Industrial Process Heating - Technology Assessment

Contents

1. Introduction to the Technology/System

1.1. Industrial Process Heating Overview

Industrial process heating operations are responsible for more than any other of the manufacturing sector's energy demand, accounting for approximately 70% of manufacturing sector process energy end use (see Figure 1) [2]. There are a wide range of process heating unit operations, and associated equipment, that are to achieve important materials transformations such as heating, drying, curing, phase change, etc. that are fundamental operations in the manufacture of most consumer and industrial products including those made out of metal, plastic, rubber, concrete, glass, and ceramics [1]. Energy is supplied from a diverse range of sources, and includes a combination of electricity, steam, and fuels such as natural gas, coal, biomass and fuel oils. In 2010, process heating consumed approximately 330 TBtu of electricity, 2,290 TBtu of steam, and 4,590 TBtu of mostly fossil fuels [2].

Process heating technologies are generally designed around four principal energy types:

1. Fuel-based process heating technologies;
2. Electricity-based process heating technologies;
3. Steam-based process heating technologies; and
4. Hybrid process heating technologies.

These technologies are based upon one or a combination of conduction, convection and radiative heat transfer mechanisms; in practice, conduction/convection dominate lower temperature processes, whereas radiative heat transfer dominates high temperature processes. Hybrid systems are an example where there is a significant opportunity for technology improvements that can lead to manufacturing efficiency improvements such as lower energy consumption, improved speed/throughput, greater product quality, etc. by optimizing the heat transfer mechanisms to the manufacturing processes.

<u>Fuel-based process heating systems</u> generate heat energy through combustion of solid, liquid, or gaseous fuels, and transfer it to the material either directly or indirectly. Combustion gases can be either in direct contact with the material (i.e., direct heating via convection), or utilize a radiant heat transfer mechanism by routing the hot gases through radiant burner tubes or panels and thus separated from the material (i.e., indirect heating). Examples of fuel-based process heating equipment include ovens, fired heaters, kilns, and melters.

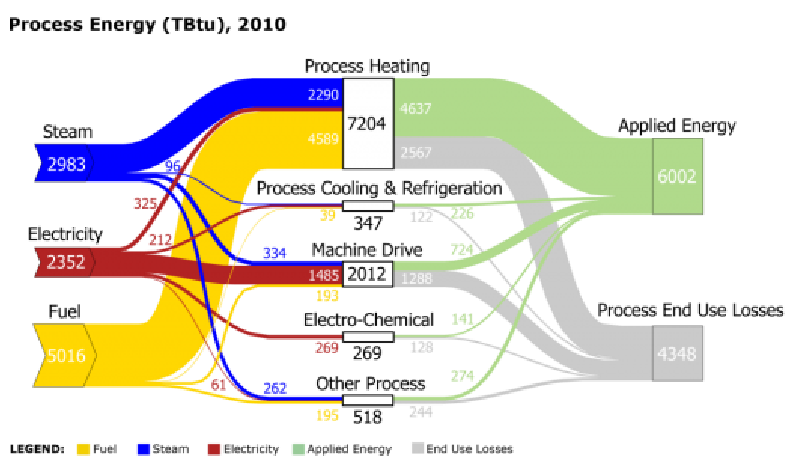

Figure 1 – Sankey diagram of process energy flow in U.S. manufacturing sector [2].

<u>Electricity-based process heating systems</u> can also transform materials through direct and indirect processes. For example, electric current can be applied directly to suitable materials leading to direct resistance heating; alternatively, high frequency energy can be inductively coupled to suitable materials leading to indirect heating. Electricity-based process heating systems (sometimes called electrotechnologies) are used to perform operations such as heating, drying, curing,

melting, and forming. Examples of electricity-based process heating technologies include electric arc furnaces, infrared emitters, induction heating, radio frequency drying, laser heating, microwave processing, etc.

Steam-based process heating systems provide process heating through either direct heating or indirect application of steam. Similar to fuel-based direct and indirect systems, steam is either directly introduced to the process for heating (e.g. steam sparge) or indirectly in contact with the process through a heat transfer mechanism. Steam heating accounts for a significant amount of the energy used in lower temperature industrial process heating (<400 deg. F.). Use of steam based systems is largely for industries where heat supply is at or below about 400 deg. F. and where there is availability of low cost fuel or by products for use in steam generation. Use of cogeneration (simultaneous production of steam and electrical power) is another example where steam based heating systems are commonly used.[1] For example the fuel used to generate steam accounts for 89% of the total fuel used in the pulp and paper industry, 60% of the total fuel used in the chemical manufacturing industry, and 30% of the total fuel used in the petroleum refining industry [2].

Hybrid process heating systems utilize a combination of process heating technologies based on different energy sources and/or different heating methods of the same energy source to optimize their energy use and increase overall process thermal efficiency. For example:

- Hybrid boiler systems combining a fuel-based boiler with an electric-based boiler using off-peak electricity are sometimes used in areas with lower cost electricity.
- Combinations of penetrating electromagnetic (EM) energy (e.g. microwave or radio frequency) and convective hot air can yield accelerated drying processes by selectively targeting moisture with the penetrating EM energy, yielding far greater efficiency and product quality than drying processes based solely on convection, which can be rate limited by the thermal conductivity of the material.

[1] See the 2015 QTR Chapter 8 CHP Technology Assessment

Table 1 - Characteristics of common industrial processes that require process heating

Manufacturing Operation	Applications [1]	Typical Temperature Range [3]	Estimated U.S. Energy Use (2010) [4]
Non-Metal Melting	Plastics and rubber manufacturing; food preparation; softening and warming	1710–3000°F	265 TBtu
Smelting and Metal Melting	Casting; steelmaking and other metal production; glass production	1330–3000°F	1,285 TBtu
Calcining	Lime calcining	1150–2140°F	525 TBtu
Metal Heat Treating and Reheating	Hardening; annealing; tempering; forging; rolling	930–2160°F	270 TBtu
Coking	Ironmaking and other metal production	710–2010°F	120 TBtu
Drying	Water and organic compound removal	320–1020°F	1,560 TBtu
Curing and Forming	Coating; polymer production; enameling; molding; extrusion	280–1200°F	145 TBtu
Fluid Heating	Food preparation; chemical production; reforming; distillation; cracking; hydrotreating	230–860°F	2,115 TBtu
Other	Preheating; catalysis; thermal oxidation; incineration; other heating	210–3000°C	925 TBtu
Total			**7,204 TBtu**

A large amount [2] of energy (7,204 TBtu/year in 2010) is used for process heating by the U.S. manufacturing sector, in the form of fuels, electricity, and steam. Common fuels include natural gas, coal, fuel oil, and liquefied gases. The petroleum refining, chemicals, pulp and paper, and iron and steel sectors also use by-product fuels from energy feedstocks. Approximately 13% of manufacturing fuel is used in generating electricity and steam onsite. Common process heating systems include equipment such as furnaces, heat exchangers, evaporators, kilns, and dryers. Characteristics of major manufacturing operations that involve process heating are shown in Table 1 above.

Key R&D opportunities for energy and emissions savings in industrial process heating operations are summarized in **Error! Reference source not found.**Table 2 below. Waste heat losses are a major consideration in process heating, especially for higher-temperatures process heating systems such as those used in steelmaking and glass melting. Losses can occur at walls, doors and openings, and through the venting of hot flue and exhaust gases. Overall, energy losses from process heating systems total over 2,500 TBtu per year. Waste heat production can be minimized through the use of lower-energy processing techniques such as microwave, ultraviolet, and other electromagnetic processing, which deliver heat directly where it is needed rather than heating the environment. These techniques also have the potential to produce entirely new or enhanced manufactured products because electromagnetic energy interacts with different materials in unique ways.

Table 2 - R&D Opportunities for Process Heating and Projected Energy Savings [4]

R&D Opportunity	Applications	Estimated Annual Energy Savings Opportunity (TBtu)	Estimated Annual GHG Emissions Savings Opportunity (million metric tons CO_2-eq [MMT])
Advanced non-thermal water removal technologies	Drying and Concentration	500 TBtu	35 MMT
Hybrid distillation	Distillation	240 TBtu	20 MMT
New catalysts and reaction processes to improve yields of conversion processes	Catalysis and Conversion	290 TBtu	15 MMT
Lower-energy, high-temperature material processing (e.g., microwave heating)	Cross-Cutting	150 TBtu	10 MMT
Advanced high-temperature materials for high-temperature processing	Cross-Cutting	150 TBtu	10 MMT
“Super boilers” to produce steam with high efficiency, high reliability, and low footprint	Steam Production	350 TBtu	20 MMT
Waste heat recovery systems	Cross-Cutting	260 TBtu	25 MMT
Net and Near-Net-Shape Design and Manufacturing	Casting, Rolling, Forging, and Powder Metallurgy	140 TBtu	10 MMT
Integrated Manufacturing Control Systems	Cross-Cutting	130 TBtu	10 MMT
Total		**2,210 TBtu**	**155 MMT**

The performance of a process heating system is determined by its ability to achieve a certain product quality under given manufacturing requirements (for example, high throughput, and low response time). The energy efficiency of a process heating system is determined by the energy use attributable to the heating system per unit processes (heated, melted, etc.). Efficient systems manufacture a product at the required quality level with the lowest energy intensity values. Energy efficient systems create a product with less input energy to the process heating systems per unit of product heated or melted at a given temperature increment.

Industrial process heating system, as defined broadly by the industry and DOE – Advanced Manufacturing Office (AMO), includes the entire system used for heating or melting of materials. A diagram of the major process heating components [5] is shown in Figure 2.

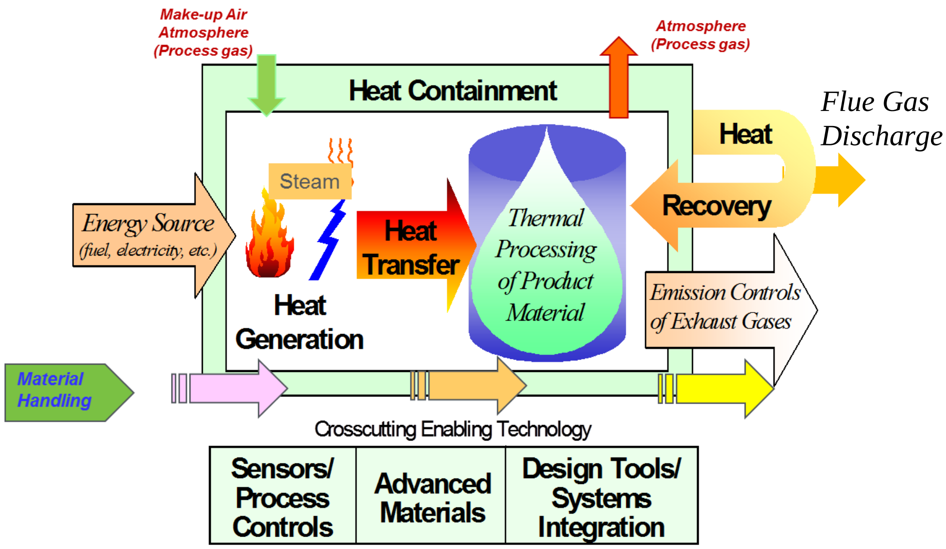

Figure 2 - Major Components or Modules of Combustion Based Industrial Heating System [5].

The system includes following major aspects, and each has an opportunity for technological improvement:

- Energy supply source (fuel, electricity or steam)
- Heat released from the supply source
- Heat transfer to various parts of heating equipment from heat source such as hot gases produced by combustion
- Heat containment that allows the user to maintain desired temperature and operating conditions such as specified process atmosphere
- Flue gas discharge with required flue gas processing
- Waste heat recovery, where applicable
- Material handling system
- Safety and process controls
- Advanced materials used in construction and operation of the system

However, systems-wide improvements leading to optimized operation requires complex multi-physics solutions; hence, there are significant opportunities for technology improvements that can benefit from high-performance computing (HPC) approaches.

In the next section, the technology assessment addresses the following three topics:

- Status of industrial process heating technologies,
- Recent advances and improvements in process heating systems, and
- Opportunities to improve process heating technologies.

2. Technology Assessment and Potential

2.1. Status of industrial process heating technologies

In the past a steady investment into research for process heating and related topics such as combustion has contributed in development of innovative technologies that have resulted in substantial improvements in energy efficiency of industrial processes. Major strides could be made towards reducing energy use and reducing Green House Gas (GHG) emissions to meet the national goals. Process heating and combustion R&D offers many incentives such as energy intensity reduction, lower energy costs, augmented national security, and above all future exports of entirely new technologies to a world becoming ever more dependent on the continuing use of indigenous fuels. At the same time indications are multiplying that strongly suggest that our utilization of carbonaceous fuels must either be restricted severely or new carbon sequestration technologies must be developed and installed, in order to limit maximum carbon dioxide concentrations in the atmosphere.

In an attempt to subdivide a very large and complex subject it is necessary to expand the field of industrial process heating into a number of smaller areas. The R&D areas directly related to process heating are as follows:

- Process Heating System Components and processes,
- Process Heating Controls
- Process Heating System Auxiliaries

Technology development and advancement in the industrial process heating area is primarily undertaken by industry even if it has only modest financial means to spend on new technology and equipment development. In addition to industrial R&D, the US government and several companies operating in the energy sector have provided funding for advancing the state of the art of combustion technology.

2.2. Recent advances and improvements in process heating systems

Although no major break-through technology additions have been made recently that have been adopted by industry, modest contributions by the industry and supported R&D can be found in these development areas:

- Digital Control Equipment,
- Reduction of NOx Emissions,
- Improvements in Thermal Efficiency of Selected Processes,
- Improvements in High Temperature Materials Availability,
- Advancements in Enhanced Heat Transfer, and
- Introduction of a Few Improved Combustion Equipment Products and Burners.

A casual analysis of reasons for this low production efficiency of sponsored technology advancement reveals at least one factor; the present system of technology advancement in mature industries is not very conducive to innovation.

There are three major actors that continue to actually advance industrial process heating and combustion related technologies by carrying out research, development, engineering, and process and equipment demonstration trials. These actors are:

- Industrial Companies Using Heating Processes,
- Industrial Companies Manufacturing and Marketing Process Heating and Combustion Equipment, and
- R&D Institutions Conducting Contract Research.

During the last 35 years two organizations have been active in funding research and development of industrial combustion systems programs while several other organizations and private industrial companies have been active in conducting research and product development. Some of these funding organizations are:

Funding Organizations

- The U.S. Department of Energy,
- The Gas Research Institute – GRI (now, Gas Technology Institute – GTI),

Research and Development Organizations

- Institute of Gas Technology (IGT), now Gas Technology Institute
- Lawrence Berkeley Laboratory
- Oak Ridge National Laboratory
- Several burner companies in collaboration with industrial companies
- Universities and several private companies.

Over the last forty years, more than five hundred US Patents [7] have been issued or assigned to the organizations working on R&D projects for the organizations mentioned above out of which a large percentage of these patents deal with process heating and combustion related technologies. Many of the project ideas were generated within the institutions mentioned above while others were proposed by industrial contractors.

The majority of the development work can be divided in the following categories:

- Development of flame based combustion devices such as burners that would improve “efficiency” of combustion, reduce emissions and enhance heat transfer from combustion products to the material processed for a variety of applications [11].
- Development of other types of combustion systems (non-burner type) such as catalytic combustion [11].
- Development of sensors and control systems related to flame or combustion products monitoring [11].
- Development of combustion system that includes heat recovery devices such as self-recuperative burners [11].
- Development of integrated heating systems such as super boiler and application of combined heat and power (CHP) [11].

Some major and some moderate advancement in process heating/combustion technologies took place in:

- Reduction of Combustion Generated Nitrogen Oxides,
- Development of High Temperature Silicon Carbide or Silicon Nitride Radiant Tubes,
- Oscillating Combustion Systems,
- Flameless combustion for high temperature processes,
- Oxygen Enriched Air and Pure Oxygen Based Combustion,
- Regenerative burners or combustion systems, and
- Flame Impingement Heating.

Some of the project ideas were generated within the five institutions mentioned above while most others were developed by the equipment suppliers.

2.3. Opportunities to Improve Process Heating Technologies

Performance of process heating steps (as described in Figure 2) is greatly affected by enabling technologies such as sensors and process controls, advanced materials, and design tools/systems integration. Opportunities for improvement are presented below for each technological challenge area, with enabling technologies discussed first because of their crosscutting nature. The R&D opportunities to overcome technological barriers to improved process heating are presented in the next section.

Low Thermal Budget Processes:
Electricity consumes a small share (325 TBtu – Figure 1) of the energy consumed by process heating. Expanded use of electrotechnologies has significant potential to reduce energy use and improve energy productivity of the process industries, materials production industries, and materials fabrication industries. Electrotechnologies that have been demonstrated to show significant benefits over traditional industrial process heating applications include infrared, microwave, and radio frequency for heating, curing and drying operations; as well as induction for heating, heat-treating and melting.[2]

There exists a significant opportunity to deploy high frequency electrotechnologies[3] for applications that benefit from selective and/or volumetric heating, which can dramatically reduce the energy requirements, but more importantly can enable the manufacture of improved or new products. For example, microwave (MW) energy has been demonstrated to accelerate chemical reactions by orders of magnitude;[4] sinter ceramics; alter grain structure in sintered metals;[5] and provide new pathways in the manufacture of carbon fiber.[6] However, the successful development of MW and RF processes requires a comprehensive understanding of the physics of the process and system.

The physics of electromagnetic (EM) wave/material interaction is complex, and are compounded by the coupled heat and mass transfer as well as the materials physics and chemistry. Further, because the material to be processed (the load) becomes an integral part of the overall system, the equipment design - especially the applicator design – is far more critical than in traditional heating processes. Benefits include significant efficiency advantages, and in many cases the EM energy becomes the *enabling technology* in the manufacture of materials and products. In recent years, commercial EM simulation programs have been adapted from communications applications to MW heating applications, but these packages are insufficient to thoroughly model all aspects of the process. This technology development process can benefit from application of high performance computing, where simulations of the EM, thermal, and materials interactions can optimize the overall process development.

Sensors and Process Controls: Reproducible product quality during thermal processing depends on the ability to effectively measure, monitor, and control process heating operations, thus minimizing product variability. This level of control requires reliable and affordable sensors and control systems that can withstand harsh environments without recalibration for a certain minimum time (on the order of one year) [8]. The key opportunities for R&D of sensors and process controls are:

- Direct process measurement sensors
- Low-cost sensors that are rugged, accurate, non-intrusive, and easy-to-use and maintain
- Reducing failures and inaccuracies of thermocouples and other sensors

---

[2] *Electrotechnology Applications in Industrial Process Heating.* EPRI, Palo Alto, CA: 2012 1024338.
[3] Cresko, J.W. "Fundamentals and Application of Dielectric Heating Technologies For Materials Processing: A review," Microwave Solutions for Ceramic Engineers; Clark, D.E. (editor), Wiley 2005 ISBN: 978-1-57498-224-4
[4] Varma; Kappe. (provide citations)
[5] Agrawal, Dinesh (provide citations)
[6] ORNL (provide citations)

- Technologies and methods to reliably monitor and control critical product parameters (temperature, chemistry, pressure, etc.)
- Cost effective overall process smart controls that can be integrated with the overall manufacturing system.
- Cost-effective flow control devices (e.g., air/fuel ratio control)

Advanced High-Temperature Materials: The ability to increase the efficiency of thermal processing is severely restricted by the availability and cost of high-performance, high-temperature materials. Use of high-performance materials can aid design of compact equipment, reduce energy and emissions, offer lower operating and maintenance costs, and increase productivity [8]. The key for R&D of advanced high-temperature materials are:

- High-temperature materials that are machineable and formable at reasonable cost
- High-temperature materials that are creep- and crack-resistant
- Cost-effective, high-performance materials, especially for heating corrosive fluids
- Strength and corrosion of metallic components for structural and sensor protection
- Coatings to operate at higher temperatures

Design Tools and System Integration: System performance is determined by equipment/component designs and system integration both within and across complex process heating operations. Models and other design tools can help achieve process specifications and optimize performance, while integration of the operations within a system can contribute to significant productivity gains. They can also help to reduce yield losses and maintain desired product quality [8]. The key opportunities for R&D of design tools and system integration are:

- Easy-to-use design tools for complex heating applications
- Expanded integration of design elements in models and simulation
- System integration in the areas of process control and heat recovery
- Design tools and integration for optimal performance for ovens, furnaces, and burners
- Techniques for repair and maintenance without shutting down equipment
- Technologies to optimize process speed and other parameters while maintaining safety
- Technologies to reduce probability of failure in complex systems
- Improved property data and validations for models
- Precise, integrated process-flow control models
- Robust, cyber-secure computer technologies

Heat Generation System: For fuel-fired systems, the challenge is to optimize thermal efficiency, operating costs, and compliance with emission regulations. This optimization depends on factors such as control of air-fuel ratios during all stages of heating, fuel-mix variability, completeness of combustion, and performance of the burner over the range of its operation. With current technology, it is difficult to cost-effectively and simultaneously reduce emissions and increase efficiency. For electrical systems, system performance and cost depend on power losses associated with transmission and distribution, system cooling losses (particularly in induction heating), and reliability of the power supply. More effective heat generation could result in significant cost savings through improved energy efficiency, productivity enhancement, reduced emissions, and a safer workplace [8]. The key opportunities for R&D of heat generation systems are

- Cost effective technologies for high-temperature indirect heating
- Technologies to limit/eliminate fouling (which results in higher energy use)
- Alternate heating methods for specific processes

- Technologies to extend equipment run life while maintaining integrity
- Improved fundamental understanding of combustion processes (turbulent mixing, soot properties/formation/loading)
- Combustion technologies that enable use of low heat-value fuels (e.g., waste fuels)
- Technologies for fuel flexibility
- Efficient air handling technologies

Heat Transfer Systems: Advancements in heat-transfer techniques and the designer's ability to reliably predict them under varied operating production requirements would have an enormous impact on process productivity, product loss rates, energy efficiency, and operating costs [8]. The key opportunities are:

- Technologies to enable uniform heat transfer
- Technologies to improve the cost –effective utilization of high-temperature direct and indirect convection systems
- High performance computing that can lead to targeted/customized solutions of complex design challenges, such as the heat transfer contribution of combined radiation and convection heating systems
- Difficulty in minimizing volume of heat transfer "box" or footprint relative to maximizing thermal efficiency, minimizing emissions, and optimizing uniform heat transfer

Heat Containment System: Controlled heat generation and heat transfer for industrial processes require the use of a "box" that can contain heat, maintain the desired atmosphere, assist in heat transfer, reduce energy losses, and facilitate material handling. Design and maintenance of the box has significant impacts on energy costs, emissions, productivity, product quality, and personnel safety. Proper design, construction, operation, and maintenance are important to industrial process heating efficiency [8]. The key opportunities are:

- Resilient high-temperature seals
- Low-density and low-permeability primary insulation products

Heat Recovery Systems: A large percentage of the total energy input to heating systems can be recovered in the form of waste heat. Waste heat is produced in many forms, such as exhaust gases from combustion equipment, cooling water, trays, belts, and fixtures and, in some cases, the heated product itself. Today's methods to collect, recover, and use waste heat often are not economically justifiable. This is especially true for low-temperature or low-grade heat (e.g., hot water or low-temperature flue products). Significant energy cost savings could be realized through advanced heat recovery systems [8]. The key opportunities are:

- Technologies to economically capture/recover low-temperature heat with existing heat exchanger or heat-storage technology
- Technologies to cost-effectively capture very high temperature exhaust heat

Emissions Control Systems: Emissions levels and compliance costs could both be considerably reduced if innovative emissions control technologies were developed for process heating [8]. The key opportunities are:

- Technologies to cost effectively generate ultra-low emissions
- Technologies to cost effectively reduce emissions and at the same time increase efficiency
- Technologies to minimize all pollutants/emissions simultaneously

- Technologies to cost effectively and simply filter nitrogen from ambient air for combustion systems
- Low-cost, reliable multi-element sensors and analyzers for combustion and process emissions

Auxiliary Inputs: Optimal product quality and heating system performance may be determined by the process atmosphere (i.e., mix of gases) used during thermal processing in several critical operations. These protective or process-enhancing atmospheres are either generated on-site or are obtained by using a mixture of stored gases (e.g., N_2, H_2, CO_2, and NH_3). Equipment and methods for using atmospheres have a significant effect on productivity and operating cost. Use of relatively pure oxygen for combustion is also becoming more common. Cost reductions in the production, storage, mixing, and control of these gases will increase efficiency, reduce emissions, and, in some cases, improve productivity and product quality [8]. The key opportunities in this area are:

- Low-cost oxygen to improve thermal efficiency of combustion equipment
- Technologies for low-cost separation of hydrogen from water

3. Program Considerations to Support R&D

3.1. Future process heating technology needs and potential R&D efforts

For industry to achieve its desired performance targets for industrial process heating systems, it must focus R&D efforts on improvements to the entire system, integrating approaches that consider all of the components and, eventually, the entire manufacturing process. R&D activities should be designed to improve the productivity, product quality, and efficiency of the systems as a whole, incorporating GHG emissions as one of the critical issues.

Fuel-based Process Heating System – R&D Needs:

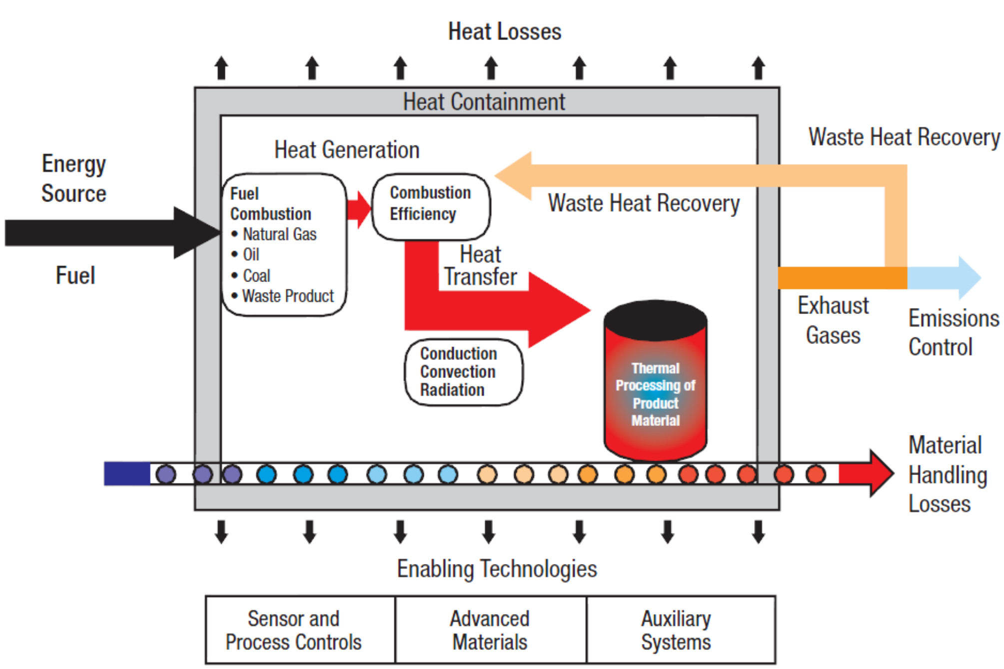

Figure 3 – A fuel-based process heating system and opportunities for improvement [1].

Tools and Models

- Computational tools that contain validated, high-fidelity combustion models
- Reliable, efficient model of turbulent, reacting flow
- Common method for measuring furnace efficiency
- Application-specific models
- Tools that account for transient phenomena
- Performance data for furnace equipment - in a standard format
- Design tools for heat recovery device design
- Robust, accurate models that consider process chemistry and fluid mechanics
- More user-friendly tools

Sensors and Controls

- Non-traditional sensors for more accurate measurement of temperatures and physical properties
- In-situ, real-time temperature sensing
- Image-based sensing to monitor surfaces
- Demonstration of real-time combustion control in pilot-scale environment
- “Smart” sensors and control systems (self-learning and -teaching)
- Robust sensors to measure critical parameters in harsh combustion environments
- Investigation of low-cost sensors used in the auto and other industries
- Low-cost reliable flame monitoring systems (flame quality, stability, etc.)
- Improved pressure measuring system and control device
- Low-cost reliable actuators
- Reliable, continuous flue gas analysis and temperature sensors
- Sensors that can accurately measure fuel and oxidant compositional characteristics
- Sensors to measure integrated energy use
- Continuous heat flux meter
- Real-time measurement of material failure

Design and Development

- Fundamentally new equipment and methods for heating and transferring heat (i.e., exothermic chemical reaction)
- New furnace design with improved efficiency (a smaller box)
- Integrated oxygen generation/furnace system (temperature- swing adsorption) such as ceramic membrane
- Enhanced heat transfer in furnaces
- Methods of indirect heating of materials
- Demonstration of atmosphere control for direct firing/heating (e.g., eliminate scale on steel)
- Alternatives for heat processing
- Hybrid systems or other methods to increase heat transfer to loads
- Innovative, cost-effective, heat recovery process:
    - Rapid cycle regenerative system
    - Low-temperature heat recovery (e.g. warm water)
    - Specific for oxy-fuel or oxy-enriched processes
- Uses of waste heat for emissions reduction

Fundamental Understanding

Better Understanding of:

- Particulate generation in combustion
- Mechanisms of product degradation
- Heat transfer and its application
- Mechanisms to generate heat with less volume
- Scale-up
- Formation of dioxins and furans below 1400 F in flue gas streams
- Flue gas stream characteristics for prediction of behavior in a heat recovery system
- Mechanism for capturing fine particulates under wet conditions (NOx conversion)
- Physical properties of different materials

Materials

- Improved materials for extending furnace life/reducing maintenance requirements
- Investigation of material compatibility data for probes and sensors
- Coatings to improve heat transfer and recovery
- Improved fabrication methods for advanced materials (i.e., for irregular shapes)

System Integration

- Combustion alternatives (e.g. induction heating)
- Systems integration analysis of combined end use to extend the co-generation concept
- Close coupling of manufacturing processes to reduce heat requirements
- Ways to reduce oxidation of reactive products
- Benchmarking classification of existing processes
- Identification of processes that have the most difficult problems with heat exchange/furnace operation
- Real-time thermal distribution

Technology Transfer

- State-of-the-art combustion lab(s) to validate CFD models and test materials
- Using information technology tools for personnel training
- Creation of development teams among users, researchers, and equipment manufacturers to focus on specific needs
- College curriculum for combustion engineers
- Characterization of the state of the industries (benchmarking)
- Development of opportunities for international cooperation on combustion technology research
- Industry certification program for safety
- Demonstration of technology developments in low-risk environments
- Identification and use of technical overlap in various industry applications
- Data transfer standards
- Combustion database integration and software engineering

<u>Electric-based Process Heating System – R&D Needs</u>:

- Improved control system to allow overall efficiency of the heating system
- Intelligent selection for induction coils for induction systems
- Heat recovery from melting systems including arc furnaces and induction melting system

- Improved materials for electrical heating elements for higher temperature applications, survival in heat treating atmospheres, radiant tubes (used for enclosing heating elements) etc.
- Development of high capacity electric glass melting furnaces.
- Multi-physics modeling software that allows proper parameter selection for electric-fuel fired hybrid systems to optimize energy use and production in high temperature applications.

<u>Steam-based Process Heating System – R&D Needs:</u>

- High convection systems for use in steam heated dryers to increase productivity and temperature uniformity
- Use of hybrid systems that use fuel firing and steam heating
- Replacement of steam heated systems by gas or clean fuel fired eating systems
- Air leakage reduction through innovative design and control for dryers
- Heat recovery from steam heated systems
- Improved materials for steam – air heat exchangers to withstand gases with contaminants.

Fundamental Understanding

Better understanding of:

- Efficient conversion of all fuels to H_2O and CO_2 (for catalytic combustion systems)
- Chemistry of the conversion of fuel nitrogen to NOx
- Heat transfer characteristics of flames and combustion products
- Water treatment chemistry

Sensors and Controls

- Improved low-NOx and CO measurement devices
- Durable sensors that can provide real-time measurement of combustion products
- Sensors and software algorithms to compute heat exchanger and furnace fouling
- Sensor that can provide high-temperature measurement
- "Smart" control system to run multiple boilers (neural networks)
- Improved measurement of steam use and temperature

Technology Transfer

- Energy technology clearinghouse to store and categorize information
- Better explanation of combustion industry's priorities to specialized R&D communities
- More expertise in trouble-shooting of combustion and heating systems
- Convenient training and education program for operators and users(easily adaptable to different boiler systems)
- Definition of separate strategies for retrofitting different boiler types to meet performance standards
- Establishment of high-level, government/industry group to set priorities for combustion technology research and joint funding
- Determination of cost/benefit of various recuperative schemes (user-friendly tool)
- Consistent government standards for energy and environment for all fuels and all industries
- Baseline energy impact on U.S. economy, security, and sovereignty
- Identification of potential combustion technologies for all fuels to meet goals
- Identification of impacts of one goal on another and examination of interactions
- Acceleration of the application, testing, and commercialization of new materials

- Cross-industry consortia to demonstrate new technologies
- Identify needs for demonstration sites
- Reduction in time for new technologies to make it to the marketplace through governmental deployment support
- Removal/reduction of restrictions to working with government (competitive information, regulatory conflicts, paperwork requirements)

Design and Development

- New boiler and combustion cycles:
    - Pressurized combustion systems
    - Turbo-charged, recuperated combinations
    - Min 1,500 psi, 1,500°F
- Use of electric fields to improve stability range and equivalence (fuel/air ratio) of lean pre-mix burners
- Integration of all established, desirable elements into a common technology platform ("super" boiler program) to develop family of advanced packaged boilers
- Exploration of stability of lean pre-mix systems using different stabilization procedures in standard boilers
- Stable combustion systems to accommodate rapid load changes
- Indirect-fired radiant air heater units and associated materials developments
- Non-invasive techniques for the removal of solids from boiler tubes
- Improved alternative materials
- High temperature steam generation (CHP or industrial power generators)
- Capture of flue gas heat through improved materials
- Filter systems for pressurized fluidized beds (possibly ceramic)
- Combustion by-product clean-up in fluidized bed
- Improved back-end materials for fluidized beds

Tools and Models

- Investigation of heat transfer characteristics through flow modeling design (number of passes)
- Testing and demonstration of hybrid systems (e.g., low-NOx burners plus post-combustion cleanup equipment) to determine their potential for meeting environmental targets
- High-efficiency, low-emission boiler demonstration program (like Clean Coal Technology Program but not specifically associated with coal)
- Testing and demonstration of fuel use (looking at emissions control and operational issues)
- Energy-efficient technology verification program
- Equivalent of the Sandia Burner Engineering/Research Laboratory (BERL) for fire-tube boilers

Fuels and Oxidants

- Low-cost oxygen generation methods
- Documentation of trade-offs and benefits of oxy-enriched burners and boilers
- Multi-fuel burners
- Methods to pre-heat fuel
- Less expensive ways to store gaseous fuels
- More efficient atmospheric fluidized-bed combustion systems for solid fuels
- Investigation of gasification

- Development of a high pressure feeder
- Examination of existing technologies that can be applied to fuel reforming to increase fuel flexibility
- Program to expand use of ash from boilers (particularly those using low-NOx burners) burning a variety of fuels
- Continued testing of fuel blends

System Integration

- Burner and combustion systems that are compatible with advanced gas turbine technology
- Integrated advanced burner concepts and boiler/duct heater combinations
- Burner component research coordinated with boiler R&D
- Steam-trap selection tool for condensate system and better steam traps
- Condensate system design that prevents contamination due to poor water quality
- Use of waste heat in condensate system
- Combined heat and power (CHP) designs that balance thermal and electricity requirements efficiently
- Capture of flue gas heat through improved process integration
- Independent evaluation of post combustion clean-up systems

Tables 3a and 3b below summarize top and high priority R&D goals listed in 2001 roadmap for process heating technology [8].

Table 3a - Top and High Priority Goals listed in 2001 Roadmap for Process Heating Technology [8]

Top and High Priority R&D Goals	Industries Impacted									
	Primary Steel	Heat Treating	Forging	Metal Casting	Aluminum	Pulp and Paper	Glass	Petroleum	Chemical	Food Products
SENSORS AND PROCESS CONTROLS										
Optimize process control protocols that integrate sensor readings with auto adjustments to the process	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cost-effective intelligent control systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Accurate, non-invasive flow measurement for hot liquids and gases	✓	✓		✓	✓		✓	✓		
On-line gas composition analyzers	✓	✓	✓	✓	✓		✓	✓	✓	
Non-intrusive sensors based on optical diagnostic technology	✓	✓	✓	✓	✓		✓	✓	✓	✓
Instability sensors that can detect approaching flame instability	✓	✓	✓	✓	✓		✓	✓	✓	✓
Variability reduction through new sensors and methods	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Non-contact pyrometry that is not emissivity dependent	✓	✓	✓	✓	✓			✓	✓	
Reliable dew point analyzers		✓			✓		✓			
Non-temperature-sensitive oxygen sensor	✓	✓		✓	✓			✓		
Non-contract, non-destructive in-situ carbon analysis	✓	✓								
Transformation structure detection	✓	✓	✓							
In-situ melt chemistry	✓		✓	✓						
Advanced sensors that measure multiple emissions	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Accurate non-contact hardness sensors	✓	✓	✓	✓	✓					
IMPROVED HIGH-TEMPERATURE MATERIALS										
Improve performance of high-temperature materials including alloy composites	✓	✓	✓	✓	✓			✓	✓	
Improved, cost-effective materials for heat recovery	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Composite materials with enhanced properties compared to existing material	✓	✓	✓	✓	✓		✓	✓	✓	
DESIGN TOOLS AND SYSTEMS INTEGRATION										
Predictive models of heat process system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Better material property data for design	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Models for heat recovery equipment/systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 3b - Top and High Priority Goals listed in 2001 Roadmap for Process Heating Technology [8]

Top and High Priority R&D Goals	Industries Impacted									
	Primary Steel	Heat Treating	Forging	Metal Casting	Aluminum	Pulp and Paper	Glass	Petroleum	Chemical	Food Products
HEAT GENERATION SYSTEMS										
Improve methods for stabilizing low emission flames	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Combustion technologies that simultaneously reduce emissions, increase efficiency and increase heat transfer	✓	✓	✓	✓	✓		✓	✓		
Heavy oil burner with gas emissions profile	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Better ultra-low NO_x burners	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Smart burners that adjust heat release profile	✓	✓	✓	✓	✓		✓	✓		
Develop the next generation of heating methods										
Hybrid gas/electric heating systems										
HEAT TRANSFER SYSTEMS										
Minimize air volume of convection ovens		✓		✓	✓	✓		✓	✓	
Enhance heat transfer (e.g., coefficients)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
HEAT RECOVERY SYSTEMS										
Low-cost, low-temperature heat recovery	✓	✓			✓	✓		✓	✓	✓
EMISSIONS CONTROLS										
Reduce the capital and operating cost of environmental equipment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cost-effective and compact emission scrubbers and catalytic converters for industry	✓		✓	✓	✓		✓	✓		
Advanced incineration, pyrolysis, and/or gasification technologies for by product reuse (e.g., solid waste)						✓		✓	✓	✓
Cost-effective N_2 filter for combustion air and fuel	✓	✓	✓	✓	✓		✓	✓		
AUXILLIARY INPUTS/SERVICES										
Generate low-cost process atmospheres and oxidants	✓	✓	✓		✓		✓	✓	✓	
HEAT CONTAINMENT										
Improve cooling technology to avoid water use/cooling	✓	✓	✓	✓	✓		✓	✓		✓

3.2. Summary

The challenges of improving industrial process heating systems are extremely complex, and the process heating equipment industry has inadequate resources to tackle them alone. While developments at the component level will remain important, breakthroughs in efficiency, productivity, safety, and environmental performance hinge on optimizing process heating systems from a total systems perspective. By approaching development, from a total systems view, research can result in increasingly efficient, clean, fuel-flexible, and reliable process heating systems, capable of producing uniform high-quality end products at high production rates. These systems will offer benefits to our nation, furthering energy security and environmental protection goals.

4. Risk and Uncertainty, Other Considerations

Many technological, regulatory, and institutional barriers prevent industrial process heating systems from achieving the best performance levels today. Risk and uncertainty with respect to the uptake of technological improvements is rooted in barriers preventing technology adoption. The following discusses the barriers common to the entire industry, as well as those specific to fuel-based, electric-based, and steam-based systems respectively.

4.1. Industry-wide Barriers

- The **financial risk** associated with adopting a new technology is considerable in the industries that use energy intensive and expensive process heating equipment. As a result, these industries are typically conservative, initiating relatively few technological changes over the past several decades. Industry, as a whole, is unwilling to risk a heavy financial burden resulting from inadequate performance of a new system. In the current competitive economic environment, incentives do not exist for either the end-user or the technology vendor to assume excessive financial risk [6].

- A further barrier to the development of new process heating system designs is the industry's **inability to accurately predict the performance** of the new systems. No standard exists for measuring or reporting performance under "standard" or agreed upon operating conditions. Additionally, technologies for measuring key process heating parameters are not adequately advanced, and industry does not take advantage of existing state-of-the-art heat transfer, combustion, or materials laboratories because the available results from the development organizations are generally detailed, micro-level data that need to be interpreted and applied for practical applications. For the most part, the size and type of laboratory test equipment available are inadequate, and the costs to rebuild them are prohibitive [6].
- **A wide gap exists between researchers**, who often work on a relatively small scale, **and the component, equipment, or systems designers**. Considerable fundamental knowledge exists or is being pursued at the national laboratories and in academic and other research institutions, but the transfer and use of this knowledge requires simplified tools that are either unavailable or prohibitive because of cost and training time [6].

Fuel-based Process Heating System Barriers:

- As already indicated, the furnace and industrial heating industry has been relatively slow to develop and adopt new technologies. This is primarily due to characteristics of the industry, including the relatively **small size of the companies** offering industrial heating systems and **the lack of communication and integration between the equipment suppliers and the end-users** [6].
- Another barrier to furnace system development is the **high level of integration** of industrial heating equipment **with the other process steps and equipment within a plant**. The operation of the entire plant is often dependent on the furnace system. Thus, the end user is hesitant to risk production downtime that may result from a new furnace technology [6].
- The **end user's requirement for system flexibility** may also pose a problem for furnace technology development. The end user will likely prefer a more reliable, less efficient furnace system if it meets the needs of the plant without exception, rather than risk limitations with a new technology [6].

Electric-based Process Heating System Barriers:

- Large differential between cost of thermal energy generated from fuels vs. use of electricity that favors fuel based systems
- Limited use of electrical systems for large energy user industries such as steel, petroleum refining, chemical etc. due to use of high (>1600^{0}F) temperature where conventional electric heating systems are limited or very expensive.
- Lack of developments of hybrid systems which can make optimum use of electrical and fuel fired systems.
- Non-availability and cost of materials used for electric systems that can be used in high temperature "contaminated" process environments.

Steam-based Process Heating System Barriers:

- Temperature limitations of steam based heating. Most systems have to be limited to less than 500^0F due to limitations on steam temperature even at very high steam pressures or superheat [6].
- Many small and medium size plants do not have access to steam and installation of steam generators requires large investments and operating cost [6].
- The variety of boilers in use today is a barrier to the development of combustion technologies that reduce emissions uniformly because an advanced burner developed for a particular boiler design may not transfer successfully to other boilers. The turndown instability of lean premixed combustion systems is a barrier to reducing NOx emissions. Additionally, because various fuels have different NOx control requirements, achieving NOx goals as well as targets for systems operations and fuel flexibility is exceedingly difficult [6].
- Another barrier to new boiler development is emission regulations. Under more stringent regulations, it may be necessary to install a particulate control system on the back end for new installations. However, commercial and developing technologies have not been adequately demonstrated as effective options for controlling fine particulate emissions (<2.5 microns) for a wide variety of process conditions [6].

5. Sidebars; Case Studies

5.1. Case study – Infrared heating reduces energy and improves material properties

Preheating of the metal billets prior to hot-forging was identified by the Department of Energy (DOE) Advanced Manufacturing Office (AMO) as an area with potential for significant energy savings for the US forging industry. Preheating of billets in the aluminum forging industry is costly, slow and energy intensive. Rapid infrared heating (Figure 4) offers the opportunity to provide a faster, cheaper and less energy intensive alternative to traditional gas-fired convection ovens which typically preheat forgings to above 800ºF [9], [10]. In this DOE-sponsored project, ORNL teamed with Queen City Forging, Komtek, Infrared Heating Technologies, Northeastern University and the Forging Industry Association to scale up a laboratory based batch-type infrared furnace from ORNL to develop an optimized continuous hybrid infrared furnace setup for an industrial forging application. Implementation of the IR furnace at the Queen City Plant demonstrated the ability to reduce preheating times for aluminum forgings from 1-6 hours to 14-18 minutes. The infrared pretreatment was 75% more energy efficient than conventional ovens. Finally, the system proved robust in industrial conditions. The IR furnace has demonstrated a downtime of less than 5% in over three years of preheating billets [9], [10].

Figure 4 - Continuous-belt IR heating furnace installed at Queen City Forging Company, Cincinnati, Ohio [10].

6. References

1. Improving Process Heating System Performance: A Sourcebook for Industry, Second Edition, U.S. Department of Energy, Industrial Heating Equipment Association (IHEA), 2007.
2. Sankey diagram of process energy flow in U.S. Manufacturing Sector. Available at - http://energy.gov/eere/amo/sankey-diagram-process-energy-flow-us-manufacturing-sector. The data source for the Sankey Diagram is the Manufacturing Energy and Carbon Footprints (2010 MECS).
3. Waste heat to power – Economic tradeoff and consideration, presented by Dr. Arvind Thekdi, E3M Inc., 3rd Annual Waste Heat to Power Workshop 2007, September 25, 2007, Houston, TX.
4. R. B. Chapas and J. A. Colwell, "Industrial Technologies Program Research Plan for Energy-Intensive Process Industries," prepared by Pacific Northwest National Laboratory for the U.S. DOE (2007), available from: http://www1.eere.energy.gov/manufacturing/pdfs/itp_research_plan.pdf. Energy use scaled to 2010 *Manufacturing Energy and Carbon Footprints (2010 MECS)* data.
5. Roadmap for Process Heating Technology, Developed by Industrial Heating Equipment Association and the U.S. Department of Energy, March 2001.
6. Industrial Combustion Technology Roadmap – A Technology Roadmap by and for the Industrial Combustion Community, This roadmap document was prepared by Energetics, Incorporated based on input provided by participants in a facilitated workshop held in August 2001, October 2002.
7. Industrial Combustion Technology Review – Oak Ridge National Laboratory (ORNL) Report by Arvind Thekdi, Klaus Hemsath, and Richard Martin, March 2007.
8. Roadmap for Process Heating Technology – Priority Research & Development Goals and Near-Term Non-Research Goals to Improve Industrial Process Heating, AHEA and DOE, March 2001. Available at: http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/process_heating_0401.pdf.
9. Infrared Billet Heating Technology Enables Production of Low Cost Diesel Engine Rotors, Oak Ridge National Laboratory (ORNL), Fact Sheet. Available at: http://web.ornl.gov/sci/ees/itp/documents/FS_QC_Impellers2010.pdf
10. Enhancement of Aluminum Alloy Forgings through Rapid Billet Heating, US DOE, June 2006. Available at - https://www.forging.org/system/files/field_document/Enhancement.pdf.
11. IMPACTS – Industrial Technologies Program: Summary of Program Results for CY2008, US DOE. August 2010. Available at http://www1.eere.energy.gov/manufacturing/about/pdfs/impacts2008_full_report.pdf
12. C. Leonelli and T. J. Mason, "Microwave and ultrasonic processing: now a realistic option for industry," Chemical Engineering and Processing 49 (2010) 885-990.
13. Z. Z. Fang, S. Middlemas, J. Guo, and P. Fan, "A new, energy-efficient chemical pathway for extracting Ti metal from Ti minerals," Journal of the American Chemical Society 135 (2013) 18248-18251.