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Sensors for Fossil Energy Applications in Harsh Environments

Susan M. Maley[1], *Robert R. Romanosky**[1]
[1] *United States Department of Energy Office of Fossil Energy National Energy Technology Laboratory, PO Box 880 Morgantown, West Virginia, USA,*
robert.romanosky@netl.doe.gov
susan.maley@netl.doe.gov

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Abstract:
Advancements in energy generation technology are poised to offer environmentally sustainable alternatives when compared to mid century combustion/steam systems. Using emerging clean energy technologies, coal and other fossil fuel based processes can operate at high efficiencies, be integrated with carbon management platforms, and offer power that is reliable and reasonably priced. To achieve the goals and demands of clean energy, the conditions under which fossil fuels are currently converted into heat and power are extremely harsh compared to previous combustion/steam cycles. Temperatures are reaching 1600 Celsius (C) in certain systems and pressures are reaching as high as 5000 pounds per square inch (psi)/340 atmospheres (atm). These conditions serve as drivers for new harsh environment sensor technology, so that these systems can be safely monitored and efficiently operated. Emerging power systems are also highly integrated with many unit operations leading to a new level of operational complexity especially when the need for cycling the plants for grid management is considered. Process control systems are a key component in managing the complexity of the emerging power systems, but new control technology is needed address complexity and the desire to optimize the integrated process for changing demands. This paper will highlight the US Department of Energy, Office of Fossil Energy and National Energy Technology Laboratory's Program in Sensors and Controls which is aimed at addressing the technology development needs and drivers through the development of new sensor materials and designs and novel control architectures.

Key words: sensors, harsh environments, energy applications

Introduction

Electrical power is an important societal component and is expected to grow in demand throughout the world. The use of fossil energy within an energy portfolio is expected to remain an important component of the portfolio; however, significant improvements to the environmental footprint of fossil energy-based systems are needed so that this resource can be both economically and environmentally viable long term. For fossil energy-based power systems, several new technologies are on the forefront of being able to generate power and effectively control emissions including carbon. Along with the new technologies, there are harsh process conditions and many new measurements that need to be made in the harsh environments to insure that these power generation systems operate efficiently and within the environmental constraints. The United States (US) Department of Energy (DOE), Office of Fossil Energy (FE) and the National Energy Technology Laboratory (NETL), there is an active program in Sensors and Controls (S&C) to perform research development that addresses the measurement and control needs for advanced power generation systems. This paper highlights the major themes of the NETL S&C Program that support development of harsh environment sensors and clean energy generation.

Motivation

Emerging clean energy technologies offer the potential to operate at high efficiencies while minimizing emissions including approaches that minimize carbon emissions. The conditions under which fossil fuel is converted and thermal energy is generated are increasingly harsh

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when compared to mid century boiler / thermal based systems which are still in operation today. Advanced power generation technologies that are considered part of a clean energy platform include coal gasification, high efficiency combustion turbines, novel oxy-combustion processes and ultra supercritical steam cycles. A summary of these technologies can be obtained from www.netl.doe.gov and the conditions for these systems are outlined in Table 1. These conditions challenge the ability to accurately and reliably measure the process, thereby limiting its operational and environmental performance.

Table 1: General Process Conditions for Advanced Clean Energy Systems

Temperature	Pressure
Coal Gasification	
1000 – 1600 C	300-1000 PSI
Highly Reducing, Molten Coal Slag, & Corrosive Gases	
Combustion Turbine	
1000-1500 C	Pressure Rations up to 30:1
Highly Oxidative, High Velocities, & Rotating Components	
Oxy Combustion & Ultra SuperCritical Steam Cycles	
760 C (Fuel Side)	5000 PSI (Steam Side)
Highly Oxidative, Highly Corrosive, High Particulate/Ash in critical combustion zones	

Developing new sensor materials and designs capable of withstanding these conditions is one of the primary motivations for NETL's research and development program in harsh environment sensor technology.

The integration of the advanced power systems with environmental control technology and carbon capture processes results in a complex plant with new challenges in coordination, operation and optimization of the plant. The ability sense, assess, and take action in order to achieve an optimized operation results in a challenging information and data management scenarios that traditional process control architectures may not be able to adequately address. The need to manage process complexity, handle high data inputs from sensors and the impetus to achieve optimum environmental performance serve as other motivating factors for new sensor and control technology.

The interest in developing technologies to address these challenges resulted in a program structure that targets commercially viable S&C technology for power generation and other industrial applications. A generalized schematic of the S&C Program is shown in Figure 1 and described in subsequent sections.

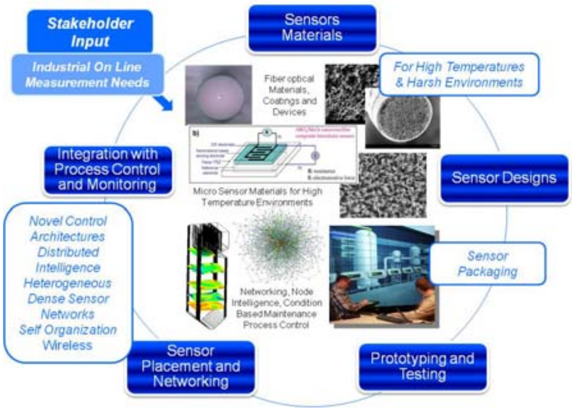

Figure 1: General Program Structure for NETL's Sensor and Control Program under the US DOE Office of Fossil Energy

Sensor Materials and Design

Two major considerations in the development of harsh environments sensors are the materials used for sensing and the design of the sensing device. Careful consideration needs to be given to 1) the environment in which the on-line sensor will be placed, 2) the measurement of interest, and 3) the accuracy, precision and lifetime needed from the sensor. Sensors materials that have proven most viable in high temperature combustion type environments include sapphire, yttria stabilized zirconia (YSZ), metal oxides including perovskites, and silica (for certain environments). These materials have been used for the design and fabrication of optically-based sensors and micro sensors (capacitance, resistive, mechanical, etc). One of the biggest challenges remaining for sensor materials in harsh environments is selectivity to a single gas (in a realistic mixed gas environment) that has reasonable and reversible response times. Sensor design also must consider materials of construction. In general, the use of dissimilar materials results in a higher likelihood of failure when exposed to extreme conditions due to thermal mismatch of the materials. The ability of the sensor material to be altered or used to fabricate the sensor device is also of interest. Previous sensor designs appear to lend themselves to probes that can be readily evaluated in a variety of experimental set-ups. As sensor materials and designs advance, the opportunities to integrate or embed sensor materials and novel sensor designs into a component or system will become available. Once of the target goals for the S&C program is to utilize sensor materials and designs in a way that enables densely distributed sensor networks. These sensor networks includes harsh environment sensors along with low cost sensors and other types of monitoring technologies for a fully integrated sensor network such that a system or component can be computationally reconstructed and visualized in near real-time using data generated from the sensor networks and other virtual sensing capability.

Sensor Prototyping and Testing

The ability to rapidly develop and evaluate sensor technology for its overall viability as a commercial device is a major emphasis of the NELT S&C program after the fundamental function of the sensor has been shown to be feasible. Development of a sensor prototype and subsequent testing lead to an enhanced understanding of sensor performance, failure mechanisms, and infer sensor survivability / lifetime. However, aggressive development cycles for this technology can challenge the expertise of the developers because a different set of expertise is needed for materials versus the expertise needed to design and fabricate a viable sensor prototype. Development teams which recognize this early on in the effort generally experience success sooner than those who take a more sequential approach to developing a new sensor technology or device.

Once a sensor design and prototype are available, NETL offers opportunities to test sensors at a bench scale before taking the new technology to pilot or full scale testing. This approach to sensor testing ultimately enables cost savings to the developers so that issues with data acquisition and packaging of the sensor can be addressed prior to expensive or prolonged full-scale testing. Development of a sensor prototype primarily considers packaging of the sensor for a specific harsh environment and the measurements of interest. Harsh environment sensing requires targeting a balance between sensor protection and adequate exposure to the conditions of interest. In addition, a sensor prototype will reflect stakeholder's requirements including systems which have complex geometry that must be factored into the into the prototype design. Figure 2 depicts the interior of a combustion turbine and represents a complex geometry that poses significant challenges to designing a sensor that can meet performance, packaging and system integration requirements.

Fig. 2. Complex geometry of a combustion turbine challenge conventional approaches to sensor design and prototypes.

As new sensor concepts progress through novel approaches as active smart coatings, spray-on/applied type sensors, and embedded sensors, the use of wireless communication and energy harvesting technologies will further challenge and advanced sensor prototypes. The NETL S&C program is targeting technologies that can function within high temperature environments and communicate sensor data wirelessly to the external environment. These novel approaches enables for more measurement locations and understanding of power systems with complex geometry such as the turbine shown in Figure 2. Integrating energy harvesting capability with sensor technology can greatly reduce the cost associated wiring and cabling required for traditional sensing approaches. In addition to these cost savings, power generation systems have many locations where waste heat and vibration are available to power sensors and the associated wireless communication hardware. Integration of these technologies with novel sensor designs will significantly change the way sensor prototypes are prepared and sensor testing is conducted.

Sensor Networking and Advanced Process Control

Networking of sensors with actuation devices and incorporation of advanced process control algorithms are the other key components of NETL's S&C Program. Transformational type research and development is underway to identify new approaches for linking heterogeneous sensor data to generation actionable generation and the ability to embed artificial intelligence at or near the sensing and actuation devices. Because the actuation hardware directly impacts the process behavior and performance, analysis of how information and decision making can be incorporated with hardware in ways that does not incorporate the complexity of a full-scale integrated advanced energy plant. Approaches to process control including algorithms and system architecture are being considered to enable optimum performance of a complete and highly integrated system. Methods to distribute intelligence to the lowest levels of the process control architecture are being considered along with introducing fundamentally new control formats that mimic the function and control of a biological system. This research is leading to new paradigms in sensing including where to sense, how many sensor are needed, the type of sensors, the sensors included in a fixed or adaptive sensor net and how the number and type of actuation hardware impact the amount of intelligence that can be distributed to the network level. Research to date has shown that a balance can be achieved between number of sensors and the control objective and this can be an adaptive methodology. New work is needed to incorporate how actuation and system non-linearity can be managed within an adaptive network. These approaches where sensors may not be viable may lead to viable alternatives to sensing in harsh environments through the use of virtual sensing and the incorporation of validated process models to predict operation parameters.

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