COMBUSTION
THE PERPETUAL BURNING PROBLEM

Professorial Inaugural Lecture

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He joined the University of Nairobi in September, 1972 after having taught in Waterloo for two years as a Ph.D. student. He left Nairobi in 1975 for appointment in the Universities of the West Indies in St. Augustine (Trinidad and Tobago), Waterloo, and Dar es Salaam before rejoining the University of Nairobi in September, 1983. During this period, on different occasions he also held appointments as Post Doctoral Fellow and Research Associate.

Professor Luti has published work on analytical and computational mass fire modelling, his main area of specialization, laboratory scaling of diffusion flames, solar energy and energy utilization. He has taught in the areas of thermodynamics, heat transfer. combustion, gas dynamics, turbomachinery, and refrigeration and air conditioning. He has been involved in consultancy work in thermal science and mechanical engineering building services mainly in air conditioning and ventilation design.

Professor Luti has received many academic awards and honors, including: University of Waterloo Tuition Scholarship along with the title of "University Scholar" won as a first year undergraduate student and retained throughout the undergraduate career, Faculty and Staff Prize, Association of Professional Engineers of the Province of Ontario Undergraduate Scholarship, nominated to "Who is Who in the American Women and Men of Science", among others.

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COMBUSTION

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NATURE OF COMBUSTION

By combustion we imply the oxidation of a fuel accompanied by the liberation of heat and light. It is an exothermic chemical reaction. Essentially all that happens is that fuel and oxidizer molecules come together and under suitable conditions react to produce other species with lower chemical potentials. The difference in energy is liberated predominantly as heat. The process thus converts chemical energy inherent in the reactants into thermal energy as evidenced by rise in the temperature of the products.

It is quite safe to say that the present civilization has been bred on combustion and it is by this process that man has conquered space. Indeed the discovery and control of fire stands out as one of the greatest achievements by man and is used as a criterion to differentiate man from his ancestors. Furthermore, for the foreseeable future, man is going to predominantly depend on combustion as a source of energy. Though nuclear science may provide a viable rival source of energy, it may be many years before combustion loses its predominance.

At this stage, we could start by mentioning some of the present day broad classes of combustion equipment which burn solid (coal, charcoal, wood etc.), liquid (petrol, diesel, alcohol etc.) and gaseous (natural gas, liquid petroleum gas etc.) fuels:

(a) Stationary: heating and power production such as steam boilers for power plant and processing, stationary gas turbine and diesel engines for small scale and emergency power production, cooking, and smelting equipment.

(b) Surface mobility: automobiles, buses, locomotives, trucks and marine propulsion.

(c) Air and space travel: aircraft and rockets.

These are by-products of the beneficial aspects of combustion. At the same time we would like to operate them at the maximum possible efficiency and with the least degradation of the environment.

The undesirable face of combustion is typified by:

(a) Fires: forest, structural (domestic and industrial structures), liquid spills (liquefied petroleum gas, highly volatile refinery products), dust explosions (finely dispersed dust in the metal, plastic, chemical, agricultural, food processing, mining etc. industries).

(b) Pollution: gaseous, particulate and thermal.

Thus, besides improving the efficiency of fuel utilization and minimizing pollution, combustion science also endeavors to understand and combat hazardous fires. But before we proceed further, it is instructive to briefly look into the history of combustion science and technology as it has a very important bearing on the present state of the art.

BRIEF HISTORY OF COMBUSTION

The pioneering "experimental" work in combustion goes back to about 600,000 years before present (BP) though recent archaeological evidence suggests a much earlier date. These initial experiments involved only flame propagation rather than ignition as initial ignition was provided by Nature, principally in the form of lightning and volcanic lava. The earliest recorded experiment in combustion is provided by Greek mythology which alleges that Prometheus stole fire from Zeus, the Greek god in charge of lightning and thunderbolts. Prior to that, early man fled whenever he witnessed this terrifying manifestation of the gods. There are also other mythologies from other cultures which also testify to the terror struck on man by fire. If we are to follow Greek mythology, then Prometheus was the first (recorded) person to overcome his fear of fire and actually probe it with a stick and walk away with the fire of the gods. These early experiments also demonstrated that a very small fire can be propagated into a huge fire. Scientifically this was equivalent to demonstrating that the heat of combustion from the small fire provided activation energy for it to propagate itself into a huge fire, depending on fuel availability.

At this stage let us digress a bit and take note of the phenomenon that Nature unleashed and man could now propagate. In modem combustion jargon it is known as a diffusion flame. In a diffusion flame, (as opposed to a premixed flame), the fuel and the oxidizer are initially separated. With inter-diffusion, mixtures within the flammability limits are established. With ignition, self sustaining and propagating reaction zone (flame) is established. As may be expected, the rate of combustion is controlled by the mixing rate since in practice it is found that the reaction rate is much more faster than the mixing rate. In other words, diffusion is the rate limiting step of the process.

The diffusion flame has been the mode of combustion that has, for all practical purposes, been predominant for the first 600,000 years of combustion. It is a phenomenon that man found in Nature and has for years just continued to utilize,fundamentally unchanged! Inherent in this mode of combustion are two fundamentally wrong and dangerous assumptions, namely:

(a) that there is an infinite reservoir of fuel, and (b) that there is an infinite reservoir for combustion products.

It is not without justification that someone has referred to diffusion controlled flame as the "cave - man model" since even "modern" combustion equipment utilizing diffusion flames (by far the majority) have not substantially improved on the original diffusion flame offered by Nature.

The next milestone in combustion occurred about 30,000 years BP. This was the first artificial making of fire and really marks the real birth of combustion. Before that, man was perpetually preoccupied with "guarding the eternal flame". In the process of tool making, mechanical energy expended on drilling and chipping was converted into thermal energy (heat). When this was deposited on small quantities of combustible matter, ignition occurred. Thus man had at last usurped the powers of the gods. He had a reproducible ignition source and there was no need to maintain and transport fire as a source of ignition when and where required.

The nature of fire has been a matter of myths and religious speculation since the stone-age. As we shall soon see, the quantitative description of fire is very modern. Combustion phenomena are as a matter of fact still less well understood than,say, nuclear processes. This is due to the complexity of the phenomenon. Even the simplest flame involves several simultaneous chemical reactions, aerodynamics, and heat and mass diffusion.

Most probably the first scientific inquiry into the nature of flames was by the Greek philosopher Heraclitus about 500 B.C. who suggested that fire was the "fundamental" substance. Later, Empedocles (500-430 B.C.) put forward the proposition that fire was one of the four elements, including water, air and earth, which made up the universe. Aristotle (384-322 B.C.) accepted this proposition and due to his great prestige, subsequent philosophers up to the Rennaisance followed suit.

It was during the Rennaisance that experimentation began to supplement speculation (theory) in many areas of natural philosophy. The first experiment in combustion was performed by Francis Bacon (about 1600 A.D.) who observed the structure of the thereafter much studied candle flame. Further observations were carried out by Boyle, Hooke and Maynow during the next 75 years. During this period, a temporary digression occurred with the birth and reign of the phlogiston theory which attributed flames to the flux of an imponderable substance. However, with the birth of quantitative chemistry, a number of elements and gases were discovered and Lavoisier laid the phlogiston theory to rest and gave birth to modern chemistry at the start of the last quarter of the 18th century. This also gave impetus to the next systematic work on combustion by such famous names as Benjamin Thomson (Count Rumford of Bavaria), Humphrey Davy and Michael Faraday. Robert Bunsen, another famous name, was the first to study flame temperatures, velocities and enthalpies.

Great strides in physics, chemistry and thermodynamics during the period after Bunsen led to increased understanding of combustion phenomena. The first modern theory of flame propagation by Mallard and Le Chatelier came up in 1883 and the hydrodynamic analysis work on detonations and flames (conflagrations) by Chapman and Jouget followed between 1899 and 1913. Between the two world wars, a lot of work was done but still experimental and analytical techniques such as mass spectrometers, gas chromatographs, precision electrical and electronic equipment, computers and high purity commercial chemicals were primitive by present day standards. However, it is fair to say that most ideas of present day combustion theory were formulated during that period.

While looking at the history of combustion, it is worthwhile to look at the philosophical and practical aspects which have guided its modern development. As in other areas of early human scientific endeavor, the early combustion "researchers" were jacks of all trades. Not only were they the first cooks, first lighting and heating engineers, but later on were the first metallurgists, chemists and many other scientists and engineers as they controlled energy source. It is with some justification that Alchemists referred to fire as the "transforming element". Throughout history, combustion has been the tool used to cut into the structure of matter and was used by such famous chemists as Lavoisier and Priestley in ushering in modern chemistry. It is only very recently when man started probing the nucleus that he required a different tool.

It is worth observing that the onset of scientific advance in combustion did not take place till its science and technology separated. This occurred when mankind acquired more leisure and wealth and is marked by the birth of alchemy and the rebirth of science and natural philosophy. This separation has carried on till the present though major efforts are being put to bridge the gap.

While technology is mission oriented (concerned with making things), the motive behind basic research is curiosity and the rift between fundamental scientists and combustion based technologists took a long time for us to realize that the two occupations were related. Fundamental research in combustion (just as in all other basic scientific inquiries), is an end in itself and its success or failure should not be judged in practical applications. As a matter of fact, flames have attracted many outstanding pure scientists due to such extreme conditions in their properties as thin reaction zones with high temperature gradients (10,000 - 100,000°C/cm) and corresponding massive heat conduction, species diffusion, flow acceleration and other disequilibria; production of lots of radical reactions, wide spectra bands, and heavy concentration of ions (up to 10,000 times those at equilibrium). In particular it should be emphasized that it is important to understand the chemical kinetics of flames even if the results turn out to be too complicated to be applied predictably for the time being. One good reason for separating fundamental combustion research from potential applications is that the majority of combustion systems (applications) in use today could not apply the fruits of such researches. However, with the bridging of the gap between the two future applications can be designed based on such basic scientific findings of which there are plenty, having been accumulated since the separation.

The major drawback in the birth of more refined combustion systems based on basic scientific knowledge has been the inertia of industrialists who could not be converted due to the fallacy of "infinite" sources of fuel and product sinks. As a result, the majority of the combustion systems employed today are of the mixing - controlled diffusion flame (the cave-man model). With this in mind the next logical step is to look at the problems that are inherent in present day combustion systems.

COMBUSTION GENERATED PROBLEMS

Though the precise nature of future energy demand may be a matter of debate, like many other natural phenomena, it has an exponential growth. Unfortunately the traditional fuel resources and waste sinks are finite and whatever the value of the fuel demand growth exponent, the finite source is bound to be exhausted and/or the sink filled within a finite time. This is of course if we do not do something to arrest the trend.

In the mid 1970's energy released by combustion accounted for 96 percent of world energy demand. This figure is expected to still exceed 80 percent in the year 2000. Furthermore, in the foreseeable future, mankind will not be able to do without combustion as a source of energy. This is due to such factors as the convenience, safety, high energy content and portability of fuels. We may note that the average human being needs the equivalent of about 0.6 litre of ethanol to fuel his activities per day, and less than that if he were to use gasoline. However, in spite of these conveniences, we are still faced with the two problems of finite fuel and sink.

The problem of finite fuel resources is at least by now almost self evident and we need not address ourselves to it any further at this stage. However, the catastrophic implications of pollution is an issue that most of our industrialists and policy makers have not seriously addressed themselves to, and this only very recently. The question actually is whether it may not be too little too late. Even if we had infinite fuel resources, combustion generated pollution would impose a limit as to how recklessly we could continue exploiting them. Other undesirable serious combustion problems are,as we mentioned, associated with such hostile fire phenomena as forest and structural fires, explosions and liquid spill fires.

We now briefly expand on some of these problems.

COMBUSTION GENERATED POLLUTION

By definition, pollution is the contamination of the environment and hence any emission from the combustion systems which disturbs the natural equilibrium of the environment is a pollutant.

Before the onset of rapid industrialization, combustion generated pollution was a local and quite often a transient phenomenon. However, today the problem is permanent with global dimensions. Since the main source of world thermal energy is the combustion of fossil fuels, principally coal, petroleum and natural gas, the main cause of air pollution is emission from systems burning fossil fuels.

Besides thermal pollution, the main pollutants from these systems are gaseous with small amounts of particulate matter held in suspension. We now briefly look at the principal culprits.

Thermal Pollution

Over heavily industrialised cities, waste heat released by combustion systems can lead to local temperature gradients which can cause inversion layers. These inversions are responsible for the trapping of gaseous pollutants by preventing them from penetrating deep into the atmosphere for effective diffusion and dilution. This can lead to serious local pollution hazards. Also, with a concentration of thermal power plants where water is used as a coolant, slight rises in temperature of water in rivers or reservoirs can lead to catastrophic effects on aquatic life.

Particulate Emissions

Combustion systems have three sources of particulate emissions, namely: matter in the fuel which is not combustible, matter which is combustible but is not burned, and matter which is formed during combustion. Particulate matter which contributes to air pollution are those particles which are small enough to be borne in suspension. Though they may be visible they may be significant sources of pollution even in low enough invisible concentrations.

Under the first category above fall metals and other solid matter in fuels which pass through the flame either unchanged or as solid oxides. It is to be noted that most of these metals, under suitable conditions, are combustible and are used as fuel in rockets and other high temperature combustion systems.

Solid carbon (soot) is by far the major particulate pollutant emitted during combustion. It can be formed from gaseous fuels but is more prevalent when liquid fuels are burned. It is the main cause of (yellow) luminosity in flames, and as a matter of fact for burners that rely on radiative heat transfer, attempts are made to promote carbon formation.

On contact with cold surfaces, soot results in coking which is undesirable for example in automobile engines. For gas turbines, radiative transfer due to the presence of soot necessitates additional cooling of combustor walls, and in addition, the presence of solid particles results in pitting of or deposition on the blades. At this time, the process of formation and growth of soot is not yet fully understood.

Gaseous Emissions

In this class, the major pollutants are oxides of nitrogen (NOx), carbon dioxide (CO2), carbon monoxide (CO), organic compounds and sulphur oxides (SOx).

Nitrogen Oxides

The main source of oxides of nitrogen is the chemical reaction between atmospheric oxygen and nitrogen at high combustion temperatures. Other sources are low temperature oxidation of nitrogen in some fuels and reaction between atmospheric nitrogen and fuel derived radicals.

The important oxides in this category are: (i) nitric oxide (NO), and (ii) nitrogen dioxide (NO2). Normally NO2 emission concentration is lower though there are some cases where high concentrations have been recorded. The interplay between these two oxides in the presence of hydrocarbons and sunlight results in the formation of urban smog. NO pollution leads to feeling of physical discomfort, eye smartening, and feeling of suffocation. NO2 is a serious health hazard and is one of the most toxic commonly encountered gases.

Spark ignition engines and aircraft gas turbine engines are major sources of urban NO_x pollution. Also, NO_x emission by supersonic aircraft in the stratosphere are a contributor to ozone layer depletion.

Carbon Monoxide

This is one of the first products of combustion to be recognized as a pollutant. It is an intermediate specie in the formation of carbon dioxide in combustion. Its control can be effected rather by completion of the oxidation process than by inhibition of its formation. The main sources of urban CO pollution are aircraft jet engines and spark ignition engines.

Sulphur Oxides

Oxidation of sulphur containing compounds in fuels during combustion results in the formation of sulphur dioxide (SO_2) and sulphur trioxide (SO_3). SO_2 is easily converted to SO_3. When SO_3 is hydrated, it can condense as sulphuric acid (H_2SO_4) on cold surfaces resulting in corrosion.

It is possible to alleviate this problem by burning low sulphur content fuels, but with fuel shortage, it is necessary to burn all fuel. In practice, the only remedies are either to remove the sulphur compounds before burning or the oxides from the combustion products before emission of products to the atmosphere.

Organic Pollutants

These are as a result of unburned hydrocarbons or incomplete combustion of hydrocarbon fuels due to insufficient mixing of fuel, air and products. Some of these hydrocarbons are known to be carcinogenic and are also a factor in smog formation.

They can be reduced by high temperature combustion with a little excess air and good mixing. However this increases NO_x formation.

The main sources of these pollutants are petrol engine exhausts, crank case, fuel tank and carburettor.

Carbon Dioxide

Carbon dioxide production is inevitable as it is a desirable end in complete combustion, along with water and nitrogen. The harmful effect of CO_2 is not local but global and its gravity was not realized till very recently. Unfortunately no simple solution is foreseen short of drastically reducing the use of combustion as a source of thermal energy.

Increasing level of CO_2 concentration in the atmosphere is gradually leading to the so called "greenhouse effect", which is the progressive warming of the global environment and the melting of polar ice, which in the long run will lead to modification of climate and in particular precipitation patterns.

It is amazing that by and large combustion engineers do not seem to address themselves to the problem of CO_2 pollution. I presume it may be because we seem to have resigned ourselves to the seeming inevitability of its formation as compared to other pollutants.

The current concentration of CO_2 in the atmosphere is about 330 ppm by volume (0.033 percent) while that of about a century ago was about 290 ppm. While consumption of CO_2 by photosynthesis about balances production by animal respiration, decaying vegetation and natural fires, that from combustion caused by man is not catered for. The current annual production of CO_2 by combustion equipment is just less than 1 percent of the total atmospheric CO_2 of 2.65×10^{15} kg. The actual increase in atmospheric CO_2 is about half of that produced by combustion equipment and accounts for a concentration increase of about 1 ppm. Thus even if the level of CO_2 production were to remain constant at the current rate, its concentration would continue to increase.

Apart from increase in demand of combustion generated energy, with the increase in the price of petroleum, of late there has been a shift to the use of coal of which the world has enormous reserves. The implication of this as far as CO_2 generation is ominous. Coal combustion generates more than twice the amount of CO_2 as compared to methane combustion, and about sixty percent more than diesel combustion (for the same energy released).

The implication of all this is that the anticipated continued use of fossil fuels could trigger long term climatic changes. Furthermore, we can safely say that the "acceptable" level of fossil fuel usage is not known. We do not know what the relevant time constant is: it could be several decades, implying that irreversible changes could be trigered before their full effects are known.

HOSTILE FIRE BEHAVIOUR

Under the category of unwanted fires fall, as we have seen, wildland and urban fires, explosions and liquid spill fire.

Annually, an estimated 40 million acres of forests worldwide are destroyed by fire. The energy released is equivalent to about 15 percent of of the total world thermal energy consumption of about 2.6×10^{20} Joules. This is a very serious problem as forests are one of man's greatest resources.

Major urban fires have been recorded in history. These are caused by either military action or by accident.

Major wartime fires include those occurring in German and Japanese cities. Incendiary alternated with high explosive bombs started mass fires whose destruction of both lives and buildings was more than two thirds caused by the resulting firestorms. The highly destructive winds recorded in mass fires have been known to uproot trees of up to 900 mm in diameter and speeds of over 110 kph have often been recorded. Mass fire activity in the Japanese cities of Hiroshima and Nagasaki were caused by atomic bombs which set large areas on fire at once. The Nagasaki mass fire covered over 15 square kilometres. Some pertinent figures for some mass fire activity recorded in German cities are illustrative:

Dresden:	Area destroyed	-	20 - 28 km^2
	Loss of life	-	130,000
Hamburg:	Area destroyed	-	13 km^2
	Loss of life	-	40,000
Kassel:	Area destroyed	-	8 km^2
Darmstadt:	Area destroyed	-	3.8 km^2

In the case of the Hamburg fire which was the most violent among the German wartime fires, a turbulent convection column about 4 km high and 2.4 km in diameter developed with trees of up to 900 mm uprooted which corresponded to velocities of up to 100 kph.

Famous recorded peacetime urban fires includes the San Francisco fire of 1906 which destroyed 28,000 buildings and caused 350 million dollars worth of damage, and the 1947 Texas City fire which caused 67 million dollars in damages. Another catastrophic urban fire in Japan in 1923 caused by an earthquake resulted in fires in Tokyo which covered nearly 18 square kilometres.

Equally famous have been wildland fires which were either naturally started by such phenomena as lightning and volcanic activity, or by man. Though these tend not to attract as much attention as their urban counterparts, they are equally devastating. The Wisconsin fire of 1871 burned more than 5,000 square kilometres and killed 1,152 people. The most documented wildland fire is the Sundance fire which occurred in Northern Idaho in 1967. This burned over 200 square kilometres with the convection column at some stage towering to nearly 10 kilometres and firebrand material being deposited as far away as 16 to 19 kilometres away. Firestorm activity resulted in wind velocities of up to 190 kph and resulted in heavy timber damage.

With the encroachment of suburban development into wildland areas, large fires of the future will involve losses to both forests and cities. In the age of multimegaton nuclear weapons, it has been estimated that the area subject to immediate ignition and subsequent burn-out could range between 1200 and 3000 square kilometres, and, under certain weather conditions, one nuclear warhead could result in the burn-out of more than 25,000 square kilometres. Under these conditions, wartime critical fire phenomena will involve both wildland and urban centres.

The last two types of hostile fire behaviour though critical are of relatively small scale. Dust explosions occur in environments with finely dispersed dust. The most common dust particles are pesticides, starches, metallic and plastic powders, carbon, graphite, coal and coke dust. This phenomenon has been widely studied and is a strong function of such factors as oxygen and dust concentration inert and volatile content of the dust, moisture content, particle size and temperature, plus pressure and heat transfer characteristics of the equipment. Pools of such highly volatile refinery products as jet fuel and liquified petroleum and natural gas in transportation containers serve as serious potential fire hazards,especially with large refinery storage capacities and large liquid gas tankers plying the oceans. A recent example of this class of fire hazard occurred in the sewer system of a Mexican city. This was due to the discharge of combustible liquids into the sewers which eventually evaporated and mixed with air to form a lethal ignitable mixture which exploded with disastrous effects. Though accidents will from time to time occur, this class of fires can be prevented.

SOME MODERN TRENDS IN TACKLING COMBUSTION PROBLEMS

It has been forecast that combustion will continue to be a major source of energy for the foreseeable future, possibly for the next half million years. This being the case, combustion scientific and technological knowhow should be used to counteract as much as possible the problems created by the process of combustion.

As pointed out earlier, the predominant mode of combustion up to today is the one inherited from mother Nature, that is, the diffusion flame. Most industrial and domestic burners and even urban,and wildland fires are in this category. This, being a mixing controlled phenomenon, it cannot be influenced through changing the reaction rate. It is characterized by low combustion rates and efficiencies. It also has, and this is a serious drawback as we have seen, the attribute of automatically adjusting itself to maximize every kind of pollutant. Over and above any impurities that may be in the fuel, the reaction rate occurs close to stoichionetric contours which also correspond to maximum possible temperature and hence optimizes NO_x generation. As the fuel approaches the maximum temperature zone from the oxygen deficient side, it tends to pyrolize to soot and other products of incomplete combustion in the zone. These pollutants, on contact with cold surfaces are quenched and thus released to the environment. It is also a tragedy of Nature that even if studies of chemical kinetics were to lead to a simple method to control and increase reaction rates, this Nature given primitive mode of combustion could not make use of it.

Although there is a generally mistaken notion that combustion having been around this long there is very little to be done about it, it is not true. Due to the complexity of and multiplicity of different aspects which constitute combustion, it is only recently that serious advances have been made towards understanding some of its aspects, thus opening the road to its modelling and modifications. Also, looming fuel shortage and environmental degradation has made it economically and socially attractive to improve combustion. To a certain extent, scientific voices have, at last, ceased to fall on deaf ears. What is required is that combustion research for energy conversion should lead to methods of alleviating pollution and combating fuel depletion. It should provide technology to burn clean and efficiently, and also burn much material not hitherto considered as fuel. The stage is now set where a little more sophistication and complexity in combustion is acceptable. At the same time the necessary tools are progressively becoming available to enable us to understand the complexity of uncontrolled fire behaviour and hence alleviate its effects by taking appropriate preventive measures.

The numerous areas of combustion science and technology are very specialized but we shall take a quick qualitative look at some of the current efforts being undertaken to modify or better understand it.

MODIFICATION OF COMBUSTION FOR ENERGY CONVERSION

Premixing

We have just mentioned how undesirable the predominant diffusion flame is in nearly every aspect. A first step in improving on the diffusion flame has been by premixing the fuel and the oxidizer. This way, by altering the mixture composition, we can control such flame properties as velocity (burning rate), ignition temperature, flame temperature, flame stability criteria and soot formation, to some extent. The drawback of premixed combustion has been due to the hazards associated with storage of explosive mixtures. The solution to this has been to premix the two streams just upstream of the combustion zone. The method adopted should be able to induce large quantities of air and effect thorough mixing within a short distance. Fairly sophisticated burners using recent developments in aerodynamics, and electrical properties of flames are being adopted by industries to effectively induct and mix the required air for premixed combustion. This has resulted in great improvements on gas and volatile fuel combustion and the replacement of diffusion flame burners. In the recent past, these had been laboratory exercises.

For solid fuels and wastes, and heavy viscous liquid fuels, fluidised bed technology, hitherto not popular with combustion scientists, is being heavily researched into and novel variations peculiar to combustion technology are finding their way to industry. Due to the heat recirculation mode in fluidised bed combustion, it has been possible to: (a) burn low quality solid fuels, (b) extend the flammability limits of mixtures and hence burn lean mixtures, and (c) eliminate high temperature pollutants. With fluidised beds it is possible to raise combustion intensities and to effectively trap certain pollutants by materials added to the bed (e.g. sulphur by limestone).

However, we should note that so long as the reaction rate is potentially faster, the burning rate will be limited by the rate at which mixing of the reactants can be effected. At present, there is still a lot of work to be done in the improvement of the aerodynamics of premixed combustion and is a fruitful area for inquiry.

Heat Recirculating Burners

The most familiar use of heat recirculation in industry has been the employment of heat exchangers to preheat combustion air by means of exhaust gases whereby overall plant efficiency is raised. Other traditional aims of heat recirculation have been in production of high temperatures, for example in melting of materials, ionization of gases for MHD generators, and in burning of some pollutants. Most combustion phenomena however have a certain level of heat recirculation. The Primus burner employed in pressure lamps, blow torches and stoves uses heat from the combustion zone to vaporize and pressurize kerosene before combustion. Though these "traditional" recuperative burners are important, the focus for the future in heat recirculation lies in combustion of lean mixtures and low heat content fuels.

In premixed combustion, as it was pointed out, the flame temperature can be controlled by adjusting the air to fuel ratio. The next desirable stage is to be able to control the reaction rate independently for any initial mixture strength. One practical method is that of heat recirculation. By controlling the mixture temperature via recirculating some of the heat from exhaust gases, it is possible to raise the combustion intensity and improve flame stability since reaction rate is a very sensitive function of temperature.

There are several types of experimental and prototype burners which have been employed to burn extremely lean mixtures. For example one experimental burner has been employed to lower the lean flammability limit of methane in air mixture from the normal 5.3 percent to below 1 percent, and it is estimated that 0.22 percent is the lower limit achievable. 0.22 percent is equivalent to 1 part methane to about 454 parts air.

An important application of recupelative burners in future is in combustion for energy conversion of many potential fuels which are currently difficult to burn. These include exhaust gases from many industrial processes, lean methane/air mixtures from wastes fermenting in air and dried sewage, just to mention a few. It has been estimated that the entire machinery of the British coal industry could be powered by burning the methane exhausted from the mines during ventilation. Combustion of these weak mixtures could not only result in getting rid of pollutants but also provide energy.

Another potential use of such systems burning nearly pure air is in space heating. Since the combustion temperatures are low, no high temperature pollutants are formed and combustion production can be injected into the heated space directly. Furthermore, the saturated vapour pressure of conventional liquid fuels at room temperature would provide combustible mixtures and there would be no need to atomize the fuel, which would result in mechanical simplicity of the burner. In a good number of hospital air conditioning applications, hundred percent air is used (no recirculation) and thorough cleaning and sterilization of the air is required. Such burners burning hydrogen rich fuels could be used in heating, sterilizing and humidifying the air.

It is worth emphasizing that availability of low grade fuels will increase in the future as we move away from the one step degradation of our prime hydrocarbon fuels. With the dwindling of our hydrocarbon reserves, it will progressively make more economic sense to use these in the chemical industry first via a chain of degrading processes with combustion (of low grade fuel) as the final link of the chain.

Also we should emphasize that it makes sense both thermodynamically and pollution - wise to burn at low temperature because: (a) conventional burner systems produce high temperature gases which we have to cool down anyway before we can utilize them in most equipment due to material limitations, and (b) high temperature pollutant generation is eliminated.

Another area where heat recirculation technology is being used is in extending the upper (rich) limit of flammability. This is of use in processes where very rich mixtures are pyrolysed or partially oxidized using some of the fuel to raise the temperature of the mixture (for example in the production of carbon black). Burning ultra-rich then minimizes the fraction of the fuel needed for heat release. Burning rich can also be employed to reduce pollution from combustion of difficult fuels. It has been demonstrated that pollution can be reduced by burning rich in a first stage followed by a second lean flame zone. Burning rich can also be used to increase the burning rate. For hydrogen rich fuels, hydrogen is released during a first rich combustion stage. Since flame velocity of hydrogen is high, this results in acceleration of combustion in the second lean stage, such that the overall burning rate is increased. This results in the reduction in size of the combustion equipment.

Catalytic Combustion

About a century and a half ago, Humphrey Davy discovered that platinum wires could promote combustion reactions in flammable mixtures. These reactions seemed to take place on the surface of the wires "without flame". This was accompanied by high radiative flux characteristic of solid emission as compared to low gaseous flame emissions. This is a typical catalytic combustion. In catalytic combustion, a catalytically active additive is used to enhance heterogeneous (surface) combustion. Common catalytic combustion systems are: (a) the "Auer light" where combustion takes place on the ash residue of a fibre bag mantle surrounding the fuel/air mixture orifice. The ash mantle contains such oxides as cerium and thorium oxide which, besides constraining the radiative emission to the visible spectrum provide catalytic activity of the mantle; and (b) automotive catalytic converters which employ (precious) metal surface catalysts to oxidize low concentrations of combustibles in the exhaust to reduce pollution.

The advantages of catalytic combustion are: (a) low level pollutant emissions especially NO_x, (b) high efficiency, and (c) relatively noise free. The incentive here is to produce cheap catalysts for high temperature combustion as the current ones (e.g platinum, palladium) are expensive.

In particular, catalysts operating at temperatures of about 1500 K are required. Furthermore there is potential for catalytic combustion of such difficult fuels as residue oils, coal derived liquids, and pulverized coal.

Over the past few years some catalytic combustion systems have moved from the laboratory experimental stage to field prototypes ready for commercialization. These include: (a) gas turbines for aircraft, automobile and stationary power plants, and (b) stationary boiler systems for power or process steam. The attractive features in (b) are primarily NO_x reduction and increased efficiency due to enhanced radiative heat transfer.

Electrical Discharge Augmentation and Plasmalets

By definition, plasmas are gases which have electrically charged particles (ions and electrons). Of interest in combustion are neutral low temperature plasmas. By this we mean that the number of positive and negative charges are equal, and the temperature does not much exceed normal flame temperatures. This contrasts with high temperature plasmas encountered in nuclear fusion where species encountered at room temperatures cease to exist and chemistry becomes irrelevant. In combustion we are concerned with chemical effects and hence our interest in low temperature plasmas.

Low temperature plasmas are used widely in ignition sources; for example the low energy spark used in ignition of near stoichiometric mixtures in automobile petrol engines. However, the novel use of plasmas in combustion involves high energy plasmas; high in the sense that the energy added is comparable to that released by the combustion of the fuel by itself.

In combustion, the three ways in which plasmas can be generated are by flame reactions, shock waves, and electric discharges. Hot products of combustion are weak plasmas which can be enhanced by seeding with easily ionizable species such as alkali metals. Also, in most flames, a highly ionized zone which is involved in flame propagation exists. This is a very thin zone which has a high conductivity. This is undesirable in that electrical discharges tend to collapse to thin channels and in most applications it is necessary to spread out the discharge by seeding or turbulence created by magnetic fields or aerodynamics.

Some of the important application of plasma phenomenon in combustion are as follows:

(a) Electrically Augmented Flames

Here electrical discharges are employed to add electrical power to flame gases in order to raise the flame temperature. Thus the final flame temperature can be varied independently by chemical (fuel) and electrical inputs. Limited flame temperature rises can be achieved by use of pure oxygen as the oxidizer or preheating the reactants but these have an upper limit in the case of oxygen and a metallurgical and other fuel behaviour limitations (e.g. preignition, fuel pyrolysis and clogging) in the case of preheating. To go beyond this the other options that could be employed are: (a) radiation into the flame which is inefficient since gases are not good radiation absorbers, (b) adiabatic compression before combustion as in the internal combustion engine which is limited by auto-ignition (in petrol engines) and deposits due to fuel pyrolysis (in diesel engines), and (c) electrical discharges. Electrical discharge methods are relatively easy and not subject to any technical upper limit. The upper limit is actually set by the cost of electrical power and levels beyond which chemistry becomes irrelevant. If cheap electrical power is available, routine electrical augmentation of flames makes sense and we may even think of combustion augmented discharges. In fact there are many industrial processes such as smelting and welding where electrical power is used which could benefit from supplying some of the energy from the chemical fuel. Electrically augmented flames are envisaged for use in welding, cutting, drilling (metals and rocks), melting, smelting, sintering, reducing ores, and synthesising endothemic reaction products. It is foreseen that the last application could also be geared towards quenching high temperature pollutants to less harmful endothemic products.

(b) Continuous Plasma Jets

It has been found that continuous plasma jets can be used in flame stabilization. With up to 10 percent input of the energy of a flame electrically supplied it is possible to increase the mass throughput of a burner by 700 percent. This is of use in such applications as flame stabilization in ram jets, high altitude jet engines and other conditions which tend to extinguish flames; piloting transient high combustion throughput such as during vertical take off; general piloting of pulverized coal flames; and starting diesel engines in cold climates.

Another novel use of continuous plasma jets is in the removal of pollutants from flames. For example nitrogen plasma has been employed to remove NO from flames by the reaction of nitrogen atoms with NO to produce N_2.

(c) Pulsed Plasma Jets

These have been used to ignite weak mixtures in internal combustion engines of up to air to fuel ratios of 25 without misfire. It has also been observed that the fuel economy is enhanced and pollutant formation is reduced for these lean mixtures, and that engine performance is insensitive to timing. Pulsed plasma jet ignition has also been found to extend the rich flammability limit, to reduce carbon formation and to raise the flame velocity. This may find use in future diesel engine ignition systems.

Electric Field Effects in Flames

As has been pointed out that the flame zone is one of rapid non-equilibrium chain reactions, resulting in high concentration of ions and electrons. The moving charges can and do create magnetic fields but these are very weak due to the low velocities involved. Of much importance in combustion is that applied electric fields can be employed to manipulate the charged particles. In particular, it has been established that soot particles are invariably charged and this has led to the hypothesis that soot nucleation centres are charged ions. Thus it is possible, using electric fields to control soot formation and its removal.

Though there are many other electric field effects on flames which have been worked on, very few have been found to be of commercial use at the moment. However, this is not to imply that scientific findings in the area will not find practical application in the future.

Pulsating Combustion

The phenomenon of flame pulsation has been known since the 18th century. This is a process whereby flame properties such as pressure and temperature oscillate. It can occur spontaneously or can be forced by an external aid such as an acoustic driver or a spark plug. Though the pulsating flame has been studied since its discovery, serious interest has been renewed recently when it was discovered that it may have beneficial application in energy production.

The simplest pulsating flame is the so-called "singing flame". This can be produced by placing a gas flame anchored on a small diameter burner inside a larger tube. Large amplitudes and sound can be produced due to the excitation of one of the acoustic modes of the larger tube. Another manifestation of this phenomenon is found in gas flames especially near the blow off limit. These have been noticed to pulsate synchronously with audible beats of all orchestra (dancing flames). In general, it has been demonstrated that open flames can be drastically affected by external sound. The first attempt to utilize pulsating combustion came around the turn of the 20th century in propulsion and gas turbine power generation.

The undesirable effect of pulsating combustion is well known to all students of combustion and is referred to as "combustion instability". When this occurs in such systems as rocket motors, ram jets and power stations, the unexpected combustion oscillations can cause such undesirable side effects as component melting due to excessive heat transfer, high burning rates of solid fuel propellants, fatigue failure of mechanical components, interference with control systems, excessive noise, and flame extinction. As a matter of fact some of the results of combustion instability studies are finding use in pulsating combustion applications. Effectively, the process is a feedback mechanism between combustion and acoustic modes of the combustor whereby combustion responds to local flow oscillations.

The recent renewal in interest in the utilization of pulsating combustion has been in four main areas:

(a) Wave Engines

The variations of the wave engine utilize the combustion and/or wave motion to achieve compression which in the normal steady jet engine is supplied by a compressor (run by a turbine). The compression and ignition is achieved by a complex cyclic motion of shock and expansion waves. Experiments and theory have demonstrated that performance of wave engine drops drastically with minor deviation from the optimum, and, furthermore, it is difficult in practice to control the complex interaction between shock waves, fluid flow and combustion inside and on the boundaries. None of the models have yet reached the practical stage and a lot of work remains to be done. A practical wave engine will provide a propulsion system without any moving parts, and there are indications that it will offer enhanced overall thermal efficiency.

(b) Pulse Jets

In the pulse jet, compression occurs during combustion and again hot gases are utilized for propulsion. Initially ignition is provided by a spark plug but after that the system is self sustaining with ignition being provided by oscillating hot exhaust gases. The first practical pulse jets powered the German V-1 rockets during the Second World War but interest was lost after the war mainly due to their low efficiency. Later interest was shows in their use in VTOL and drone aircraft propulsion but lately this has waned.

(c) Gas Turbines

The pulsating combustor can be used to replace the normal steady flow combustor of a gas turbine. Since there is a pressure gain with pulsating combustion, it has been shown both theoretically and experimentally that this results in increase of the overall system efficiency and decrease in fuel consumption.

(d) Heating

A lot of work has been done in the energy production sector where pulsating combustors can be used to fire boilers and provide heat for other processes. Research and development work has been carried out for gaseous, liquid, solid, and pulverized fuels. It has been demonstrated that: (i) since pulsating combustion is accompanied by pressure gains,need for fans has been eliminated or reduced, (ii) pulsation results in improved mixing and hence more intense and efficient combustion, (iii) good mixing reduces excess air requirements and hence improvement of the efficiency as it reduces the amount of heat required for preheating, (iv) scrubbing action cleans heat transfer areas and hence enhances heat transfer while reducing the need for cleaning maintenance, and (v) reduces capital cost of boiler. Currently, pulsating combustors, mostly gas fired, are being used on a regular basis for water heating.

In concluding this section, we should note that there remains a lot of work to be done in order to understand the basic quantitive physical and chemical processes governing pulsating combustion in order to enhance further development of its applications.

MASS FIRE RESEARCH

Mass fire research started receiving serious consideration in the 1960's. A major effort was mounted by the U.S. Department of Agriculture between 1964 and 1967. This was the "Project Flambeau" whereby several large test burns were undertaken with comprehensive instrumentation. The largest of these fires covered 50 acres. One other notable test burn was later undertaken in Australia. Needless to say that these are very expensive exercises.

Another important exercise has been to study actual wildland fires (e.g. the Sundance fire) but the chances of being ready with the personnel near the site is very slim.

The reason for going to full scale test burns is that it has been found impossible to scale some of the important fire parameters in a laboratory. It has been shown that there are no less than 28 relevant dimensionless scaling parameters. Granted not all of them need to be scaled at the same time as it is possible to do repeated "partial modelling" and subsequently delineate the most important parameters controlling a fire.

However, as we have noted, some of the important parameters have proved impossible to scale in a laboratory burning fire.

Other problems also crop up with full scale tests. These are due to the fact that the phenomenon we want to simulate is not a well set one. Onset of critical fire behaviour is a combination of several parameters, some of them environmental, which we cannot duplicate and have to take them as they develop during the duration of the test burn.

As a result, the major thrust in tackling this problem has been by mathematical simulation. The ultimate goal is to simulate such large fires that the question of a test burn simulation does not arise. Here we are at liberty to vary the parameters and see their effect on the fire. Of course this is on the assumption that we can come up with a realistic model.

The most successful models to date have been based on the treatment of the mass fire as an interaction between a heat release source (boundary) and the environment. Some of the inputs into this model in the form of assumptions and some burning parameters have been predominantly from test burn observations. To date, these studies have shown that critical mass fire behaviour lies in the environment and the heat source acts only as a trigger which of course has to be sufficient to precipitate mass fire behaviour. In other words, the largest ground ignition source will not cause a firestorm if the combination of environmental parameters is not right. We should also note that even these theoretical studies have employed "partial modelling" techniques.

It has been established that the most important parameters in precipitating mass fire behaviour are the source area and intensity; relief; and such environmental parameters as stratification, wind (both the intensity and vertical profice), and humidity. Establishment of flow blocking, horizontal vortices, and waves not very different from those observed in flow over hills causes channeling of flow and hence high velocities (storms) which are the predominant cause of mass fibre havoc. Thus ignition only serves to set rolling the massive destructive energy in the atmosphere. The phenomenon is actually a forced flow situation rather than a free convection one as set up by small fibres.

The ultimate goal of mass fire,studies is to enable us to either predict how an existing mass fire will develop, and hence take the necessary evacuation measures, or design effective fire breaks to prevent their onset or spread. By knowing the flame and velocity structure we shall be in a position to predict heat transfer to adjacent fuels or flame propagation by spotting due to transport of burning solids over long distances by the high velocities. At the same time we should be aware that the same information is useful in warfare and has been used to cause mass fires and so it is a double edged sword.

CONCLUSION

In conclusion, I would like to emphasize that the combustion "problem" will be with us for the foreseeable future, whether in power generation or as hostile fire phenomena. The ensuing problems are going to be there but it is foreseeable that most will be continuously conquered or reduced to tolerable levels by combustion specialists. We should also note with alarm the trend of shifting towards such predominantly carbon fuels as coal and wood and its products as hydrocarbon fuel reserves continue to dwindle and become more expensive. This, as we have noted earlier, makes worse the CO_2 problem for which we do not seem to have a cure in sight. We have yet to understand the full impact of CO_2 on the global environmental change. When will it be too late? Is combustion a perpetual or a terminal problem? One answer gives us hope, the other despair. Let us hope it is perpetual.