Ultra-High Efficiency Industrial Steam Generation R&D Opportunities

Results of the U.S. Department of Energy's *Advanced Steam Generation Workshop*, Held August 25, 2004

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Overview

Industrial steam is used to provide heat energy for processes in almost every industry. Over 35 percent of all the energy used in U.S. manufacturing is consumed in the form of steam. However, approximately 20 percent of this energy (~1.2 quads) is lost in steam generation due to system inefficiencies. At an average cost of $6 per 1000ft^3 of natural gas, these energy losses translate to almost $7 billion in capital losses. Additionally, with the rising cost for natural gas, these losses will have a much more severe economic impact. The development and commercialization of ultra-high efficiency industrial boilers would significantly reduce the energy losses from steam generation, thereby reducing natural gas demand.

The U.S. Department of Energy's Combustion Program works in partnership with industry to conduct R&D that will improve the energy, environmental performance, and cost savings of steam systems. On August 25, 2004, DOE hosted the "Advanced Steam Generation Workshop" to identify the top R&D priorities for ultra-high efficiency steam generation boilers. The objective of the workshop was to generate a discussion on today's most advanced boilers and identify opportunities for the next generation superboiler.

The workshop captured the inputs of 35 attendees, including government representatives, industrial steam users, and boiler manufacturers. The workshop began with a presentation from Rick Knight from the Gas Technology Institute (GTI) who described the status of the Superboiler Project. At the end of the presentation, participants attended either of two concurrent sessions: i) watertube boilers, and ii) firetube boilers. In a watertube boiler design, a burner fires into a furnace where water flows through encased tubes. The water is heated, producing steam in a steam drum. Watertube boilers are typically available in large sizes, and are capable of handling high pressures and able to attain high temperatures. In a firetube boiler design, hot flue gases travel through tubes that are surrounded by the fluid to be heated (i.e. water to make steam).

This report summarizes the results of the workshop, provides a list of participants (Appendix A), and highlights the desirable characteristics identified for the next generation superboiler. The categories for boiler improvements are identified in Exhibit 1. This document should provide government decision-makers with a perspective on the R&D priorities critical to the development of advanced steam boilers.

Exhibit 1 – Categories for Boiler Improvements

- **Combined Heat and Power and Hybrid Technologies**
- **Combustion**
  - Combustion principles
  - Fuel – types, flexibility, preparation requirements.
  - Air mix and separations
- **System Efficiency**
  - System Requirements (temperature, pressure, etc.)
- **Sensors and Controls**
  - Automation
  - System integration
  - System diagnosis
  - Cost requirements
- **Heat Transfer**
  - System design
  - Materials
  - Insulation
- **Heat Recovery**
  - System components
  - Materials
- **System Integration**
  - Energy sources
  - System design requirements (efficiency, size, and components)
- **Other/Miscellaneous**
  - Education
  - System economics

Opportunities for Watertube Boilers

A number of system improvement R&D opportunities have been identified in the watertube boiler session. These opportunities could help improve energy efficiency as well as increasing the emissions reduction of watertube boilers. The highest priority opportunities are in the areas of system efficiency, sensors and controls, and system integration. The top opportunities are identified below.

Under the category of *system efficiency*, the development of high-pressure, high temperature boilers is considered highly desirable. This presents a challenge to industrial boiler manufacturers and requires the control of several variables such as vessel construction, safety, materials, size, and others.

In the area of *sensors and controls*, the development of fully automatic self-diagnostic boiler with auto set-up and steam production forecast capabilities was given high priority. Improvements in sensors and controls are considered key to system automation and self-diagnostics.

Within *system integration*, hybrid technologies such as combined heat and power (CHP) are a high priority and an overall system efficiency of 85 percent is desirable.

Another high-priority item in the area of sensors and controls is the development of very low-cost sensors for O_2, CO, and NOx emissions. Improvements in combustion include investigating the part-load requirements of industrial boilers and avoiding oversizing. A challenge remains to achieve part-load operation while maintaining low excess air. Fuel flexibility of boilers also remains highly desirable and presents a R&D challenge. Heat transfer R&D priorities consist of investigating alternative mediums for immersed tubes (other than air), which could improve heat transfer capabilities.

Other R&D priorities in the area of system integration include reducing the size of boilers by a factor of 10. Research should focus on how to achieve the size reduction and consider the integration between the burner and furnace. Exhibit 2 summarizes all the identified opportunities for watertube boilers.

Exhibit 2 – Priority R&D Needs for Watertube Boilers

Combustion

Part-load requirements of industrial boilers ● ● ● ● ● ●
- currently way oversized
- need to have part-load operation while maintaining low excess air

Fuel flexibility ● ● ● ●
- solid
- liquid
- gas

Integrate membrane technology for air separation into the boiler

What are fuel requirements/specs? ● ●
- more may be needed
- may have to deal with swings (supplier)

Fuel preparation for solid fuels ●
- get the water out (of wood, grass, etc.)

Boiler process with lower Btu/ft3 from biomass fuels ●
- bigger mass flow

Operation with low or no excess air (<0.5% O_2)

Acoustically enhanced combustion

Zero emission boiler ●

Surface combustion: approach an infinite number of burners (very small, very controlled) using more wall surface for combustion

Fuel pretreatment (especially solid fuel)

System Efficiency

High-pressure, high-temperature boilers ● ● ● ● ● ● ● ● ● ● ●

Overall review to make sure improved efficiencies are being achieved ● ●
- broaden system boundaries to make sure

How to reduce pressure drop, fuel and pressure requirements and still maintain process

Latent heat removal and use

Steam accumulators for peak load flexibility

Cost-efficiency, small steam turbine generator (microturbine for steam)

Thermal storage

Sensors/Controls

Fully automatic self-diagnostic boiler ● ● ● ● ● ● ● ● ●
- auto set-up
- capability to forecast steam production

Very low-cost sensor (allows redundancy) for O_2, CO, NOx emissions for reliable operation ● ● ●

Enable smart control systems ●
- develop fast-response, parts per-billion analyzers for excess air, etc.
- control loops

<10% of total cost on control and sensor costs ●
- custom engineering drives up overall system cost

Smart sensors and controls (active control)
- autodiagnosis (feedback on performance)

Solid fuel combustion
- real-time fuel analysis ●

Sensing the combustion process as it occurs
- control the two zones more carefully

Improved or more meaningful operator interface

Exhibit 2 – Priority R&D Needs for Watertube Boilers (Continued)

System Integration

- Hybrid technologies ● ● ● ● ● ● ●
  - CHP
  - bottoming cycle
  - generate power at 85% efficiency
- Reduced boiler size ● ● ● ● ● ●
  - how to do it
  - integration between burner and furnace
  - reduce size by a factor 10
- Modular boiler design ● ● ● ● ● ●
  - once-through forced circulation
- Hybrid heat pump/boiler using adsorption technology
- Re-examination of forced circulation coil-type technology
  - achieve very high P
  - fast start-up
- Use renewable energy sources to preheat feedwater
  - solar
- Oxy-fuel combustion with CO_2 recovery
- Trend to smaller-footprint boiler combined with staged combustion (to achieve very low mass flow) ●
  - optimize geometry
  - re-think how combustion occurs
- Flexible boiler ● ●
  - could be integrated into industrial process
  - could be in CHP system
- Look at overall system
  - overall horsepower for pumps, etc.
- Water treatment ●
  - include whole water system in a system study
- Alternatives to CHP
  - thermophotovoltaics
  - thermoelectric
  - organic Rankine cycles
- Reduce noise pollution ● ●

Heat Transfer

- Immersed tubes (in medium other than air) in an incandescent burner to enhance heat transfer ● ● ● ●
  - packed bed
- Intermetallics and surface treatments
  - corrosion reduction
- Improved insulation
- Extended surface heat transfer
- Technologies for self-cleaning boiler tubes ●
- Higher heat flux materials
  - coatings
  - other materials
- Application of 2-stage combustion with inter-stage cooling concept to watertube boilers ● ●
- Catalytic combustion on tubes
- Thermal fluids, including hybrid designs ●

Other/ Miscellaneous

- Economic assessment of the total system ● ● ● ● ●
  - superboiler
  - other new technologies
- Education ● ● ● ●
  - of boiler users
  - of consultants
- New fabrication technologies

Opportunities for Firetube Boilers

Opportunities for maximizing the energy efficiency of firetube boiler systems were identified and classified into six categories, presented in Exhibit 3. These opportunities provided direction for future firetube boiler research and development (R&D), while also providing insight to the most desirable characteristics and technologies a next generation Super Boiler should possess. The principal opportunities future Super Boiler R&D are identified below.

Distributed steam generation is a practical solution to reducing energy waste. Thus, next generation boilers should incorporate novel cogeneration and CHP technologies. Suggestions for implementing CHP in boiler systems included:

- Gas-fired small turbines with ultra-low NOx burners to generate electricity and process steam;
- Staged combustion integration with CHP back to the firetube boiler;
- Turbo-drivers for combustion air; and
- Partial process steam generation from exhaust created by a firetube boiler-powered steam/electric turbine.

To take full advantage of cogeneration opportunities and increase boiler flexibility, R&D must also target increased pressure tolerance in firetube boilers, which now have a maximum threshold of approximately 400 psi.

Novel heat exchanger designs to improve heat recovery at low- and mid-fire represent another prime opportunity to increase firetube boiler system efficiency. Cost-effective materials development for heat exchangers coupled with new heat exchanger designs are required to advance heat recovery in several key areas such as the stack, feedwater pre-heater, and combustion air pre-heater. Heat recovery should be addressed via a holistic, system-wide approach that plays a stronger overall role in boiler design considerations.

Real-time, integrated sensors and controls between boilers and auxiliary systems, incorporating improved signal processing devices, represent a vital opportunity to achieve superior boiler efficiency. Continuous NOx sensors, programmable logic control (PLC) devices, and software to integrate data and system control represent some of the key areas requiring R&D in this crucial aspect of boiler design.

Research on efficient, multi-fuel combustion technologies capable of utilizing alternative fuel energy sources is critical. Aside from potential efficiency benefits, the ability to burn alternative fuel sources would not only reduce demand from electric utilities, but also diminish reliance on fossil-fuel energy and enhance combustion system flexibility.

Other R&D areas important to increasing the efficiency of next generation boilers included identifying means to achieve parasitic load reduction and defining optimal boiler turndown. Continued training and energy management education for technicians and boiler operators is also fundamental to reap maximum efficiency gains and discover additional areas for improvement.

Essential to the success of all new boiler technology is performing a baseline economic evaluation of the complete boiler system, including a life-cycle costing analysis, to determine the cost-competitiveness and footprint of new materials and technology relative to those now in use. New designs must also maintain, and preferably improve upon, current safety levels; this is compulsory for customer acceptance.

Exhibit 3 – Priority R&D Needs for Firetube Boilers

Combustion

- Alternative fuel energy sources (e.g., hydrogen) and combustion technologies ● ● ● ●
  - requires streamlined integration of multiple energy sources
  - reduces demand from electric utilities
- Explore air heater temperature effects on super low-NOx capability
- Address adverse effects of combustion chamber acoustics such as:
  - acoustic instability effects on boiler structure (e.g., vibration)
  - thermally induced stress fractures
- Fuel pretreatment to reduce excess air required for solid fuel combustion
- Research optimal boiler turndown to determine specifications for target boiler technology ● ●
- Cross-fertilization of new technologies and methods to improve combustion efficiency, based on what is being developed in other industries such as:
  - preheating of combustion air
  - direct oxygen injection
- New methods for more efficient energy delivery into the combustion system

CHP

- Novel cogeneration technologies such as: gas-fired small turbines with ultra-low NOx burners to generate electricity and process steam, integration of staged combustion approach with CHP back to firetube boiler, incorporating addition of turbo-driver for combustion air, and use of 400 psi firetube boiler to power steam/electric turbine and use exhaust from turbine for process steam.

  ● ● ● ● ● ● ● ● ● ● ● ●

  - target achieving increased pressure tolerance in firetube (e.g., 1,800 psi)
  - firetubes currently have ~ 400 psi limit
  - higher pressure tolerance provides increased boiler flexibility
  - distributed steam generation is a practical solution to reducing energy waste

Heat Transfer

- Optimizing the <u>tube</u> in firetube boilers ● ●
- Completely new technologies to generate steam
  - departure from aging, traditional boiler design philosophies may be necessary to realize more than piecemeal, incremental efficiency gains
  - paradigm shift needed
- Advanced materials of construction to assist:
  - back pressure reduction
  - heat transfer surface extension
  - improved insulation

Exhibit 3 – Priority R&D Needs for Firetube Boilers (Continued)

Sensors and Controls

- tegrated sensors and controls etween boilers and auxiliary stems, incorporating improved nal processing devices ● ● ● ●
  continuous NOx sensors
  programmable logic control devices (PLCs)
  software to integrate data and system control
- nsors and controls to reduce ssion testing needs and ociated costs on customer end
- etwork-based sensors and controls r real-time monitoring and arnings via system feedback
  ability to independently adjust controls without presence of a boiler operator using "master" computer
- mproved control of heat recovery riables

Heat Recovery

- Novel heat exchanger designs to improve low-T heat recovery from the stack, feed water pre-heater, and combustion air pre-heater ● ● ● ● ● ● ●
  - 100° - 300° stack temperature
  - explore changes needed on combustion side to aid low-T heat recovery
- Cost-effective materials development for heat exchangers ● ● ●
- Improve efficiency of heat recovery at low and mid-fire ● ● ● ● ●
- Incorporate waste heat from external plant sources into boilers
- Develop a systems-approach to heat recovery opportunities (as opposed to a component-based focus)
- Design philosophy change away from over-designing equipment solely to achieve maximum capacity reliably
  - factor waste heat recovery into design considerations

Other / Miscellaneous

- Baseline economic evaluation of system and life-cycle costing analysis to determine cost competitiveness and footprint of new materials and technology versus those presently in use ● ● ● ●
- Component integration throughout the entire steam generation system for:
  - instantaneous, dynamic response
  - instant-on boilers
- Parasitic load reduction (e.g., fans, motors in system ● ● ● ●
- Education and training of technicians and boiler operators

Appendix A
Workshop Participants

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