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HIGHLIGHTS OF APPLIED COMBUSTION RESEARCH ACTIVITIES IN THE WESTERN WORLD

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by

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ABSTRACT

Energy forecasts indicate that the worldwide demand for thermal coal will expand significantly over the next 15 years and that most of this demand will be required to fuel dry pulverized-fired systems. Major coal development and demonstration programs are in progress to improve the energy conversion efficiency and to reduce the environmental impact of coal burning. Programs of priority interest in the western world include slagging combustion, advanced fluidized-bed designs and coal/liquid mixture technology. Basic research in support of these programs is centered around coal reactivity, ash fouling and slagging mechanisms, non-invasive flame probing and furnace modelling concepts.

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INTRODUCTION

Research on industrial flames and combustion processes has only recently evolved from an art to a science. Prior to 1960, there were few reliable systems or probes for measuring flame and heat transfer properties. In addition, burner and furnace designs were largely developed through theoretically-based, empirical calculations that were derived from full-scale operational experience with specific fuels.

In the late 1950's the International Flame Research Foundation pioneered in-flame probing and many of their probe designs are still used as "standard" equipment around the world. In the 1960's and 70's measurement techniques including continuous physico-chemical gas analyzers rapidly developed, and in the 1980's two important breakthroughs were made. The first was non-invasive flame probing by laser technology, and the second was the application of high-speed, micro-computers for data analyses of real-time measurements.

The availability of universally accepted techniques for characterizing and interpreting the complex chemical, aerodynamic, thermodynamic and geometric parameters that influence fuel utilization for heat, has since 1960, provided the stimulus for the establishment of numerous combustion research facilities around the world. These facilities are designed to duplicate or closely simulate the following full-scale combustion conditions:

a) fuel reactivity
b) suspension or fluidized-bed firing technology
c) heat transfer phenomena
d) fireside deposits and corrosion
e) pollution generation and control, and
f) process instrumentation.

Although much of the pre-1970 work was concentrated on oil and gas flames, the energy crisis of 1973 emphasized the need for both energy security and the optional use of low-grade, indigenous fuels. Consequently, the major effort in international combustion research has, for the past 10 years, centred around the expanded use of coal for both heat and electricity under environmentally acceptable conditions.

My presentation today will highlight applied flame and combustion research activities now in progress in the western world, with particular reference to those which could have application in China over the next 10 - 15 years.

A summary of the activities highlighted in this presentation is given in the following pages under three main topics: pulverized coal combustion, coal/liquid mixtures and fluidized-bed combustion.

PULVERIZED COAL COMBUSTION

Current energy forecasts predict an increasing global dependence on coal (a) to replace oil and gas in existing boilers and (b) to satisfy a significant proportion of the growth in electrical and steam generation for the remainder of this century. Furthermore, it is highly likely that pulverized-coal combustion will continue to be the dominant technology for extracting energy from coal for the foreseeable future. Research and development efforts, at present, are being concentrated on delineating and solving potential problems associated with the emerging use of unknown quality coals and coal rejects in utility boilers and with the design of new systems to burn successfully coals with widely variable moisture, ash, volatile matter and reactive maceral contents.

Combustion Performance Evaluations

In this work, unique pilot-scale furnaces are used to evaluate the behaviour of coals from newly-opened seams under practical combustion conditions and to assess potential problems in ignition, fuel burn-out, ash deposition and pollutant generation. These research rigs are being used widely to study the integrated effect of a number of controlled input parameters such as (a) fuel preparation (b) excess combustion air (c) flame type and stability (d) heat absorption (e) ash fouling and slagging propensity and, (f) particulate and gaseous emissions on system performance when high and low-quality coals are burned either separately or as a fuel blend.

The rigs, which incorporate furnaces and burners of various configurations, range in size from 5 to 2000 kg/h of fuel input and are specifically designed to investigate either a single topic such as flame or near-field mixing phenomena, or a multiplicity of operational problems including combustion performance, fly ash precipitation, fireside fouling and slaggng and control of acid rain emissions.

Validation trials in operational boilers provide the empirical or similarity correlations necessary to properly extrapolate pilot-scale data to full-scale practice.

Flame and Burner Characterization

Flame research furnaces designed for easy measurement and observation of combustion conditions are widely used to determine the effect of burner geometry and aerodynamics on fuel ignition, flame size and shape, modes of heat transfer and pollutant specie generation. They are particularly useful for relative comparisons of the burning characteristics of a known and any substitute fuel, under aerodynamically similar conditions.

Most of these furnaces are designed to have a minimum cross-sectional area of about 0.75 m^2 and a minimum fuel input of 0.7 MWt in order (a) to generate flow patterns representative of industrial-scale, turbulent diffusion flames (b) to minimize the flow disturbances caused by intrusive probing and (c) to accommodate burner designs and sizes of industrial interest.

Spatial velocities, temperatures, specie concentrations and flow patterns in real time can be obtained within the flames together with emission levels at the furnace exit. Heat transfer, both convective and radiative, can be measured along the furnace and total heat absorption rates can be altered to simulate a variety of heat processes by the addition or subtraction of cooling circuits.

Coal Reactivity Studies

To better understand the mechanisms involved in the ignition, devolatilization and char burnout regimes of turbulent coal diffusion flames, a number of controlled-mixing history reactors (CMHR) have been designed and commissioned. These units are capable of producing a simplified combustion environment typical of that which coal particles encounter as they pass through a flame, but without the added complication of aerodynamic flow patterns found in practical flames and combustors. Because of the variability of the burning characteristics of different locations, a rapid yet simple method evaluating coal reactivity is needed and it is anticipated that CMHR's will fill this need. These furnaces typically consist of a vertical ceramic tube heated from the outside by glow bar heaters. Pulverized coal (<100 μm) entrained in a flow of air, is carried from a fludized bed or other type of micro-feeder where it passes down the heater tube. The residence time of the coal is less than 1 s and the feed rate can be as low as 20 mg/s. The coal particles should be subjected to a heating rate of at least $10^4 Ks^{-1}$ in order to simulate real flame conditions.

A variety of techniques can be used to sample the devolatilization and combustion products. An incremental or a total sample probe can be inserted from the bottom of the furnace to collect an area averaged sample at any axial location. Also, optical probes can be used to measure radial and axial temperature and composition profiles along the furnace.

The reactors should preferably incorporate a microprocessor-based temperature controller to alleviate thermal shock problems as the wall temperature is increased. A computer model of the heat and mass transfer inside the ceramic tube can be developed and validated against the experimental data.

Advanced Combustion Diagnostics

The probes used at present to study large flames are usually massive, water-cooled instruments designed to withstand flame temperatures and corrosive combustion gases. Such probes, however, disturb the combustion environment into which they are placed to make measurements. For this reason, research on non-intrusive diagnostic probes for measurement of temperature, gas composition, velocity and particle size distribution within pilot-scale flames has been initiated in a number of countries, principally the United States.

The gas temperatures and species concentration measurements can be made using a Coherent Anti-Stokes Raman Spectrographic (CARS) method, and Laser Doppler Anemometry (LDA) can be used to measure both the gas velocity and the particle size distribution in a flame. In addition various flow visualization techniques such as schlieren, interferometry and shadowgraphy are in the process of development to study flow fields in tunnel furnaces.

Laser schlieren systems have been used to make high-speed cine films of the flow fields around a burning free jet, and it is anticipated that the CARS equipment can be used to map temperature fields. High speed photographs and film is also to be used to study the burning and devolatilization of single coal particles.

Furnace Modelling

Computational techniques for reliably predicting the heat transfer performance of industrial furnaces have been developed for gas and oil flames and fairly sophisticated models are being routinely applied in engineering design. The extension of these models to pulverized coal combustion systems, however, presents a number of complex modelling difficulties because factual data on particle/flow interactions, devolatilization, volatile and char combustion rates and gas/particle radiation phenomena are still very limited.

Over the next few years rapid advances in predictive methods for coal-fired furnaces can be expected as modelling specialists, combustion research laboratories and boiler manufacturers integrate their efforts to bridge the critical gaps in knowledge, that presently hinder the development of generalized models for designing furnaces with a high degree of confidence.

Low NO_x/SO_x Burners

The control of acid rain emissions is a major objective of virtually all research involving new pulverized-coal burner technology, because flue gas scrubbers have generally proven to be energy intensive, expensive and complex. At present, three concepts for simultaneous reduction of NO_x and SO_x by flame modifications are being pursued.

The first, the addition of a sulphur sorbent such as limestone or dolomite to the coal prior to pulverizing, has been most effective for high-moisture, low calorific value coals. If NO_x is not a problem because of low flame temperatures and low furnace heat release rates, no burner alterations are necessary and the sorbent is metered into the coal feed or the pulverizer inlet. Tests on a brown-coal-fired boiler have demonstrated that sulphur emissions can be reduced by 50% at Ca/S mol ratios of 3 and that $Ca(OH)_2$ is more efficiently utilized than limestone. Sorbent optimization studies to determine the benefits of increased surface area versus mass ratio are in progress and a demonstration project on a 300 MWe boiler is in the planning stage.

If both NO_x and SO_x reductions are required, for example, in a tangential fired unit, the burner arrays are designed to provide a fuel rich core and an air rich annulus with the sorbent being added to the fuel as described above. Field trials on a 300 MWe lignite boiler have yielded 50% reductions in both NO_x and SO_x.

The second, known as Limestone Injection Multi-Stage Burner (LIMB) technology, uses concentrically staged combustion to control NO_x and powdered sorbent injection to control SO_x. In this technology (a) the pulverized coal/primary stream produces a fuel-rich core having a stoichiometric ratio of about 0.6 (b) the balance of the air for combustion is added as secondary and/or tertiary air and (c) limestone or other sorbent is injected with either the secondary or tertiary air to prevent "dead burning". Reductions of up to 70% in both SO_x and NO_x have been reported and demonstration trials on a 600 MWe boiler are in progress. The reducing conditions in the primary stage of this burner favour the transformation of fuel nitrogen to N_2 rather than NO, whereas the lower temperature outer flame regions are optimal for reaction of SO_2 and CaO to $CaSO_4$.

The third utilizes a multi-stage slagging precombustion chamber with coal, and sorbent if required, being fed simultaneously through an injector. Calcium either from the coal ash or as an additive provides sulphur capture during combustion and the primary stage stoichiometry inhibits NO formation.

Pilot-scale combustor tests have indicated that 70% sulphur capture is achievable with a low sulphur coal and that NO_x emissions could be controlled to <100 ppm. This advanced burner concept, which is suitable for retrofit, has both benefits and limitations. The benefits are:

a) up to 75% ash is removed as easily disposal, non-polluting slag;
b) less ash to deposit on boiler surfaces and to remove in dust collector systems;
c) more effective utilization of calcium in coal ash and/or sorbent than LIMB, and
d) lower NO_x and SO_x levels than LIMB.

Some limitations are:

a) high-fusion ash coals are not suitable for efficient sulphur capture,
b) slag flowability controls turn-down ratios and,
c) combustor length could increase the space requirements around a boiler, especially a retrofit installation.

Future work will concentrate on designing and then field testing combustors as large as 100 GJ/h input.

COAL/LIQUID MIXTURES

The effect of the instability in world oil prices and the insecurity of off-shore supplies, coupled with the abundance of domestic coal in many countries has led to many research and technology programs on the production and combustion of coal-liquid mixture (CLM) fuels.

CLM technology provides a short to medium term energy source, which has significant potential in reducing oil consumption by power stations, industrial steam plants and process equipment that (a) was originally designed for oil-firing and (b) cannot readily be converted to alternate fuels.

Coal/oil mixture combustion has been extensively demonstrated in both utility and industrial boilers. These demonstrations have shown that mixtures containing up to 50% oil can be successfully burned in boilers designed for oil with only a minor derating. Problem areas, which included significantly increased fly ash emissions and erosion of both pumps and burner tips, led to the general use of cleaned instead of raw coal in the slurry production process.

Recently, however, coal/water mixtures have attracted widespread interest because of the excellent prospects for significantly reducing fuel costs relative to coal/oil. Coal/water slurries containing up to 75% coal with less than 1% sulphur and 1% ash can be prepared using a variety of proprietary processes, many of which involve superfine grinding to remove finely dispersed mineral matter.

The feasibility of converting an oil-fired boiler to burn coal/water mixtures depends to a large extent on the influence of the following factors on unit performance:

a) the size and depth of the radiant furnace

b) the configuration and tube spacing of the convection passes

c) fuel ignitability and carbon burn-out

d) flame length and heat release patterns

e) fouling and slagging tendency of coal ash

f) boiler derating and availability

North American computer studies suggest that the use of coal/water slurries in oil-fired tangential or front-wall fired boilers could result in reductions of up to 50% in steam output. Other studies, embracing both demonstration and research support, are underway to:

a) study the effect of atomizer design on both droplet and coal particle size on residual char agglomeration;

b) investigating the wear characteristics of various burner nozzle materials;

c) evaluating burner performance with respect to carbon burnout, excess air, NO_x, and CO emissions;

d) evaluating boiler performance with respect to efficiency, changes in heat transfer characteristics and stack gas emissions.

A separate but related development, coal/water pipelining, could substantially improve the economics and supply of either a prepared slurry or a slurry feedstock. Direct utilization of coal/water slurries from a pipeline would eliminate the need for disposal, clarification or recycling of the water carrier.

FLUIDIZED-BED COMBUSTION

The application of fluidized-bed combustion systems for energy production, although well established in China, is a fairly recent development in the western world.

Bubbling Fluidized Beds (BFB)

Bubbling beds with in-bed heat recovery have been operational for less than a decade in Europe and have only reached the demonstration stage over the past few years in North America. These bubbling beds, which are mainly installed in industrial steam boilers, are operating efficiently on highly reactive fuels including wood chips, high-volatile coal with sulphur capture and prepared waste. Research efforts in this field are continuing to:

a) demonstrate the feasibility of BFB's for utility boilers;
b) characterize limestones for sulphur capture efficiency;
c) evaluate the operational life of materials for in-bed tubes;
d) optimize bed operating parameters;
e) develop automatic controls for control of steam output and combustion conditions;
f) identify uses for spent bed material; and
g) improve distributor plate designs.

In general the combustion performance of BFB's on low reactivity fuels such as oxidized coals or petroleum coke has been only marginally satisfactory.

Circulating Fluidized Beds (CFB)

Circulating fluidized beds were pioneered in Germany and Finland. They differ from BFC's in that combustion air is admitted through the distributor plate as well as at several levels above the bed so that the gas velocity, usually over 3 m/s, always exceeds the particle fall velocity. The coal and sorbent feed for CFB's, typically $>$ 6 mm, are much finer than for BFB's. These features provide staged combustion for minimizing NO_x formation as well as total transport of any entrained fuel and sorbent particles from the freeboard. All of the coarse, partially reacted particles are collected in a hot cyclone and continuously recirculated to the bed until burn-out and sorbent reaction are essentially complete.

Some heat transfer by radiation is designed into the combustion chamber with the balance of the heat transfer by convection downstream of the hot cyclone. This arrangement prevents erosion of convection tubes by particulate matter, because over 95% of the particle mass flow from the combustor is recycled.

Perceived advantages of the CFB over the BFB are:

a) Ca/S ratios <2 for 90% sulphur capture

b) high combustion efficiency with low reactivity fuels

c) improved steam quality and load control

d) NO_x emissions <200 ppm

e) reduced bed area

f) relatively fast start-up and shut-down and

g) capability of burning both high and low reactivity fuels efficiently.

A 65 MWt CFB steam plant has been operating in Finland since 1981. It is (a) completely computer controlled, (b) co-fired simultaneously with peat, wood refuse, coal and limestone, and prepared garbage and (c) used to generate steam for electricity, district heating and paper processing steam. Another unit, under construction in West Germany, will supply 67 MW of electricity and 138 MW of steam for district heating using coal as a fuel. In Canada work has started on building an experimental 22 MWe utility boiler for research work on co-firing an 8% sulphur coal with a low grade oil shale; the calcium in the oil shale will be used for sulphur capture.

A number of pilot-scale CFB's in the 1 to 5 MWt range are being used to study the same research topics described under BFB combustion, with the combustion performance of finely sized fuels receiving priority attention.

Pressurized Fluidized-bed Combustion (PFB)

Pressurized fluidized-bed combustion (PFB) is a potentially more attractive concept for producing electricity from coal using combined power or co-generation cycles than atmospheric pressure systems because of the following factors:

a) smaller furnace bed areas and volumes for the same steam output;
b) higher combustion efficiencies without recycle;
c) lower SO_x and NO_x emissions;
d) thermal efficiency of the cycle is higher due to the use of a gas turbine generator.

Research work on PFB combustion was initiated in England in 1969 and pilot-scale facilities have been built in several countries, notably the United States. Progress has, however, been slow because of unconventional equipment requirements which are very expensive, very complex and largely unproven. Nonetheless, considerable advances have been made in understanding mechanisms associated with:

1) combustion and sulphur retention efficiencies;
2) elutriation and particle breakdown characteristics
3) in-bed heat transfer;
4) cyclone collector efficiencies and gaseous emissions;
5) dynamic response data at full and part load;
6) erosive and corrosive propensities of flue gas on in-bed and turbine blade materials.

One demonstration-scale combustor, rated at 75 MWt has been built and tested at Grimethorpe, England. The installation, originally funded under an International Energy Agency Agreement, is now the responsibility of the UK National Coal Board. The existing system incorporates a combustor with in-bed steam tubes, fuel and ash handling systems, a steam turbine/air compressor set and a cascade section to evaluate the erosiveness of ash on gas turbine blade materials.