boron-content ferrite steels (B-9Cr) and low-carbon steels (9Cr, LC-9Cr and SAVE12AD) have been chosen for temperatures below 650°C. FENIX-700, LTES700R and TOSIX alloys are recommended choices for turbine rotors.

These materials have been tested for durability and fatigue/corrosion resistance when exposed to fuel combustion products and their oxidation stability in steam environment. Studies were carried out to achieve a minimum 100,000-hour strength limit of 90 MPa at 750°C for reheater pipe materials (HR35, Alloy 617, Alloy 263, Alloy 740, Alloy 141); a minimum of 90 MPa at 700°C for large-diameter steam transfer pipes (HR6W and HR35), and 80 MPa at 650°C for chromium steels (9Cr, B-9Cr, LC-9Cr and SAVE12AD).

A preliminary design of a 1000 MW steam turbine with 5 cylinders (ultrahigh/high/intermediate/2 x low-pressure) was prepared.

Structural members are being tested for long-term strength beyond 30,000 hours.

The following activities will have to be carried out at subsequent stages:

- Manufacturing reheaters, steam pipelines (including large-diameter pipes) and valves and testing them in an operating boiler, testing three turbine rotors made of three alternative materials with 700°C steam at rated RPM to evaluate reliability of each component (2015/2016).
- Studying high-temperature corrosion upon exposure to combustion products from co-firing of coal and biomass, evaluating the stability of deposits on heated surfaces after operation for a long time.
- Evaluating long-term reliability, fatigue strength and high-temperature corrosion resistance of heated surfaces and the oxidation resistance of interior surfaces of steam lines.
- Completing long-term stability tests of structural members and estimating their operating lives; devising non-destructive testing techniques and working out repair welding processes for subsequent development of repair techniques.

3.4 China

The recent decade has seen rapid progress in Chinese power generation technology. The first domestically built 600 MW USC unit rated for 24.2 MPa/566°C/566°C was commissioned in 2004, and the first 1000 MW A-USC unit rated for 26.25 MPa/600°C/600°C followed in 2006. By late 2010, as much as forty-four 600 MW USC units and seventy-three 1000 MW A-USC units were operating or under construction, and an experimental power plant had begun trial operation with 2x1000 MW units employing double-reheat steam cycle at 31 MPa/600°C/610°C/610°C with a 47.6% efficiency factor and 258.5 g/(kW·h) specific fuel equivalent consumption. China ranks the first in the world with its installed capacity of power plant employing SSC steam (more than 70 GW) – the downside being its status as the world's second-largest CO_2 emitter. The power plant technology in China can be considered as state-of-the-art on the global level [5, 20].

On June 23rd 2010 the Ministry of Energy of China has officially announced the commencement of a government plan for an experimental A-USC plant firing organic fuel that may be built as early as 2018. The National 700°C USC Coal-Fired Power Generation Technology Innovation Consortium has been set up to bring together research centers, manufacturers of materials and equipment, and utility companies: Xi'an Thermal Power Research Institute, Shanghai Power Equipment Power Research Institute, Institute of Metal Research (Chinese Academy of Science), China Iron&Steel Research Institute Group, Electric Power Planning&Engineering Institute, China Power Engineering Consulting Group, Shanghai Electric Group, Dongfang Electric Corporation, China First Heavy Industries, China National Erzhong Group, Baoshan Iron&Steel Co., Dongbei Special Steel Group Co. Ltd, China Huaneng Group, China Datang Corporation, China Huadian Corporation, China Guodian Corporation, China Power Investment Corporation. Scheduled up to 2021, Consortium's program targets efficiency factors beyond 50% at steam temperature of 700/720°C and pressure of 35 MPa with a simultaneous reduction of CO_2 emissions level.

The Consortium includes 4 subcommittees for power plant design, materials research and development, turbine design and boiler design [14]. The program is scheduled for 10 years with 50 million yuan (about US$8 million$) funding by the Ministry of Energy, National Scientific Research Foundation, the Ministry of Science and Technology and other state structures. It includes the following modules:

1. General engineering and design studies for key components of generator units rated for 700°C.
2. Choosing, designing, evaluating and optimizing materials for structurals operating at high temperatures with the goal of identifying heat-resistant materials for a 700°C Chinese generator unit.
3. Developing technology for manufacturing basic heat-resistant materials and key structurals.
4. Designing components of a high-temperature test facility to ensure reliable monitoring of critical members.
5. Creation proof-of-concept modules for 700°C A-USC steam to enable comprehensive testing of main technologies for coal-fired power plant employing USC steam.
6. Surveying the opportunity for designing a proof-of-concept power plant.

Consortium's activities are organized into 5 sections:

1. General design proposal (2011–2013).
2. Choice, design, evaluation and optimization of high-temperature materials (2011–2017).
3. Manufacturing of major parts of primary equipment and high-temperature pipelines (2011–2018).
4. Setting up a test facility for key components of boiler and valves (2011–2017).
5. Proof-of-concept generator units (2015–2021).

Consortium's Work Plan is intertwined with Ministry of Science and Technology's project titled Manufacturing Mission-Critical Piping for 700°C A-USC Units (funded with 29.5 million yuan or approx. 4.7 million USD) containing the following sections:

- Manufacturing of mission-critical piping for 700°C A-USC units – choosing materials rated for 600…700°C.

- Evaluating the GH2984 alloy made in China and process opportunities for its use in 700°C generator units.
- Researching new types of high-temperature austenitic steels for 650°C A-USC generator units.

In addition, multiple research activities related to the performance of Consortium's plan are funded by national research foundations. These include research relevant to 700° power plant units:

- Boiler screening panels.
- Boiler reheater components.
- Boiler manifolds.
- High-temperature steam pipelines and boiler fittings.
- Manufacturing processes for high- and intermediate-pressure turbine rotors.
- Manufacturing processes for bodies of high-temperature turbine cylinder valves.
- High-temperature blades and gates, wear-resistant internal parts of valves.
- Forged components of high-temperature turbines.
- Cast components of high-temperature turbines.

Current activities of the Consortium and associate contractors under the A-USC coal-fired power plant include drafting a general design proposal, choosing, designing, evaluating and optimizing high-temperature materials (Alloy 617M, Alloy 617CN, Alloy 740, Alloy 740H, Alloy 740HM, T24, HCM12, GH984, G115/G112, CH2984G, T91, T92, P92, P112, NF709R, Sanicro25), manufacturing key components of primary equipment units and high-temperature pipelines (steam pipelines and major boiler components, turbine forgings and major components, high-temperature pipelines and valves, high-temperature high-pressure valves), designing and setting up a CTF-700 test facility for major boiler and valve components.

4 Conclusions

As early as in September 1968, the USSR pioneered with an SKR-100-300 A-USC unit at Kashira Power Plant operating at 30 MPa and 650°C with reheat steam at 10 MPa/565°C. This unit remained in operation into mid-1970s. The creation of SKR-100 was preceded by the startup of 60-OP, world’s first experimental boiler rated for 30 MPa/600°C steam (30 MPa/650°C after retrofitting), at the power plant of the All-Union Thermal Engineering Institute in 1949, and the PK-30 boiler rated for 700°C/40 MPa at the Central Boiler and Turbine Institute in 1964 [12].

Today, Russia is lagging behind European countries, the USA, Japan and China on track to the deployment of “clean” coal technology; however the government policy is oriented toward fostering a domestic coal market.

Coal-fired plant supplies one-fifth of Russia’s total electricity needs and is responsible for one-half of total electricity production in Siberia and Far East. Based on global trends and findings testifying to feasibility and economic viability of A-USC coal-fired power plant designs, and leveraging Russia's existing scientific and technology potential, large-scale efforts for designing domestic high-efficiency domestic A-USC power plant must begin immediately.

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