Technical Challenges and Scientific Approach for a Sustainable Energy Efficient Future

Gabriel D. Roy

Abstract The energy landscape is rapidly changing and the availability of fossil fuels in abundance at affordable prices in the future cannot be assured. It is time now to focus attention to produce sustainable alternate fuels, further improve the energy conversion process, and develop new and more efficient energy conversion devices. Environmental constraints and geo physical changes restrict the selection and utilization of fuels for the future. Continuous availability of feed stock for alternate fuels at affordable prices and to convert those to fuels with required properties, as well as to control the combustion process, poses challenges. Alternate fuels for propulsion, in particular for aero-propulsion are required to meet varying and often contradicting performance parameters. These issues are elaborated and technical solutions are attempted in this chapter. Economics will play a major role in the successful use of alternate fuels. Future energy conversion devices (engines and turbines) will operate on higher pressures and temperatures and will offer challenges in the production of new materials and coatings.

Keywords High-energy-density fuels · Fuel injection strategy · Soot formation control · Alternative fuels · Noise foot print · Nano-size toxic particles

1 Introduction

The energy landscape is rapidly changing, in particular during the past few decades, and the energy demand from the developing and under developed countries is on the rise. Availability of fossil fuels in abundance at affordable prices in the future cannot be taken for granted. Along with the escalating depletion of natural resources, politics and international situations also play a role in causing uncertainties in the supply of fuel. Environmental regulations, eco awareness, and geophysical changes restrict the selection and utilization of fuels to meet full

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compliance. The challenge on the one hand is to make sure that the demand for the right type of fuels is met and on the other hand that the energy conversion process meets new standards. The technical challenges comprise of the production of the energy source (fuels), the energy conversion device (engines and turbines), and the energy conversion process (combustion/detonation) and vary with the energy application.

1.1 Energy Conversion Demands

Various criteria are to be met depending on the application such as stationary or mobile, on site, or remote site energy conversion.

1.1.1 Stationary Power

For stationary power conversion efficiency, maintenance, manpower, and environmental compliance are key factors. The goal is to have the lowest cost per kW of electricity. The energy conversion process should use efficient thermodynamic cycles, efficient components, and reliable control.

1.1.2 Road Transport

Cost of fuel, conversion efficiency, emission standards are key factors; and the aim is to get the best miles/gallon or km/liter from the fuels used. Emission regulations vary from country to country (and even state to state) requiring operational flexibility in order to be cost-effective.

1.1.3 Civil Aviation

Cost per passenger mile or km is the criterion. Lower cost of fuel, efficient engines, lower maintenance cost of aircrafts and infrastructure are the key factors including salaries of personnel (ground staff and flight crew), environmental compliance, and airport taxes.

1.1.4 Military Aviation

Thrust per unit of fuel is the major criterion. Increased energy content and density of the fuel and flexibility, wide operational envelope are key factors. Cost is an important issue now. The contradictory requirements pose additional technical challenges.

2 Scientific Approach

In order to meet the demands in energy conversion (of the afore-mentioned sectors), marginal evolutionary improvements will not suffice, rather revolutionary advances are in order. Development and production of alternate and high-energy fuels form an integral element, along with optimal conversion processes, for a sustainable energy future.

A carefully planned and well-executed international research and development program with participation from academia, government, and industry laboratories is essential with consumer interaction and participation. A "Fuels to Emissions" approach is needed in order to tackle the various aspects of the affordable, sustainable, eco-friendly energy scenario (Roy 1998). This approach comprises of the element shown in Fig. 1. In a nut shell, new fuels for specific applications need to be developed along with new thermodynamic cycles that will provide maximum conversion of the stored chemical energy of the fuels into thermal and/or mechanical energy. Basic studies targeted toward the reduced chemistry and reaction pathways of the fuels need to be done analytically, numerically and experimentally in order to burn the fuel most effectively in combustion or detonation modes. As the combustion process occurs at faster rate, pertinent diagnostics and measurement tools need to be developed. Current engines are designed for maximum efficiency, and minimum specific fuel consumption and emissions. However, even small improvements in these make a substantial impact in overall economy and ecology of the energy sector.

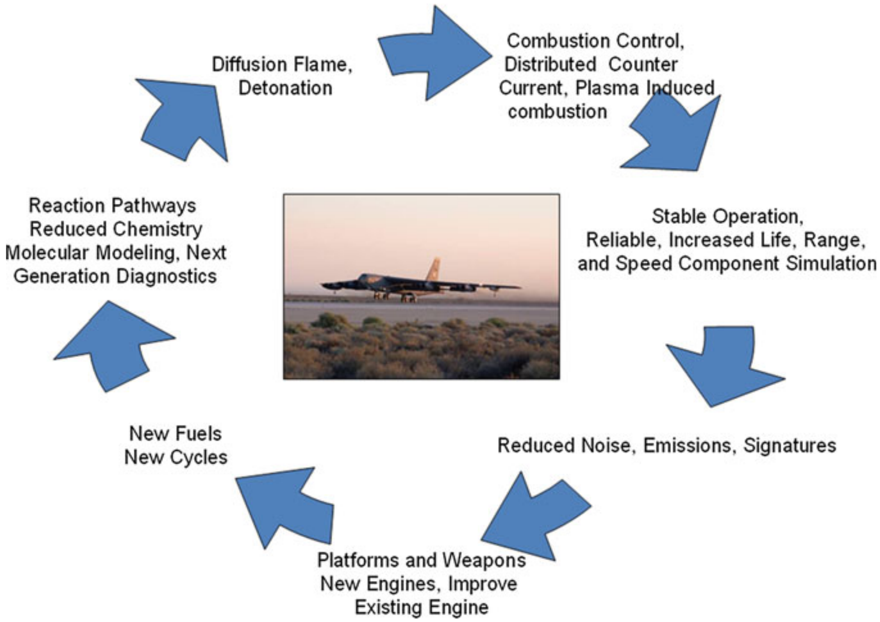

Fig. 1 Fuels to emissions approach to develop engines for stationary and propulsion applications

3 Fuels

Conventional fossil fuels are getting depleted rapidly due to the ever increasing demand. Political and economic instability causes difficulty not only in the production and acquisition of fuels, but also in transporting from place of origin to the demand sites. Nuclear energy is still controversial, and wind, geothermal, and other energy solutions are not going to be a full substitute. Under the circumstances, either new and more energetic hydrocarbon fuels or alternate fuels (such as biofuels) need to be developed. While the former provides an alternative to develop smaller engines with smaller fuel tanks to provide the same range as with a larger ones (for military applications), the latter provides a sustainable alternative for civilian and commercial applications.

3.1 High-Energy-Density (HED) Fuels

HED fuels are formed by manipulating the long-chain hydrocarbon molecules to form triangles, squares, and polygons and then further into tetrahedrons and cubes, etc. (Fig. 2). Fuels, such as, benzvalene, cubane, dihydrobenzvalene, and dimethyl cubane fall in this category.

Here, the increased density due to compacting the molecule, the strain energy added during the synthesis, and the higher carbon-to-hydrogen ratios account for the increased volumetric energy release rates.

These fuels will be of particular interest to military applications as these can increase the range and speed of a given system or provide the same speed and range

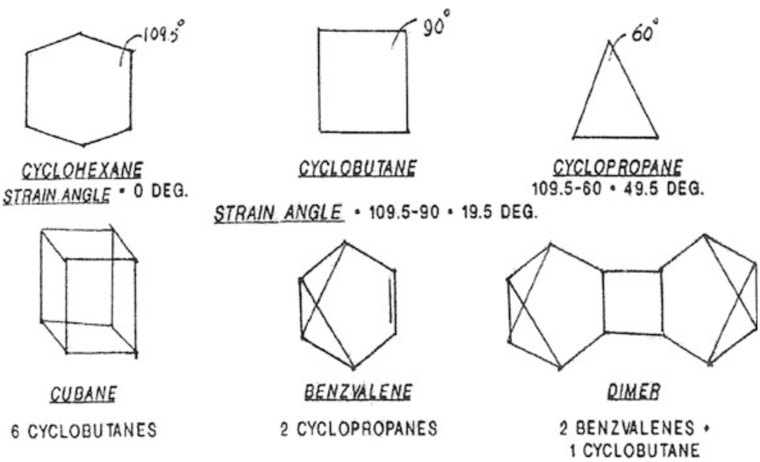

Fig. 2 High-energy-density (HED) fuels

with a smaller system. The high carbon-to-hydrogen ratio of these fuels makes higher soot emission in issue. In particular, the increased soot can increase the possibility of the source (platform) of the weapon being detected more easily. Research studies have shown that sequential timed fuel injection with respect to the incipient vortex can reduce the soot by orders of magnitude (Fig. 3). Also reactant stream velocity studies indicate that the soot production can be controlled by the relative velocity of fuel and oxidant streams (Fig. 4).

When the density of the fuels is increased, the gravimetric energy density usually decreases. But with this family of strained hydrocarbon fuels, energy density increases providing a double advantage (fuel density + energy density), thereby making it very advantageous for volume-limited propulsion systems.

However, there are several technical challenges. Fuels have been synthesized in small quantities only, and the number of steps involved in the synthesis should be reduced. Pilot plant to full-size production facility requires substantial investment. Development and facility buildup and maintenance could cost more than conventional plants. However, the advantages could justify the added cost for military applications.

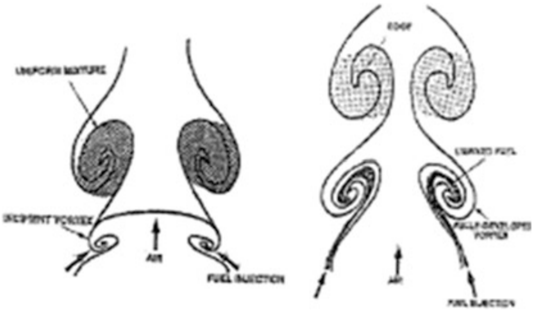

Fig. 3 Effect of sequential fuel injection

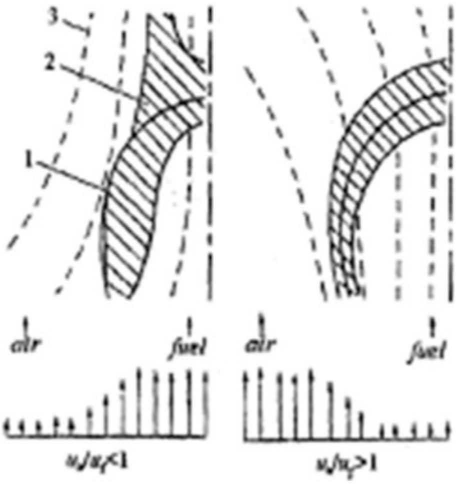

Fig. 4 Soot control by changing onsoot formation reactant stream velocity

Combustion without soot emission is still a challenge and should be addressed in large continuous combustion test facilities. Though the physical and chemical properties are similar to conventional hydrocarbon fuels, engine modifications might be necessary. Further, properties of HED fuels can vary from batch to batch.

Pioneering research in the synthesis and combustion of this type of fuels has been done over two decades ago in the United States and currently pursued in India. However, due to the limited demand of such fuels, major oil manufactures have not played an active role in the development and production HED fuels.

3.2 Biofuels

The most plausible candidate now for alternate fuels is biofuels with the potential of sustainability and has drawn international attention in the past couple of decades. Government mandates and financial support, consumer advocates and green energy supporters together with the keen interest from academia, government, and industry—in particular small business—gave a boost to biofuel development. In the United States, organizations such as Commercial Alternate Aviation Fuels Initiative (CAAFI) with participation of government, industry, and academia leaders aid in promoting biojet fuel research and development. Biodiesel fuel development also gets equal attention, and gas stations selling biodiesel fuel are common sight in Asian countries. While biofuel development based on current technologies is an evolutionary approach, there are several limitations to those.

Transesterification of vegetable oils to produce biodiesel has the disadvantage of using food sources and only limited parts of the plant source. Further, it has higher viscosity and freeze point, poor cold flow properties, and limited shelf life. Conventional hydro-processing is low in efficiency, higher in hydrogen consumption and operating costs and results in undesirable byproducts. The entire plant material is not fully utilized. In conventional biochemical conversion, and ethanol produced from starch and grains divert valuable food sources. Cellulosic biomass to fuel is still under development with challenges in hemicellulose and lignin conversion to sugar. The process produces only gasoline additive and not a biojet or biodiesel fuel. Biomass/coal gasification produces pollutants (NO_x and SO_x) and requires expensive upstream air separation. Fischer–Tropsch process, though extensively used, involves expensive liquifaction.

3.2.1 Feedstock Challenges

Biofuel production is getting serious attention from the fundamental aspects to production plants. Some of the biofuel feedstocks with their oil content are shown in Fig. 5.

Innovative technologies will need novel catalysts and reactors. Sufficient knowledge of the chemistry, process flexibility, and pretreatment requirements must

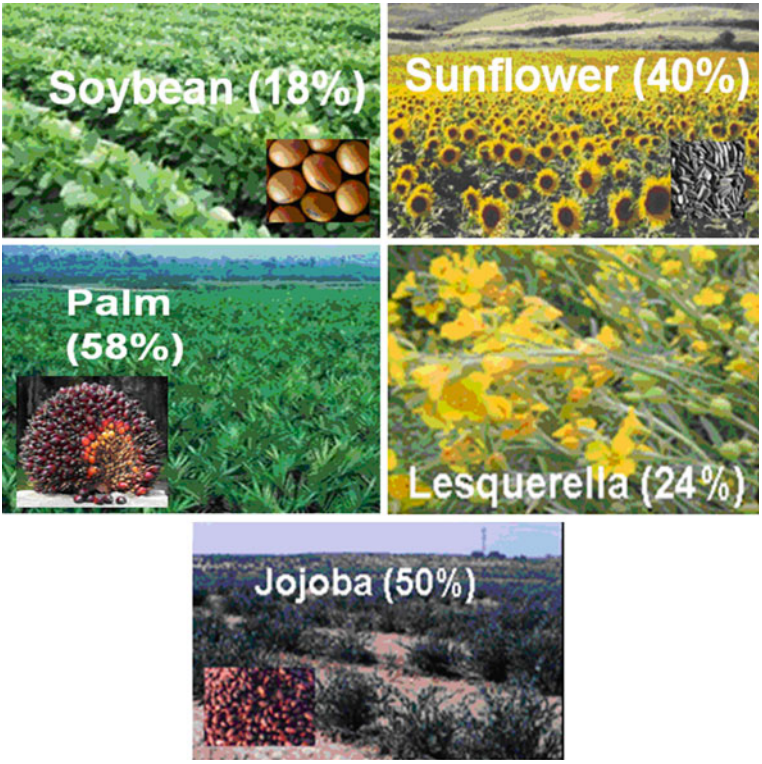

Fig. 5 Typical biofuel feedstocks and oil content

be acquired before making large investments, and the long-term availability of the feedstock also should be determined. Rather than utilizing edible feedstock, attention should be paid in using various types of algae, marine sources, cellulosic and waste materials, and grass and weeds as feedstock options. Even with the same type of feedstock (due to the nonhomogenity), the fuel characteristics can vary from day to day and even from batch to batch. This requires not only the plant to be flexible, but also the engine or energy conversion device that uses the fuel.

As the production rate increases due to increasing demand of the fuel, fuel stock required should keep up the pace. "Irrespective of crop one acre of land, pond, or bioreactor can annually yield about enough biomass to field one motor vehicle (Walker 2009). If Virgin Atlantic is to power its entire fleet, half of UK's arable land will be required to get sufficient feedstock." This limits the production capability of several nations with limited free land available for this extra production of feedstock.

Oil content from plants and seeds could be season-dependent, which may require extra expenditure in growing the feedstock. In India, though substantial investment was made in growing Jatropha including the establishment of the Center for

Jatropha Promotion (CJP) for biodiesel production, the endeavor did not succeed as planned due the lower oil content and increased water demand. The increased cost made the private companies to drop out from further investment. Though edible feedstocks such as coconut, soybean, sugarcane have good oil content, these can no longer be used because they deprive of food stock and drive up food costs. Plants with good oil content used in cosmetic and pharmaceutical industry are not logical candidate for energy production.

3.2.2 Production Challenges

As steady world economic growth cannot be taken for granted, cost of production of biofuels will play a major role—in other words, these fuels need to be produced at competitive price with conventional fuels now available. Feedstock may be cultivated at remote places, and transportation costs to get the stock to production sites could be excessive. Transportation of cellulosic and biowaste materials needs extra care. Bacteria and other organism-based fuel production require extra protection from all possible harmful consequences. When cultivation of feedstock requires a certain seasonal cycle, storage could be a challenge.

3.2.3 Performance Challenges

Several engine and flight tests have demonstrated acceptable aircraft performance with biofuels. However, consistent energy density and specific thrust are key factors for military applications in particular. (If these fuels are used in air crafts that take off from flight decks, and in those demanding strict thrust performance.) Other challenges include the shelf life, long-term stability of the fuels, possible coating formation on components (by combustion products), and CO_2 emissions.

3.2.4 Possible Benefit from Biofuels

Noise produced from aircraft jet engine exhaust had been an issue for the past several decades, and engine and airplane manufacturers have invested substantially to reduce it. Cabins in modern jet aircrafts are quieter and together with noise canceling headphones provide a comfortable space. However, the noise produced from military fighter jets is extremely high, and a person exposed to these noise levels over a short period of time can become partially or fully deaf. Figure 6 shows a comparison of noise foot print from commercial and military aircrafts. As can be seen, the noise footprint of a small military aircraft is much larger than the jumbo Boeing 747 airplane.

The exhaust from the combustion of present jet fuels contains nano-size toxic particles that can enter the cochlea through the ear canal (Fig. 7) or by conduction through the skin increasing the risk of ear injury and hearing loss—as opposed to

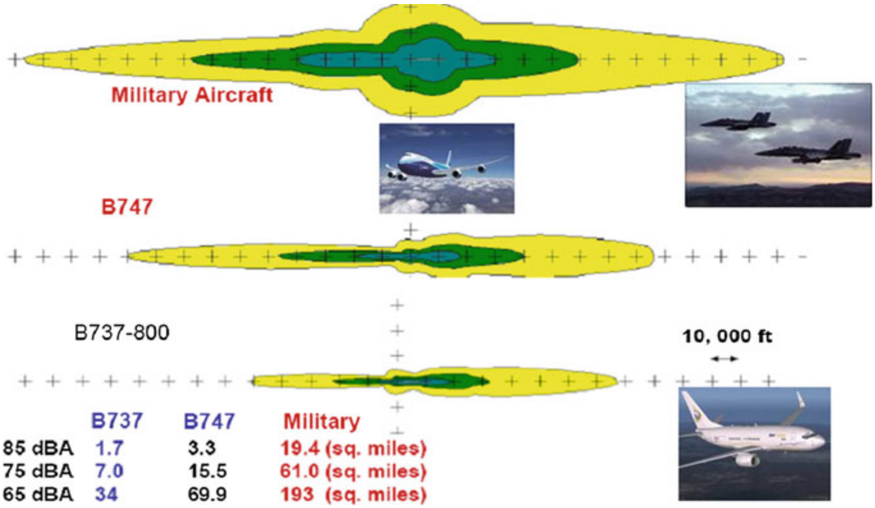

Fig. 6 Noise foot print comparison of commercial and military aircrafts (*Courtesy* Vishwanathan, Boeing Company)

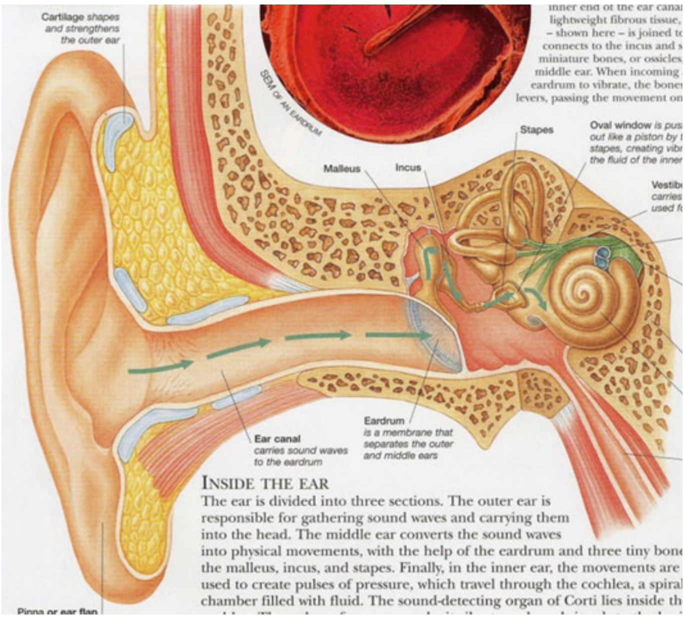

Fig. 7 Physiology of human ear

clean noise. The challenge here is, is it possible to develop less toxic biojet fuels compared to conventional fossil fuels, thereby reducing toxic emissions and reducing hearing impairment? If so, it will of great benefit to commercial and military aviation.

3.2.5 Economic Challenges

Ultimately, the land or marine biofuel must be available at competitive price (the drop in alternate fuels as envisioned by CAAFI) resulting in reduced cost/passenger mile (km) for commercial aviation, miles (km)/gallon (l) for transport, and specific thrust/gallon (l) for military aircrafts. Development of these fuels requires large investments, and the challenge is to get together governments and industries (both manufacturer and user), international collaboration, and exchange of scientific information over a long period of time. The Republic Acts, such as the Biofuel Act of 2006 and the Renewable Energy Act of 2008 executed in the Philippines, and consortia such as CAAFI, are vital for developing, coordinating, and sharing findings and promoting progress. Keeping up the momentum toward commercial production of a less toxic and sustainable biofuel is a challenge not only to the investors, but also to those who execute such programs. Continued basic research in genetically altering the algae growth and plant oil content, finding new tailor-made catalysts, bacteria interaction with cellulosic materials, biofuel combustion gas interaction with engine components, etc. will aid in reducing the development time and cost of these fuels by eliminating the unwarranted candidate fuels.

4 Combustion Challenges

Though modern power plant turbines, automobile engines, and aircraft gas turbines are designed to operate at today's maximum energy conversion efficiencies, any small further increase will result in billions of dollars of energy savings. Increasing the pressure ratios and peak combustion temperatures can result in improved performance, there are associated materials challenges. Controlling and enhancing the combustion process by various means offer the potential to improve performance.

4.1 Flameless Combustion

A recent development in the combustion process with the goal of increasing the energy release as well as reducing the heat losses is colorless distributed combustion or flameless combustion (Gupta 2003). This has been shown to produce a flat hat temperature profile, reduce NO_X formation, and improve combustion stability and

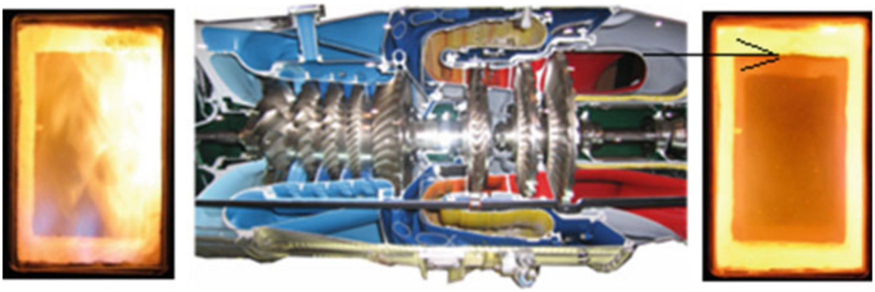

Fig. 8 Colorless distributed combustion, CDC (green combustion turbine)

efficiency. The physical color change from yellow flame to colorless flame (Fig. 8) and the reduction in exhaust temperatures have been observed at low pressures.

The challenge is to apply this to higher pressures involved in aircrafts. Though space is not a limitation in stationary applications (such as in electrical power plants), it is a challenge in aircraft engines as the add-on components will increase the weight and volume. Clever designs with minimal weight and volume penalty should be sought. Computational studies and system optimization consistent with new fuel characteristics are also challenges.

4.2 Porous Inserts

Studies have been made to evaluate performance of combustors with high-temperature foam material introduced at different locations within the combustion chamber (Ref. Agrawal). The idea is to stabilize the high-temperature combustion flow and to eliminate hot spots. High-temperature HfC/SiC-coated foam inserts at appropriate positions (as a ring at the inner periphery of the chamber) has been found to reduce combustion noise, mitigate combustion instability, and reduce CO emission (Fig. 9).

4.3 Supersonic Combustion

Supersonic combustion will play a major role in the combustion scenario in the near future due to the advent of hypersonic propulsion. For scramjet combustion, mixing of fuel and oxidant has been an issue and a number of researchers addressed this. Radial fuel injection, steps, and countercurrent combustion seem to improve the mixing and combustion. Recently, fin guided fuel injection (Ref. Yu) has shown to produce a twofold increase in fuel penetration and 45 % reduction in jet-induced shock strength (scramjets—Fig. 10).

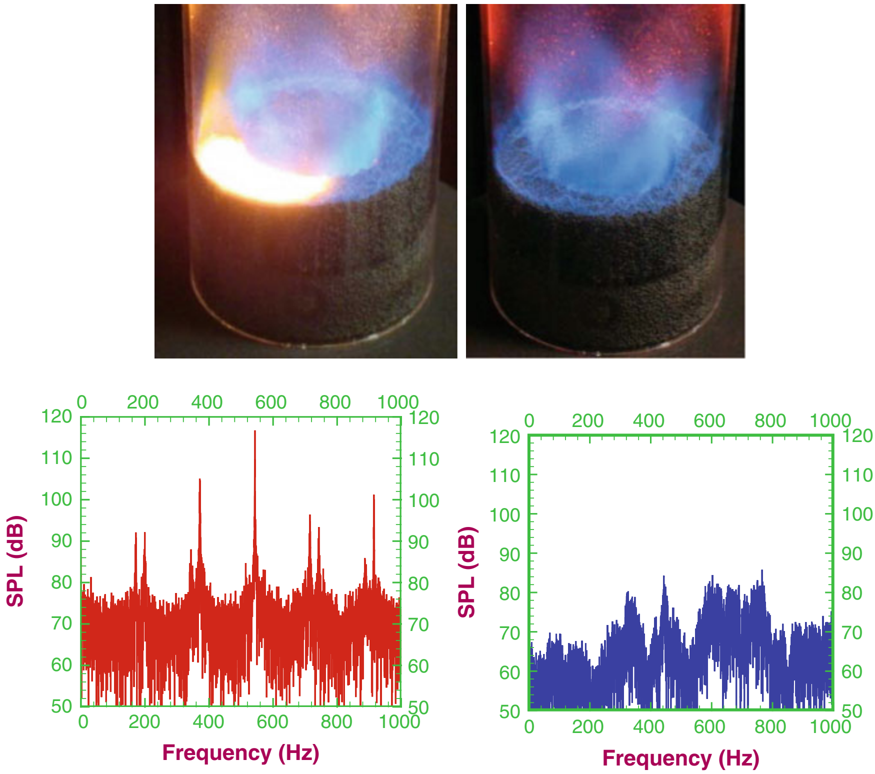

Fig. 9 Noise-level distribution in combustion chamber with foam inserts

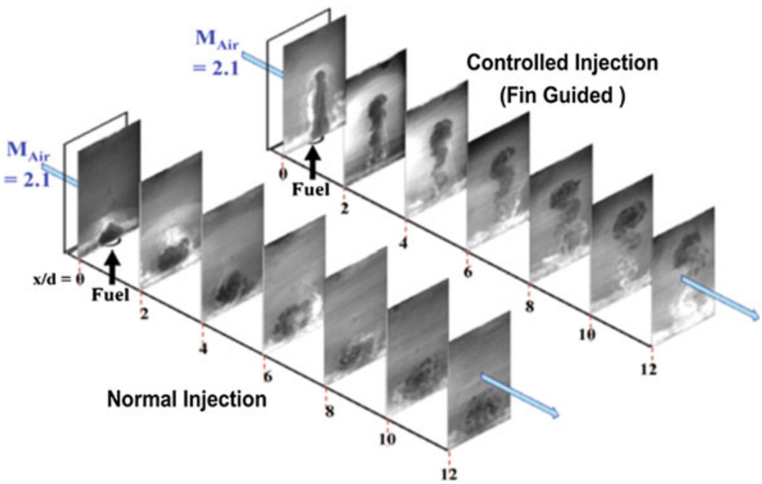

Fig. 10 Fin-guided combustion

5 Material Challenges

With the demise of the Concord aircraft, supersonic air transport came to a halt for commercial aviation. However, research and development of new engines for supersonic aircraft for military applications continues, and eco-friendly engines (low emission and noise) that operate at higher temperatures and speed pose additional challenges. Though commercial hypersonic aviation may not happen in the next few years, the challenges need to be solved as early as possible. As the speed, altitude, and operational temperatures increase, new materials need to be developed both for airframe and engine components. Hypersonic research has attracted worldwide interest, and a number of bilateral and multilateral collaborations have been signed off by several countries, and joint laboratories and development centers are already in operation. The major issues are wall cooling, environmental effects, high heat release rates, high speed flows and wall interactions, fatigue, crack propagation, abrasion, and drag. In order to solve these, research should focus on new light weight and stronger materials with fatigue and abrasion resistance. Further, self-healing coatings that heal themselves when a crack or skin damage occurs, is of interest. Other coatings include flexible coatings that will not crack when the base material is subjected to thermal and mechanical fatigue.

Research on materials and coatings for hypersonic applications will naturally benefit in manufacturing other products for longer life and eco-friendly operation.

6 Conclusions

As the energy landscape is changing, it is not prudent to depend on fossil fuels alone for the future. It is equally important to develop alternate sustainable fuels from land and marine sources, as finding new gas and oil resources. The selection of alternate fuels depends upon the natural resources and geography of the particular country. For example for countries such as Malaysia and Philippines with the extensive shore lines, algae based fuel is a natural choice. Nations with large available land areas such as the United States, India, and China, plant-based fuels present a reliable opportunity. The challenges in the production and utilization of alternate fuels, such as biofuels, must be thoroughly addressed before production to meet public and industry demand. Since economy plays a major role in the development of alternate fuels, attention should be paid to focus only on promising candidate fuels. Tailored fuels for specific applications are still in need, and clever means of converting the chemical energy contained in the fuels with maximum conversion efficiencies and minimum chemical and noise pollution need to be discovered. Functional materials, tailored coatings, and surface treatments to satisfy individual application requirements should be given utmost priority by the materials research community, as the future energy conversion systems will be operating in more demanding environments.

Interdisciplinary research, collaboration of government, producer, and consumer, and international cooperation are vital to meet these challenges and to look forward for a sustainable energy efficient future. The success of the effort will depend upon the passion and desire of those who invest and manage, and the dedication of those who make things happen.

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