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Energy Recovery Opportunities from Wastes

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Energy recovery opportunities from wastes are discussed, together with associated challenges on the environmentally benign energy recovery. The amount of waste generated worldwide has continued to increase in the current century. Most of the wastes have significant energy potential. The utilization of wastes can save millions of dollars on the national scale. However, difficulties exist for their utilization in propulsion and power systems in an environmentally acceptable manner. It is anticipated that the amount of waste generated will continue to grow in the next millenium, along with associated changes in its composition. The thermal destruction of wastes to the molecular level allows one to more cleanly convert waste into usable energy. The challenges provide opportunities for combustion engineers, whose research is now becoming even more important with new emphasis. Research in combustion-related areas has expanded significantly in recent years, particularly in areas related to fossil fuels and wastes being used as fuels. The field of combustion is further diversified by the complex nature of most reaction processes. Fuel chemistry, fluid mechanics, convective and radiative heat transfer, gas-phase elementary reactions, turbulence, and particle kinetics and dynamics are relevant processes that often have a direct, and sometimes controlling, influence on the behavior of a particular combustion system. Sensors, diagnostics, and miniaturization of the system continue to be of major importance for successful implementation of this new technology.

Introduction

IN recent years, much emphasis has been placed on energy recovery from wastes. The main problem for combustion engineers has been how to recover maximum energy from waste (fuel) with minimum pollution, using existing, modified, or newly designed equipment. The energy recovery opportunities from wastes discussed here provide unique challenges to combustion engineers for environmentally benign energy recovery. The amount of waste generated is projected to grow in the foreseeable future. Almost all waste has significant energy potential and its utilization can save millions of dollars on the national scale. The old practice of waste disposal has been to dump in open landfills, which results in garbage in and garbage remains. The landfill results in odor, bacteria growth, and the slow release of greenhouse gases. Some materials in the waste (such as plastics, metals, and ceramics) are not biodegradable. This exacerbates the offensiveness of the existence of landfill waste sites. The goal for the new millenium must be garbage in and energy out, in an environmentally acceptable manner. We anticipate that the amount of waste generated will continue to grow in the next millenium, along with associated changes in its composition. The thermal destruction of wastes to the molecular and atomic level allows one to more cleanly convert waste into usable energy. The challenges provide opportunities for combustion engineers, whose research is now becoming even more important with new emphasis on wastes. Fuel chemistry, fluid mechanics, convective and radiative heat transfer, gas-phase elementary reactions, turbulence, and particle kinetics and dynamics are relevant processes that often have a direct, controlling influence on the behavior of a particular combustion system. Sensors, diagnostics, and miniaturization of the system will continue to play an important role in this new technology.

The general desire in experimental diagnostics is that only techniques that are sensitive to both the magnitude and direction with required temporal and spatial resolution should be used. Recent developments in optical diagnostics has finally provided the prospects for obtaining this needed information about variables, such as size, velocity, species concentration, temperature, and the correlations between them.

In combustion systems, the designer must accomplish efficient and environmentally benign energy conversion. The thermal and chemical behavior of the flow in most propulsion and power systems is complex. In design situations, experimental data are used to verify and develop models. These mathematical models then supplement and reduce the amount of costly and time-consuming experimental procedures. These models have benefits and entail costs. Benefits include knowing quantitatively, in advance, what will be the performance of equipment that has not yet been built or has not yet been operated in the manner under investigation. Most mathematical models simulate the physical processes, e.g., turbulence, radiation, combustion, pollutant formation, and multiphase effects, by solving an associated set of coupled partial differential equations. A rational approach of parallel efforts between modeling and diagnostics has the most promise for a cost-effective solution to the successful design and development of combustion systems.

Many important combustion problems of today involve multiphase situations. In two-phase flows, accurate size and velocity measurements of liquid sprays or solid particles are important for a broad spectrum of applications. Complete characterization of local properties in a spray includes such attributes as particle size distribution and number density, a velocity distribution function related to droplets of different size, mean velocity of the gas phase, local gas and liquid temperatures, composition of both the gas and liquid phases, turbulence

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properties, etc. In particle-laden flows, the influence of turbulence on the particles and vice versa is important. The reliable and precise measurement of any one of the preceding properties is a nontrivial task.

Magnitude of the Waste Problem

The U.S. generates about 2 kg (~4.4 lb) per person per day of solid waste.[1] This translates to over one billion tons of municipal solid waste generated annually. In addition to this, the U.S. also generates about 300 million metric tons (where 1 ton = 1000 kg) of hazardous wastes, and over the last one or two decades it has been growing at a rate of about 5–10% annually. Oppelt[2] reviews the information. Medical waste (heating value ~14 MJ/kg or 6000 Btu/lb) generated in the U.S. varies between 4180 and 14,000 ton/day. Hazardous wastes are produced by many industries, and according to the Environmental Protection Agency (EPA), ~10–17% of all chemical wastes generated are hazardous.

A number of surveys have been made to evaluate the magnitude of the problem.[3] The 1985 EPA survey identified 2959 facilities, regulated under the Resource Conservation and Recovery Act, which managed a total of 247 million tons of wastes per year. The Chemical Manufacturers Association conducted a survey to determine hazardous waste generation by its member companies. The total waste generated was about 213 million tons per year. The Congressional Budget Office estimated the hazardous waste generation in 1982 to be between 223 and 308 million tons. The Office of Technology Assessment arrived at between 255 and 275 million tons of hazardous waste in 1983.

Whatever the source of information, the magnitude of the problem is very large. For example, the U.S. Navy generates about 1.5 kg (~3.4 lb) per person per day of solid waste. In addition, liquid waste (black water, gray water, and bilge water) generated onboard mission ships is very large, and this must be processed before discharging to sea, particularly near coastal areas. The disposal of both solid and liquid waste into ocean waters is becoming increasingly important. The problem involved with a densely populated ship city disposing of its waste in an environmentally acceptable way is very challenging. According to an EPA estimate, 80–90% of this waste is disposed of improperly. It is estimated that there are over 760,000 generators of hazardous wastes, and about 40,000 produce less than 12 metric tons per year.

The composition of the waste varies significantly from source to source and also from season to season. The composition of the waste stream is therefore heterogeneous. Typical composition of the dry municipal solid waste (MSW) is given in Table 1.[4]

The presence of moisture, which can vary from 10 to 66%, can have a significant influence on the heating value of the waste. Dry MSW has an approximate heating value of 16.2 MJ/kg (or equivalently 6968 Btu/lb) (Table 2). As an example, a 10% increase in moisture will reduce the heating value of waste by about 1.67 MJ/kg (or equivalently 717 Btu/lb). The decrease in heating value (in Btu/lb) with an increase in moisture content can reasonably be estimated from $(6968 - 71.7x)$, where x is the moisture content in weight percent. The average moisture content in material depends on the material type. Food waste may have a moisture content of about 70%, whereas plastic and leather have a very low moisture content of about 2%. There are seasonal variations of the moisture and energy content of the wastes. Therefore, the sorting of the material cannot only provide near uniform chemical composition, but also energy content. A comparison of heating values of municipal waste with various other waste fuels and biomass is given in Table 2. The data show that the energy content in the MSW is comparable with some wood material and cellulose.

Table 1 Characteristic composition of the dry MSW[4]

Component	Average content, % by weight	Heating value, dry, Btu/lb
Food waste	33.5	6528
Paper, cardboard	33.5	7500
Plastics	9.2	14,000
Ferrous metal	7.8	300
Glass	5.8	250
Leather and rubber	4.8	13,000
Textiles and rags	3.7	7652
Stones and ceramics	1.5	652
Nonferrous metals	0.2	13,000

The composition of solid waste has been changing over the last two decades. This is because of the changing needs of society as well as some of the process and manufacturing needs and refinements. Table 3 shows the immediate past, present, and near-term projected refuse composition.

Irrespective of the type and amount of waste, the quantity of wastes generated is increasing. From the energy availability, there are significant opportunities. In rural areas, the waste energy can be converted to useful electrical or mechanical energy. The environmental issues are of concern because the amount of pollutants emitted from wastes are often higher than that generated from clean fossil fuels, which also have high energy content. In urban areas, the energy recovery from wastes must be carried out in an environmentally benign manner. Many of the waste-to-energy conversion systems utilize extensive clean-up devices to the exhaust system. The emission of all criteria pollutants must meet federal, state, and local emission standards. In some locations, the local standards are more stringent than the federal levels. The allowed emission levels depend on the type and capacity of the system, the year of installation, and the type of fuel burnt. Table 4 gives some guidelines on the emission standards. It must be emphasized that this table should only be used as a guide. Many of the pollutants given here may have more stringent emission levels than the values given in the table. In addition, local and state standards may have additional emission regulations.

Table 2 Comparison of heating values of MSW with other wastes, refuse derived fuels, biomass, and fossil fuels[4]

Waste (fuel) type	Heating value, Btu/lb	Heating value, MJ/kg
Cellulose	7300	17.00
Lignin	9111	21.20
Wood (pine)	9600	22.30
Wood (oak)	8296	19.30
Coal (subbituminous)	11,729	27.30
Peat	8237	19.20
MSW (dry)	6968	16.20
MSW (50% moisture)	3380	7.90
Refuse derived fuel	7942	18.50

Table 3 Average composition of the past, present, and near-term projected wastes[6]

Composition, wt%, as discarded	1997	1998	1999	2000
Paper	37.4	40.1	43.4	48.0
Yard wastes	13.9	12.9	12.3	11.9
Food wastes	20.0	16.1	14.0	12.1
Glass	9.0	10.2	9.5	8.1
Metal	8.4	8.9	8.6	7.1
Wood	3.1	2.4	2.0	1.6
Textiles	2.2	2.3	2.7	3.1
Leather, rubber	1.2	1.2	1.2	1.3
Plastics	1.4	3.0	3.9	4.7
Miscellaneous	3.4	2.7	2.4	2.1
Total	100	100	100	100

Table 4 Pollutants emission standards[a]

Pollutant	Amount
Gas	
Carbon monoxide (CO)	50 ppm
Hydrocarbons (HC)	6.8
Oxides of nitrogen (NO_x)	180
Hydrogen chloride (HCl)	25
Sulfur dioxide (SO_2)	30
Solid	
Particulate	15 mg/dscm
Metal	
Lead (Pb)	0.1 mg/dscm
Mercury (Hg)	0.1 mg/dscm
Cadmium (Cd)	0.01 mg/dscm
Organic	
Dioxins/furans	0.2 ng/dscm
Opacity	10%

[a]At 7% O_2 and 293 K.

The energy recovery from wastes, although a challenge, is not really a major problem compared with environmental issues. Any waste recovery or conversion of waste to some other form of useful energy, including chemical, must be environmentally benign. The real challenge lies in making the system environmentally acceptable at reasonable costs, so that one cannot only provide permanent disposal of the waste, but also recover energy. The environmental issues are expected to become even more important in the next millenium, so that opportunities from wastes will only continue to grow in the early part of next century. We also envision significant opportunities from other types of wastes such as liquid, chemical, mixed, and industrial wastes. Because the chemical and physical properties of each type of waste is often significantly different, research and technology efforts must be implemented for various kinds of wastes to achieve clean energy conversion.

Sources, Disposal, and Recycling of Wastes

In recent decades, the increased use of plastics in domestic and industrial sectors, including automobiles, homes, boats, and aircraft, has caused serious concern on their proposed disposal. Plastics in automobiles play a major role in enhancing fuel efficiency through weight reduction and aerodynamic vehicle improvements, in addition to improving safety, durability, reduced cost, and design flexibility. As an example, the use of plastics has increased from about 86 kg (~190 lb) per vehicle in 1980 to over 150 kg (~350 lb) in 1991. These larger amounts of vehicle plastics will increase automotive shredder residue (ASR) and the proportion of plastics in ASR. It is estimated that 2 billion old tires are in America's dumps and on its roadsides, with more than 200 million added every year. Tires have a high energy content (about 30 MJ/kg or 13,000 Btu/lb) and are environmentally unfriendly because of unacceptable levels of pollutants emitted during their combustion. They are nonbiodegradable, and under normal ambient condition, they are indestructible. They attract mosquitoes and rats and cause fires that can smolder for long periods of time.

Without recycling options for automotive plastics and proper disposal of industrial, commercial, and residential wastes, the old practice of landfilling will see an increasing amount of materials that could otherwise be put to use. Decreasing numbers of available municipal landfills is escalating technology development in waste recycling and treatment. Improper disposal of household wastes, runoff of lawn and garden chemicals, and misuse and improper disposal of chemicals by businesses and institutions are important contributions to nonpoint source discharges in many states. Some of the waste that is generated may be hazardous. In many situations, the users and disposers are unaware of the environmental and economic benefits to be derived from source-reduction activities. Although many communities in the U.S. sponsor periodic waste-collection programs, and a few have permanent collection stations, only a small portion of the population is served in this way. The high costs of conducting household waste collection days have deterred wider implementation of such programs. Because household waste (both nonhazardous and hazardous) is not regulated, public education is a key ingredient in achieving proper management and reduction in the generation of these wastes. Hazardous wastes exhibit characteristics of reactivity, ignitability, toxicity, and corrosiveness, and include many household cleaners, paint and related products, automobile-related wastes, pesticides, batteries, hobby items, etc. Unfortunately, these wastes too often find their way into storm water and freshwater collection systems and eventually into streams and lakes. If these products are placed in municipal solid waste landfills or disposed of on landfills or disposed of on land, the potential of leachability and groundwater contamination, respectively, exists. If incinerated, these wastes may contribute hazardous emissions from stack and ash.

Regarding automobiles, engineers have done an outstanding job of meeting federal and local emissions standards, safety, and efficiency. However, today's vehicles are not designed for ease of disassembly and recyclability. Industry figures show that design for recycling initiatives implemented today will take about 12 years to impact recyclability. Recovery economics for plastic parts/materials are directly related to ease of disassembly, volume of material recovered per part, time to decontaminate, and value of the material. The plastic recycling industry is in its infancy, with minimal sorting, washing, pelletizing, and compounding capabilities. Current plastic recycling processes are highly sensitive to contamination. This makes intermediate processing to remove contaminants absolutely necessary. Recycling of engineering-type resins, used in automotive applications, has been limited to clean, postindustrial scrap and postuse battery cases. The costs of dismantling and removing contaminants can be up to about $1.05/kg of waste. The total cost associated with the recovery and reclamation, including the costs of transportation, distribution, and collection, can be up to $2.50/kg of plastic.

Waste Disposal Options

Several waste disposal options used to date include direct landfilling, storage in surface impoundments, physical/chemical/biological treatment, chemical stabilization, and thermal destruction. The landfilling, storage, and mass burn incineration (thermal destruction) were options of the past, so that we can only expect to see an increased rejection of these practices. The last option offers an attractive permanent disposal option for waste, because of maximum volume reduction (up to 99.9% of the original waste), energy recovery (heating value of compounds in the waste is in the range of about 12–24 MJ/kg or 5000–10,000 Btu/lb), and by-products may be used in a variety of ways. For the case of solid waste, the heating value can be enhanced by presorting the waste and removing metals and glass. Thermal destruction removes the local spatial and temporal variation from the gases evolved from solid wastes. Pyrolysis, gasification, combustion, or some combination of these processes can describe almost all types of thermal destruction processes. Chopra et al.[1] and Oppelt[2] expand on these waste disposal options. Recent texts by Brunner[5] and Niessen[6] deliberate on these incineration problems.

Based on the type of thermal destruction process selected, there are several different commercial designs and configurations of the reactor that have been utilized for a particular application. Some of the most commonly used technologies include rotary kilns, starved air incinerators, fluidized beds, mass burn incinerators, electrically heated reactors, microwave reactors, and plasma and other high-temperature thermal destruction systems.

Low-temperature oxygen/air enriched systems include rotary kiln, fluidized bed, and mass burn incinerators. These types of systems are sometimes suitable when there is no preprocessing of waste required and noncombustibles are removed prior to combustion of the waste. Fluidized beds require complex shredding and sorting of waste because of the difficulty in the removal of waste from the bed material. They offer advantages for low NO_x pollution because of their low operational temperature, around 800–850°C (~1472–1562°F). At this temperature, the oxidation of atmospheric nitrogen is negligible compared with high-temperature operating systems. However, the thermal destruction efficiency is not as high as for systems operating at higher temperatures. In size the system is large, as is the expensive postprocessing of effluents.

Low-temperature starved air systems, e.g., rotary kiln, fluidized bed, and other reactors, have been used with varying degree of success both in the combustion and pyrolysis modes. These systems are less effective and require longer residence time, of the order of hours. This translates into larger size of the system. A secondary combustion chamber is required for the oxidation of gases formed from the pyrolysis reactions in the first stage. The advantages of easy recovery of metals and glass from the residue are often not enough to offset the increased size of the system, initial cost, and postprocessing of the effluent gases. High-temperature operating systems (such as a plasma arc system) offer the advantage of reduced system size and less pollution control devices, increased the processing rate of waste, and reduced volume of the by-products.

The effectiveness and reliability of the thermal destruction system depends not only on the design and type, but is critically dependent on the operational parameters of the system, such as, operating temperature, heating rate, residence time, waste chemical composition, excess air, and chemical and thermal environment surrounding the waste. Lower pollution and higher thermal destruction efficiency requires controlled conditions throughout the waste heat up, pyrolysis, and combustion periods. Each of the thermal destruction processes involves a variety of equipment types and methods. Major differences in the processes arise from factors such as heat source, temperature, physical configuration, heat transfer medium, quantity of air used, and feed preparation.

Pyrolysis is controlled thermal decomposition of an organic material into one or more recoverable substances through the application of heat in an oxygen-free environment. The process is used to decompose cellulose, plastic, and rubber types of material into chemical products that can be reused while preserving their energy content. Pyrolysis should not be confused with incineration, which is the total oxidation of all the organic material. The end result of incineration is usually ash and metals, which may be used for landfill or construction. Pyrolysis is not new and has been used to reduce the stockpile of scrap tires in the U.S. and plastic and rubber waste in Europe. The plastics used in automobiles is roughly 22% polyurethane, 15% polypropylene, 13% polystyrene, 11% vinyl, 10% nylon, 5% polyester, and the remaining is 24% resins. All of these materials can be pyrolyzed for chemical and energy recovery. The materials from pyrolysis decompose into three major substances of pyro-gas, pyro-oil, and solid by-products. The gas is similar to natural gas in performance and can be further processed into thermoplastics: asphalt applications such as shingles or paring.

Gasification is a thermochemical process in which the organic substances are converted into combustible gases with the aid of air, oxygen, carbon dioxide, steam, hydrogen, or a mixture of these gases. Gasification has an advantage over pyrolysis because it promotes the char (residue) conversion to gas; therefore, reducing the volume of solid residue and releasing chemical energy contained in the char. Gasification is a heterogeneous solid-gas reaction. The factors that influence the kinetics of reaction in pyrolysis also influence gasification. The gasification of MSW gives rise to low to medium heating value gases as compared with high heating value gases in pyrolysis. However, the volume of gases evolved is much higher with gasification than with pyrolysis. The heating value can be increased if the material is gasified in an oxygen-enriched environment. The gasification with air or oxygen has a significant effect on the volume of gas produced and their associated heating value and the amount of remaining residue.

Thermal Destruction of Wastes

Combustion of any moisture-containing organic material takes place in the four stages of drying, pyrolysis, gasification, and combustion of the volatiles and char produced. No comprehensive scientific kinetic or burning rate data are currently available for MSW. Most of the available data are on operational experiences with a particular system. The system is often custom made or developed by a trial and error method. Significant amounts of aerospace-related research and development efforts have assisted in designing better thermal destruction systems for different kinds of solid, liquid, and gaseous wastes, but much more is needed. Studies carried out on the wood, lignin, biomass, and biomass-related materials revealed that the operating temperature, oxygen concentration, moisture content, size, and shape of feed particles has a significant effect on the burning rate (analogous to that found for various propellants). High operating temperatures or excess enthalpy combustion methods are favorable for devolatilization and evolution of gaseous products, which, in turn, assist in establishing the flame around the solid material. Available data show that the volatile burn time reduces by about 70%, i.e., from 40 to 12.5 s, with an increase in temperature from 900 to 1200°C (~1600–2100°F). It is expected that high operating temperatures (or ultrahigh temperatures within materials' limit of the incinerator) will reduce the residence time of the feed particles, and hence, the size of the reaction chamber, for the same feed rate.[1]

Additional information regarding the effects of chemical composition of waste, surrounding gas composition, flow aerodynamics, turbulence levels, temperature, heating rate, residence of feed particles, radiation, and energy feedback, using, e.g., excess enthalpy flames, will assist in the design of advanced incineration systems.[7] Generally speaking, if the waste can be incinerated, energy can be recovered from it by a properly designed system. However, some wastes contain high amounts of nitrogen (4–8% for polyurethane plastics), sulfur (from rubber), and chlorine (from plastics). This leads to excessive levels of NO_x, SO_x, chlorine, and HCl, in addition to the formation of dioxins, furans, and polycycloaromatic compounds that are known to be carcinogenic and mutagenic. In addition, some waste also contains glass and metals that could produce particulates, ash, and slag. The emission of some heavy metals can be health hazardous.[2]

Diagnostic Tools

Reference 8 provides an extensive review of the flowfield modeling and diagnostic situation, with many citations to specialized studies. Modern measurement techniques are described by Eckbreth[9] and Chigier.[10]

Basic flow visualization studies are undertaken to enable the main features of a flowfield to be characterized, including streamline patterns and recirculation zones. Usually a major portion of the flow domain is captured at once on film, and regions requiring more detailed study are quickly identified and subjected to more intense scrutiny. Recirculation zones are important to combustor designers, and the size and location of these regions in isothermal flows are readily deduced from flow visualization photographs of tufts, smoke, bubbles, and sparks responding to the experimental flowfield patterns. These techniques provide experimental characterization of corner and central recirculation zones.

Laser velocimetry, e.g., may be used for local particle and gas velocity measurements, particle size, and fluctuation measurements. The diagnostic techniques for studying turbulence effects on pulverized coal combustion are fairly well developed. Measurement of particle and gas temperature in two-phase flows is a problem but more recent studies, e.g., rainbow interferometry, show that it is now possible to measure particle size and temperature. Recent attempts on the measurement of mean and fluctuation particle temperatures, using a two-color optical pyrometer, show good promise for measuring mean particle temperatures greater than about 1000 K. Measuring particle temperatures below 1000 K using a two-color pyrometer is a problem area because of a poor signal-to-noise ratio. As long as the flow is optically thin, which is usually the case for model experiments, flow visualization, direct high-speed photography, shadowgraph, Schlieren interferometry, holography, speckle metrology, etc., is not more difficult than for gas flows. Some techniques, like direct high-speed photography, are much simpler for two-phase combustion than for gas flames, because of the strong radiation from flames. Particle sizing using photographic techniques requires the use of very bright light sources to pass through the luminous flame zone. These investigations are extremely time consuming and difficult. Multipoint conditionally sampled measurements have to be done for flame structure studies, combined probe, and visualization measurements developed, and advanced data reduction techniques applied for evaluation and interpretation purposes to be able to extract information about individual events. Especially interesting in this context is the development of controlled excitation studies that provide the convenience of investigation of the details of coherent structures via phase lock on the induced perturbations.

Significant developments are expected in the future for laser-based probes for flames and practical environments. To complete the flowfield description, temperature, major species densities, and fluctuating mass flux of the flame gases are required. In large-scale flames, optical access is a particularly difficult problem involving a full-scale dirty, vibrating, and confined environment. The development of compensating optics for aberrations introduced into the light beam is well overdue. The application of fiber optics and miniaturization of optics should be encouraged. Research activity on the miniaturization and their application to harsh and hostile environments are worthwhile.

The techniques currently being developed at a rapid pace are vibrational Raman scattering, coherent anti-Stokes Raman scattering (CARS), Rayleigh scattering, and laser fluorescence. CARS shows promise of a more sensitive method for temperature measurement in hot gases, which may be less susceptible to interference from fluorescence and particulates. This has been an active research field at various research establishments. Laser-induced fluorescence spectroscopy has been used and has the potential to measure several combustion intermediates, e.g., CHC_2, HCH, OH, NO, NO_2, HNO, C_2O, halogenated hydrocarbons, and polycyclic aromatic hydrocarbons.

Combustion Modeling

Standard texts including the application of computational fluid dynamics to chemically reacting flow situations are available.[8] The discussion here is limited primarily to the fluid dynamics aspects and aimed at alternative fuels with different physical and chemical properties than conventional fossil fuels. Here, the following three flow domains are of particular importance and can be distinguished in any two-phase combustion system: flowfields connected with injection of fuel and air, flow regions dominated by free convection currents located far away from burners, and flow along the cooled walls of the combustion chamber. Extensive reviews of the application of the classical turbulent combustion modeling methods have been presented for fossil fuels. For alternative fuels, it has been pointed out the major differences in the combustion of coal-derived liquids and shale oil in gas turbine combustors. Texts include Bartok and Sarofim[11] and Keating.[12]

Turbulent Flame Understanding

A complete and comprehensive mapping of a turbulent flame, e.g., mean and rms velocity, temperature, species concentrations and their correlations, has, as yet, not been accomplished. The developments of correlations, such as the velocity-temperature correlation $u'T'$ using, e.g., simultaneous LV and Raman scattering, should be encouraged and is now becoming a reality. This capability needs to be developed first for benchtop measurements prior to extending to scale-model measurements. Because of the highly nonlinear dependence of radiation energy flow on temperature, the average temperature is almost useless in computing local radiant heat flux. Techniques for measuring the mean and fluctuating local concentrations in large-size flames nonintrusively are also required. A comprehensive set of such detailed measurements could allow the testing and development of mathematical models. Achievement of this goal is in sight, and several investigators have demonstrated the feasibility of measuring many of the quantities and their correlations.

The development of model laws is urgently needed to account for the interaction between fluid dynamics and combustion. Both experimental and theoretical studies are needed. Extensive measurements should cover a wide range of dimensionless variables, and include mean and fluctuating data and their correlations to aid the modeler. Empirical and physical hypotheses and laws need to be further investigated, verified, and refined. Computational studies should include macro- and micro-approaches, calibrate model laws and parameters with available data, and predict phenomena outside the range of previous experimental study. Here, the efficacy of the modeling approach reveals itself. Regarding combustion studies, after success with fluid dynamic model laws with a given fuel, extension to a wider range of fuels and operating conditions are required.

There is a need to define and incorporate new finite difference schemes and/or error reduction techniques into currently existing computer code models. Improvements in accuracy of representation (differencing schemes) and rapidity of convergence (solution algorithms) are being sought before computer codes can give quantitative, rather than qualitative, predictions. Better numerics and improved understanding of inlet flow, turbulence modeling, and understanding of unsteady problems are required. Techniques for improved accuracy (including several bounded versions of skewed upwind differencing), improved versions of the pressure-velocity coupling technique, and methods for speeding convergence of iterative procedures are needed. Further information about turbulent flame understanding may be found in Refs. 13–21.

Prospects and Challenges for Energy Recovery from Wastes

Despite the gaps in technology, America today disposes of nearly 5 million tons of hazardous wastes by burning them in 184 incinerators and 171 industrial furnaces, including 34 cement kilns. This volume is equivalent to full tank trucks stretched nose to tail from Washington, D.C. to San Francisco. How we safely dispose of this great quantity of waste is an issue that affects the health and safety of all Americans. These words conjure up a picture of hundreds of thousands of tank trucks containing hazardous materials inundating our highways on their way to dump their loads at incineration facilities that pose dangers to public health. Thermal destruction combined with proven chemical engineering operations is a logical technology for reducing the volume of waste and for conversion to environmentally benign material. As a result, we have seen major growth in utilizing aerospace-related technology for waste incineration as well as in the combustion of hazardous waste in boilers and industrial furnaces. An interesting synergy exists in the use of cement kilns, which convert limestone to lime. Lime is an excellent trap for acid gases, so that burning, e.g., chlorinated organic wastes in a cement kiln, provide a solution for both the ash disposal problem and effluent gas treatment problem in one simple solution.

Waste destruction by thermal decomposition makes good technical, environmental, and economic sense. Systems can be designed to meet almost any emissions standard: oxygen could be used instead of air (even in excess enthalpy combustion systems) to achieve higher temperatures and reduce the amount of effluent gas; a catalytic afterburner could be used to ensure complete combustion of trace compounds.

Solid-gas separation systems are available for removing trace particles that can then be packaged into an environmentally benign form. Solid adsorbents can be used for final gas cleanup. Water scrubbing streams can be processed through membrane separation systems to recover dissolved mineral matter and the recycled water. Despite the availability of technology for traditional thermal destruction of waste, a fundamental need exists for a better understanding of the basics involved in thermal destruction and pollution control, cost and size reduction, in addition to the associated sociological issues. The aerospace experience obtained in the areas of fundamentals of combustion, high-temperature materials engineering, plasma physics, mixing processes, high-temperature chemistry, etc., can make major contributions to manage the growing problem of wastes. Indeed this is a particularly good opportunity for what is being termed a technology conversion.

Conclusions

It is anticipated that the amount of waste generated will continue to grow in the next millenium, along with associated changes in its composition. The utilization of energy from waste can save millions of dollars. The thermal destruction of wastes to the molecular level allows one to more cleanly convert wastes into usable energy. The challenges provide opportunities for combustion engineers, whose research is now becoming even more important. Research in combustion-related areas has expanded significantly in recent years, particularly in areas related to fossil fuels and wastes being used as fuels. Advanced combustion concepts for waste usage require a detailed understanding of the physical and chemical processes that occur during combustion. Advanced new technologies will require some tradeoff between waste fuel properties, energy conservation, efficiency, and environmental pollution control. It is a challenge for combustion engineers to handle the emerging environmental problems from wastes with spatially and temporally changing compositions.

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