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A Contemporary Study of Research on Tactical Missile Propulsion

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Abstract (not more than 200 words)

In this study, the ongoing global research pertaining to tactical missile propulsion is surveyed. The aim of the study is to find the current research trends in the areas of relevance. The topics considered include liquid rockets, solid rockets, hybrid rockets, nozzle design, solid rocket case design, propellant development, solid rocket plumes, gas turbines, liquid- and solid-fueled ramjets, combined cycles, scramjets, and pulse detonation engines.

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Rapportens titel (i översättning)
Omvärldsanalys av forskning kring framdrivning av taktiska missiler

Sammanfattning (högst 200 ord)

I den här studien ges en överblick av pågående, världsomspännande forskning inom områden som är relevanta för framdrivning av taktiska missiler. De områden som behandlas är vätskeraketer, fastbränsleraketer, hybridraketer, dysdesign, rakethöljesdesign, drivämnen, raketplymer, gasturbiner, vätske- och fastbränsleramjets, "combined cycles", scramjets och pulsdetonationsmotorer.

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Contents

Executive Summary

Syftet med föreliggande rapport/omvärldsanalys är att ge en överblick av den pågående, världsomspännande forskning som bedrivs inom områden av relevans för framdrivning av taktiska missiler.

Som utgångspunkt för studien valdes boken "Tactical Missile Propulsion" [532], utgiven 1996. Detta material delades upp sinsemellan av rapportförfattarna, som redovisade respektive ämne för de andra två i studiecirkelsliknande form. Den andra delen av studien bestod av att leta information om pågående forskning inom respektive område. För detta ändamål valdes den årliga konferens som anordnas gemensamt av AIAA, ASME, SAE och ASEE. Fördelarna med att använda detta material är dels att konferensen har mycket stor bredd samt att resultaten är "färska". Den tidsperiod som täcktes in var åren 2000–2005.

En stor del av den pågående forskningen syftar till att öka förståelsen av grundläggande förbränningsprocesser; både med numeriska och experimentella metoder.

Gasturbiner kan betraktas som ett moget område där drivkraften är att erhålla högre prestanda och/eller mindre miljöpåverkan.

Även om pulsdetonationsmotorteknologin är omogen kan man skönja en stadig trend mot fungerande system.

Det förnyade intresset för hypersonisk framdrivning har de senaste åren resulterat i ett flertal nya nationella och internationella (t.o.m. interkontinentala) forskningsprojekt. Dessa sporras naturligtvis av de lyckade friflygningsprov som skett under senare år.

Vätske- och fastbränsleramjets samt duktraketer betecknas, precis som gasturbiner, som mogna teknologier. Här finns dock ingen direkt strävan mot bättre prestanda eller mindre miljöpåverkan.

Avseende plymer från fastbränsleraketer är förståelsen ofullständig för hur modelleringen av de olika fysikaliska fenomenen som spelar in/växelverkar bör ske. På den experimentella sidan har dock framsteg gjorts; ffa. avseende detektering.

Vidare gällande fastbränsleraketer görs stora ansträngningar inom utveckling av avancerade numeriska simuleringsverktyg för att beräkna strömningsfälten (inklusive förbränning) inuti motorer.

Utveckling och provning av vätskeraketer och deras delsystem är ett mycket stort forskningsområde. Till stor del beror detta på rymdprogrammen, men resultat därifrån kan naturligtvis i stor utsträckning tillämpas även på missiler.

Toxiciteten hos nuvarande vätskeraketbränslen, t.ex. hydrazinbaserade bränslen, har intensifierat strävan att hitta icke-toxiska eller "gröna" alter-

nativ. För fastbränsleraketer är forskningen fokuserad på kompositkrut med minimal rök, baserat på t.ex. ADN, och, då rök är av underordnat intresse, på högprestandakrut med inblandning av aluminiumpulver i nanostorlek.

1 Introduction

The topic of this report is the ongoing global research pertaining to tactical missile propulsion. The basis for the study was the textbook by Jensen and Netzer, [532], and further excursions in the respective fields are based on the propulsion conferences jointly organized by the American Institute of Aeronautics and Astronautics (AIAA), American Society of Mechanical Engineers (ASME), Society of Automotive Engineers (SAE), and American Society for Engineering Education (ASEE) during the years 2000–2005.

The report is organized as follows. Section 2 describes the background for the topics of relevance for tactical missile propulsion. Section 3 is devoted to recent research and the current status of these topics. The conclusions and an outlook round up this report in Section 4.

This report was typeset by $\mathcal{A}\mathcal{M}\mathcal{S}$-LaTeX, the LaTeX macro system of the American Mathematical Society.

2 Background

In this chapter a brief account of topics of relevance for tactical missile propulsion is given. It is mainly based on [532].

2.1 Liquid Rockets

Liquid rockets use a liquid propellant that is fed, under pressure, into one or more thrust chambers from one or more tanks. The propellants then react in the thrust chamber(s), thus generating hot gases that are ejected through a supersonic nozzle and thereby give rise to the thrust.

The most obvious advantage of liquid propulsion systems, as compared to its solid counterparts in general, is the thrust management and control. Liquid propulsion systems are often considered to be too expensive for the one-time operation of tactical applications, however it is possible to design systems that are very cost-effective.

The first consideration of the system design for a liquid rocket is to decide which type of propellant to use for the specific type of mission. Here one differentiates between monopropellant rockets, where the liquid contains both oxidizer and fuel, bipropellant rockets, where liquid oxidizer and liquid fuel are stored in separate tanks, and gelled bipropellant rockets. The (current) limitation of gelled propellants to bipropellant systems is due to poisoning of the catalyst that is necessary in the monopropellant system.

The main disadvantage of a monopropellant system as compared to a bipropellant one is the lower specific impulse, approximately 200 s vs. 300 s. The monopropellant system is however very attractive from both an economical viewpoint, as the hardware is quite simple, and from a safety viewpoint, as the need for a highly reactive oxidizer is eliminated. That a simpler hardware can be used for the monopropellant rocket stem from a lower temperature of the exhaust gases (less than 1350 K) which permits the use of conventional materials. The lower temperature also lowers the signature of the rocket. By using a gelled bipropellant one adds safety as the intensity of the combustion in a spill is decreased. This comes at the cost of a slightly lower specific impulse.

A number of other factors, concerning e.g. storage, expulsion of the propellant into the thrust chamber, pressurization, toxicity, and production cost, should also be considered in the design of a liquid rocket. For a deeper coverage of these matters the reader is referred to [543, 545] and references therein.

2.2 Solid Rockets

The major advantages of solid propellants as compared to liquid ones is the high density (as designs are often volume-limited) and that they are chemically stable for many years. The two main disadvantages are the inferior specific impulse and the difficulty to vary the thrust on demand.

Solid rocket propellants of today usually contain a crystalline oxidizer embedded in an elastic polymer matrix. This type of propellant is known as a composite propellant and the solid oxidizer of choice has, for at least 40 years, been ammonium perchlorate, AP (NH_4ClO_4). The purpose of the polymer matrix, also known as the binder, is to form a solid, elastic body of the propellant ingredients with sufficient mechanical properties. The binder is also used as fuel since it mainly contains hydrogen and carbon. The most common polymer used in composite propellants is hydroxyl terminated polybutadiene, HTPB, cured with diisocyanate. Propellants based on AP and HTPB have a number of desirable properties such as low glass transition temperature, sufficient mechanical properties and high performance.

2.3 Hybrid Rockets

Hybrid rocket propulsion systems usually comprise a liquid oxidizer and a solid hydrocarbon fuel. They possess many advantages including on/off capability, improved operability of motor performance, minimal environmental impact, and most importantly an inherent safety. They are expected to meet all insensitive munitions (IM) requirements because the oxidizer and the fuel are stored separately.

2.4 Nozzle Design

The nozzle is an important component in tactical solid rocket motors (which is the focus of the chapter on nozzle design in [532]). Cost has to be kept at a minimum, while maximizing motor ballistics (i.e., pressures and burn times), exit cone thrust, while at the same time minimizing weight.

The purpose of the nozzle is to: direct subsonic motor gases, provide a ballistic throat and provide additional motor thrust. The nozzle can conceptually be divided in three distinct regions: the inlet, the throat where the choked flow maintains the chamber pressure of the motor, the exit cone were supersonic gases are expanded to obtain additional thrust.

There are two main types of of nozzles: fixed and thrust vector control (TVC) and/or movable. The different types can further be subdivided into the categories external, submerged or blast tube.

The most common type in tactical missiles are fixed, external designs without any TVC.

2.5 Solid Rocket Case Design

As the mass, size, shape, and purpose of different tactical missiles can be considerably diverse, it is clear that their design is largely individual. However, the following general considerations apply for each design of a motor case:

- Performance
- Structural
- Internal heating
- External heating
- Vulnerability
- Development/Qualification/Quality assurance

These issues will be discussed briefly below.

Apart from a performance requirement concerning the total impulse of the motor, constraints pertaining to the launch platform (e.g. mass, length, diameter, attachment points, and fittings for wings) and environmental conditions (e.g. wide temperature variations and vibrations) have to be met. The prime concern here is mass as the larger the mass of an inert component, the lower the impulse. A closely related issue is the size as larger diameters and greater length increases the aerodynamic drag, thereby reducing the available impulse. Constraints pertaining to environmental conditions are primarily dictated by the application; usability under wide temperature variations is needed for land use and the need to withstand vibrations is essential for air use.

For the structural design it is beneficial to decompose the case in its components and consider each in turn: (i) the body tube which is subjected to the main loading, consisting of internal pressure stresses, bending stresses, and local stresses at wing and launcher attachments, (ii) the end rings that provide attachments for the end closures, (iii) attachment features (e.g. launcher hooks and wing fixings), (iv) the end closures, and (v) the blast tube (which is sometimes needed for ducting hot gases past the guidance system). These components are mostly made of steel, aluminum alloys, titanium alloys, or composite materials.

The internal case insulation protects the structure against possible overheating due to the high temperature of the combustion gases in the motor. Internal insulants are mostly elastomeric as they are effective insulators, withstand high temperatures for short duration, and are fairly resistant to both chemical erosion due to reactive species and physical erosion due to particles.

When aerodynamic heating is of concern, it is necessary to use a thermal barrier to protect the propellant as its burning rate is related to the temperature. This obviously results in mass and volume penalties.

Another important aspect of the motor is its vulnerability to fragment or bullet attacks and to fuel fire. Considerable work has been done on this subject and there is also a lot of work-in-progress.

After these design considerations the motor has to be developed and qualified to see if the specifications are met. If so, predefined quality assurance tests should be undertaken.

For a deeper coverage of these matters the reader is referred to [528] and references therein.

2.6 Solid Rocket Plumes

The earliest concerns of rocket exhaust plumes were jet engine flameout, due to ingestion of the rocket exhaust gases, and plume interference with microwave guidance signals. Later, detectability by primary and secondary smoke as well as effects of smoke on optical guidance systems became important aspects. Other missile signatures such as body emissions, body scattering, and body radar cross section (RCS) are also routinely considered nowadays for plume predictions as new materials and non-axisymmetric configurations are used.

The most important factors for plume signatures are

1. Afterburning of plume fuel, e.g. carbon monoxide and molecular hydrogen, resulting in IR-, UV-, and RF-signatures

2. Base recirculation, generally resulting in more pronounced afterburning

3. Solid and liquid particles in the plume

As measurements of plume properties are expensive, especially for free flight, computational tools have been developed since the 1970s. Most of these tools are based on analytical methods, but refined computational models have been used more recently as the plume flowfields are very complex. Even though the understanding of plume effects has increased due to evolution of the computational tools, areas of incompleteness remain.

For a deeper coverage of these matters the reader is referred to [544] and references therein.

2.7 Gas Turbines

The turbine engine has many qualities which make it suitable for use in tactical missiles, of which the specific impulse perhaps is the most salient. However, the use of this type of engine in expandable systems puts higher demands on the cost of each unit when compared to turbines used in reusable vehicles. The major challenges are to be found in areas such as cost, reliability and performance. Typical performance measurements are: net thrust (sum of internal and external forces acting on the engine), specific thrust (net thrust normalized with the massflow of air), and thrust specific fuel consumption (mass flow of fuel divided by net thrust).

The actual performance of the engine depends on the performance of all of the major components composing the engine:

- Inlet.
- Compressor.
- Burner.
- Turbine.
- Nozzle.

These components have to be optimized, and since they are not independent of each other the problem of finding an "optimal" design is a formidable endeavor.

Of the different units in the list above, the design of the combustor is probably the most difficult one. It contains elements such as injection and atomization of the fuel, mixing of fuel with air, ignition of the mixture, and creating some kind of recirculation zone in order to stabilize the flame. When treated through experimental means optical methods are required to study the characteristics of the flow field, and the results from these measurements will only reveal the flowfield in limited parts of the combustor. The difficulties involved when attacking the problem by numerical means are formidable, and it has only recently become possible to obtain realistic results, e.g. by using methods such as LES (Large Eddy Simulation). With LES it has become possible to accurately simulate the interaction between the finer details of the flow field and the combustion.

2.8 Liquid Fuel Ramjets

The use of liquid fuels in ramjet engines offer several advantages as compared to the use of solid fuels. The most important are

1. Larger specific thrust
2. Higher modulation ratios
3. Compactness and optimization of available space as the fuel tank can have any shape

The disadvantage, however, is that these systems are more prone to combustion instabilities (and associated vibrations that can be harmful to both the mechanical and electrical equipment) than their solid fuel counterparts.

A liquid-fueled ramjet consists of three parts:

1. Air supply system
2. Fuel supply system
3. Combustion chamber and nozzle

The inlet collect and slow down freestream air, resulting in a pressure rise, just as for a gas turbine engine.

The fuel supply system can be divided in three separate parts:

1. Storage tank and pipes for transferring the fuel to the combustion chamber
2. Regulation system for variation of fuel flow
3. Injection system supplying fuel at the correct location and rate for efficient combustion

Its performance is essential for the combustion efficiency, the appearance of instabilities, and the ability to follow specified envelopes.

The compactness that is usually required for these systems is handled by incorporating the booster into the combustion chamber. The effect of this constraint is that the chamber must be compatible with both air intake shutoff devices and ejectable nozzles. Furthermore, the possibility to use flame stabilization devices is impaired.

Nozzles have been discussed earlier in this work, see Section 2.4.

For a deeper coverage of these matters the reader is referred to [527] and references therein.

2.9 Ducted Rockets

A ducted rocket is defined as a ramjet combustor whose fuel is injected from a gas generator where a fuel-rich solid grain is burned. The main merits of a ducted rocket is its simplicity, ruggedness, and ease of handling. These merits can favor a ducted rocket propulsion system instead of a liquid-fueled ramjet even though the performance might be halved. A ducted rocket is also less prone to flameout and to experience combustion instabilities.

The simplest ducted rockets use a fixed flow from the gas generator through a constant area-port. An end-burning grain is often used in order to maintain a constant fuel flow into the combustion chamber.

It is also possible to use a throttle valve to change the fuel injection rate from the gas generator. In practice this amounts to adjusting the exit area of the gas generator.

The above concepts both use choked flow through the gas generator throat, but at unchoked conditions the pressure changes in the combustion chamber are communicated to the gas generator and thereby control the gas generation in a self-throttling manner.

For a deeper coverage of these matters the reader is referred to [536] and references therein.

2.10 Solid Fuel Ramjets

A solid fuel ramjet is very similar to a liquid-fueled one, the differences being the type of fuel used. The main advantage of this type of engine as compared to a liquid fuel ramjet is that the energy release is not as localized, and therefore less prone to couple with the acoustics or vortex shedding frequencies of the motor. The problem with combustion instabilities is thus seldom observed.

For a deeper coverage of these matters the reader is referred to [537] and references therein.

2.11 High Mach Number Applications: Combined Cycles

Combined cycle propulsion refers to the combination of different propulsion elements in a single engine with cycle-process interaction between the elements.

The main motivation behind combined cycle engines is to take advantage of the performance advantage of the different cycles in different flight regimes. For example, a turbojet has superior specific impulse at lower speed, while ramjets excel at higher speeds. Further, it is the minimization of weight and space which leeds to the combination of the different cycles in the same engine, i.e., the sharing of common components such as inlet, combustor and nozzle.

Three different types of engines are described in [532]: turboramjet, air turborocket, ejector ramjet, which are briefly described in the sections below.

2.11.1 Turboramjet

As the name indicates this type combines the turbojet engine with a ramjet engine. Typically the switch to all-ramjet operation occurs at about Mach 3. Different types of this engine exists, a common essential feature is some kind of door which blocks the air to the turbojet at the higher Mach numbers.

2.11.2 Air Turborocket

The air turborocket, or ATR, is essentially a combination of turbojet, rocket and ramjet. The key feature of the ATR is that the turbine is not a part of the main airflow, but is separately powered by a gas generator (the rocket). This means that one typical drawback of a turbojet at higher speeds — high inlet temperatures to the turbine — is eliminated, and hence the ATR can be operated at higher flight speeds. However, at high speeds (over Mach 3) the rotation speed of the compressor has to be limited, and the engine operates essentially as a ramjet. The ATR needs to be accelerated by some kind of booster to around Mach 0.3 before it can produce adequate levels of thrust.

2.11.3 Ejector ramjet

The ejector ramjet is an air-breathing engine with one (or several) rockets situated upstream of the combustor. The gases from the rockets have momentum high enough so that it increases the combustor pressure and thereby the performance over that obtainable in a conventional ramjet. Instead ordinary fuel injectors are used to inject the fuel in the main combustor. The main advantage of the ejector ramjet over that of ducted rockets (or conventional ramjets) is the ability to produce thrust even at subsonic operation.

2.12 Scramjets

When flight in the supersonic regime (Mach 3–5) is considered, the propulsion system of choice is a ramjet. Beyond this regime, i.e. in the hypersonic regime with Mach 5–15, a ramjet with supersonic combustion, *viz.* a scramjet, should be considered. This is due to the dramatical increase of losses by the slowdown of the incoming air to subsonic speed. The major obstacle faced in supersonic combustion is the short residence time in the combustion chamber, about 1 ms, if it has a feasible length. During this short time, the fuel has to be mixed with the air and the chemical reactions have to be completed in order to achieve maximum efficiency.

For further details, see e.g. [525].

2.13 Pulse Detonation Engines

The Pulse Detonation Engine is a rather new concept, with early experiments reported in the beginning of the nineteen-forties. Up until today – to the knowledge of the authors – no flying applications powered by this engine exists, but both numerical and experimental investigations show that the PDE has several attractive characteristics:

- High thermodynamic efficiency, and hence high specific impulse.
- The principle of the engine is simple, and the engine therefore has the potential of being significantly less complex than a turbojet engine to produce (and hence less expensive).
- Applicable for a wide range of velocities, as well as having the ability to alter the thrust of the engine abruptly.
- Not limited to circular geometries, and the PDE should therefore be relatively easy to incorporate inside the structure of the aircraft.
- Can be used both in rocket- and in air breathing mode, and it would be possible to design an engine which uses the oxygen from the surrounding air while traveling at lower altitudes and uses oxygen carried on board while reaching higher altitudes.

The two main advantages of the PDE – efficiency and simplicity – are a direct result of the combustion taking place in detonative mode (which also leads to its major drawback, the noise). The cycle is efficient because of the high level of precompression due to the strong shock wave in the detonation, and the simplicity of the device is a result of the fact that the shock wave is an integrated part of the detonation and therefore precompression through mechanical devices is not necessary. In this sense the PDE is similar to both the pulse jet (e.g., the engine used for propulsion of the V-1) and the ram jet engine. But in these cases the mechanism behind the precompression is completely different.

For the pulse jet the precompression is a result of momentum effects of the gases, and are a part of the resonance effects of the engine. The resonance effects are influenced rather strongly by the external conditions of the engine, and the thrust is drastically reduced at higher speeds. Furthermore, both the specific impulse and the specific thrust is significantly lower than for turbojet or turbofan engines. This is is due to the fact that the levels of preconditioning that can be obtained through the resonance effects are rather low.

In the ram jet the precompression is obtained through the ram effects as the air is decelerated from supersonic to subsonic. The major drawback with this concept is that the engine is ineffective for speeds lower than around $Ma = 2$.

In the PDE the precompression is instead a result of interactions between the combustion and gas dynamic effects, i.e., the combustion is driving the shock wave, and the shock wave (through the increase in temperature across it) is necessary for the fast combustion to occur. In general detonations are extremely complex phenomena, involving forward propagating as well as transversal shock waves, connected more or less tightly to the combustion complex during the propagation of the entity. Due to the high temperatures introduced by the shock waves the combustion does not take place as ordinary deflagrations, but can instead be characterized as "convective explosions", see [534]. The main reason for the high thermodynamic efficiency of the PDE are the high pressure levels involved in the detonation (depending on the fuel, but 50 bar is not unusual).

The biggest obstacles involved in the realization of an air breathing PDE are the initiation of the detonation and the high frequency by which the detonations have to be repeated, [539].

Typically hundreds of Joules are required to obtain a direct initiation of the detonation in a mixture of the most sensitive hydrocarbons and air, [533, 526, 540], which prevents this method to be used in a PDE (if oxygen is used instead of air, these levels are drastically reduced, [535]). On the other hand, to ignite an ordinary flame requires reasonable amounts of energy, but a Deflagration to Detonation Transition (DDT) requires lengths on the order of several meters to be completed, see [540, 542, 538], making even this method unpractical to use.

A common method to circumvent these difficulties is to use a pre-detonator – a smaller tube or a fraction of the main chamber filled with a highly detonable mixture (typically the chosen fuel and oxygen instead of air) – in which the detonation can be easily initiated. The detonation from the pre-detonator is then supposed to transmit to the main chamber and initiate the detonation there, [530, 531]. The extra component carried on board for use in the pre-detonator will lower the specific impulse of the engine, and it is important to minimize the amount of this extra component.

Since it is essential that the combustion occurs in the form of a detonation it is crucial to understand the events involved in DDTs. These are characterized by very fast processes, by large differences in important time and space scales and by severe instabilities. Because of this they are extremely difficult to study, both by numerical methods, [541], and through experimental techniques, [542], and there are fundamental gaps in the physical knowledge concerning DDTs.

3 Recent Research and Current Status

In this chapter we consider recent research in the respective areas, based on contributions to the Joint Propulsion Conference (JPC) during the years 2000–2005.

3.1 Liquid Rockets

Since such a large part of the JPC is devoted to liquid rockets, we shall focus on propellant development in this report. During the period of interest for this study, 2000–2005, there were 45 sessions (and hence more than 300 individual papers) mainly devoted to testing of liquid rockets and their subsystems. The effort needed to cover all this material in this report was found to be too large.

3.1.1 Bipropellant development

The most commonly used bipropellant for liquid rockets is monomethyl hydrazine, MMH, in combination with dinitrogen tetroxide, N_2O_4 [313, 314, 315, 316]. This propellant combination has a high specific impulse. The ignition is obtained spontaneously on mixing in the combustion chamber. Spontaneously igniting propellants are referred to as hypergolic propellants. Hypergolic propellants are desired since it enables the engine to be restarted or to operate in pulsed mode.

Toxicological concerns about the use of hydrazine based fuels and dinitrogen tetroxide as rocket propellants have led to renewed research interest in hydrogen peroxide, H_2O_2, as an oxidant [43, 87, 242, 294, 338, 454]. Hydrogen peroxide is environmentally friendly and when combined with a suitable fuel has a high density specific impulse. Hydrogen peroxide is, however, not hypergolic with most non-toxic fuels, as different alcohols, and thus research on new hypergolic fuels are performed [40, 61, 123, 163, 220, 223, 515]. Due to the relative poor stability of hydrogen peroxide studies is devoted to its stability, compatibility and safety [42, 208, 290, 291].

Another way to improve the handling safety of liquid rocket propellants is to transform them in to a non-Newtonian gel. The benefits of gelled propellants include improved safety in storage and handling, better compliance with IM (Insensitive Munitions) requirements, lower toxicity and fire hazards, reduced leakage, spillage, and slosh problems, and higher energy density, when solids loaded [89, 90, 95].

3.1.2 Monopropellant development

Hydrazine, N_2H_4, is today the most widely used monopropellant. The last years however, there has been a considerable interest to find a possible substitute. The reason is the highly toxic nature of hydrazine, requiring costly safety measures during handling and testing. A non-toxic monopropellant is thus expected to offer substantial cost savings due to its ease of handling [317].

One of the most promising alternatives to hydrazine is energetic ionic liquids based on an oxidizer salt dissolved in a hydrocarbon fuel/water mixture. This type of monopropellants is sometimes referred to as green monopropellants and their density-impulse is up to 70% higher than hydrazine. As oxidizer salts, hydroxylammonium nitrates, HAN (NH_3OHNO_3) [94, 147, 224, 295] and ammonium dinitramide, ADN ($NH_4N(NO_2)_2$) [2, 207, 452, 520] have received particular attention.

Hydrogen peroxide is also receiving new interest as monopropellant due to its low toxicity. Hydrazine and hydrogen peroxide are decomposed in the combustion chamber using a catalyst. Due to the renewed interest in hydrogen peroxide, substantial research is devoted to the decomposition and the development of suitable catalyst beds [41, 60, 88, 209, 210, 211, 222, 292, 293, 453, 499, 516, 517].

Catalytic ignition is also considered for energetic ionic liquids. Energetic ionic liquids however, have a substantial higher combustion temperature than hydrazine or hydrogen peroxide. This and the fact that hydrazine and hydrogen peroxide and the energetic ionic liquids are very different, both physically and chemically, require development of new catalysts or alternative ignition methods [107, 221, 337, 498, 520]. This has accentuated the development of catalyst screening techniques to avoid costly trial runs and to accelerate the selection process [39, 170, 417].

3.2 Solid Rockets

Minimum smoke rocket propellants have been in use for over 60 years. The principal benefit of these types of propellants is their lack of visible signature. This enables the firing point to remain concealed and thus less vulnerable to hostile action [470]. Smoke from a propulsion system is generated when droplets or particles are formed in the exit plume. This is a problem particularly for solid propellants using ammonium perchlorate as oxidizer. To obtain composite rocket propellants with minimum smoke characteristics, other solid oxidizers than AP, such as AN, HNF and ADN [4, 7, 470] are studied.

Smoke is also generated when metals are used as fuel. For many applications there is a trade off between performance and signature, and metal particles, mainly aluminum, are often used as fuel due to its high heat of combustion. The ignition and combustion of aluminum powder are thus extensively studied [17, 21, 22, 171, 138, 199, 245, 325, 522, 523]. The last years there has been a considerable interest in the use of ultra- or nano-sized aluminum powder in solid rocket propellants since they can increase the burning rate and the combustion efficiency [100, 137, 246, 328, 354, 463, 464, 518, 521].

Good mechanical properties are essential to ensure that a solid rocket motor will perform as intended. In fact the major cause of failures is linked to the structural integrity of the propellant grain. Several papers addresses the prediction of solid propellant rocket motor grain fracture analysis and crack initiation [18, 99, 153, 462], as well as characterization of the propellants viscoelastic material properties [6, 268]. Since solid rocket propellants are based on polymer materials, they are subjected to aging due to oxidation or degradation. This will mainly influence the mechanical properties and thus the aging of propellants is an important field [5, 96, 97, 340, 445, 481, 482]. Currently costly destructive testing is used for service life evaluation of aged solid rocket motors. Non-destructive surveillance testing, using embedded sensors are thus studied [98, 510, 511].

To design and to evaluate solid rocket motors a number of ballistic computer programs have been developed [264, 265, 272, 273, 274, 524]. Designing a solid rocket motor requires that the burning rate of the solid propellant grain are known. The burning rate, and the different factors influencing it, is thus an area that is extensively studied. Due to the complexity of the combustion process, the regression rate is determined experimentally. A well established method to measure the burning rate of solid propellants is to burn a strand of propellant at a constant pressure. The burning rate can also be measured by ultrasonic techniques. This enables to measure the burning rate in an actual rocket motor [16, 76, 401, 200, 244, 444, 507]. To achieve a better understanding of the combustion, efforts are made to numerically model the combustion [19, 135, 367, 402, 438, 439, 440, 441, 479, 480, 497, 500, 519]. Some of the factors that are studied more in detail are the influence of the particle size of the AP used [15, 169, 326] and the erosion due to high cross flow velocity inside the motor [136, 323, 324, 329, 327]. The combustion of new energetic material, such as ADN, HNF, GAP and other polymers, are also studied [165, 243, 419, 478].

One severe problem concerning solid rocket motors is pressure oscillations that occur during combustion. These can in some cases lead to the failure of the motor. To understand the formation of the oscillations, and methods on how to prevent them, have received a considerable attention [20, 71, 72, 73, 74, 75, 400, 442, 446]. Pressure transients and flame spreading during ignition are also areas where a substantial amount of research are performed [46, 164, 201, 202, 203, 206, 339, 443, 508, 509].

A relatively new concept is variable thrust solid rocket motors. By using a variable thrust solid rocket motors a single missile can either fly fast to short range targets or slow to maximum range, to meet different mission requirements. Variable thrust can be achieved by using a variable nozzle throat area [341] or, to some extent, by using a double pulse motor [366]. Variable thrust solid rocket motors are believed to offer substantial benefits in the future.

One important aspect that is extensively covered in [532] is insensitive munitions, IM, technology. This area is however not well covered by the JPC. In fact only a few papers are addressing this topic thru the years [275, 470]. As the IM status and policies in the world has been considered earlier, see e.g. the FOI report [529], there is no need to repeat this here.

3.3 Hybrid Rockets

The past years have seen many significant development programs in the field of hybrid rocket propulsion [308, 349, 350, 351, 353].

Since the oxidizer and fuel-pyrolysis products are not premixed in the hybrid rocket motor, the rate of the combustion is diffusion-limited. Essentially, the combustion process is dominated by the rate of mixing and reaction of pyrolyzed fuel species with the oxidizer from the convective stream. To understand and optimize a hybrid rocket substantial efforts are devoted to develop models and theories to predict the regression rate of the solid fuel [28, 29, 84, 180, 269, 284, 287, 307, 376, 455, 456, 458, 490]. To measure the regression rate in real time, ultrasonic [28, 284] and X-ray [285, 491] techniques are used. Another way is to measure the frequency of the bulk-mode oscillation of the motor. This technique is based on the principle that the frequency is inversely proportional to the square-root of the chamber volume [288]. Combustion instability and chamber pressure oscillations are also studied [270, 271, 457, 488].

Traditional solid polymer fuels used for hybrid rocket propulsion systems have a relatively low regression rate and density impulse that limits the application to volume limited systems, as tactical missile propulsion. To overcome this, a variety of different methods has been studied. By incorporation of nano-sized energetic powder such as Al, B, W and B_4C in the solid polymer fuel the regression rate can increase by more than 100% [125, 179, 286, 412]. Another way is to increase the regression rate is to add a solid oxidizer into the solid fuel. This is referred to as mixed hybrid propellants. By adding

25% of ammonium perchlorate the regression rate can be increased by 300% [127, 306, 415, 459]. Research is also done on new fuels based on new binders and high energy density fuels such as dicyclopentadiene [27, 289], paraffin fuel [490] and metal hydrides, such as $LiAlH_4$ [289] and AlH_3 [414]. Swirl imposed in the oxidizer stream is another method to increase the regression rate. By this way the regression rate can be increased several times [126, 181, 378, 377, 489, 492].

As oxidizer for hybrid propulsion systems hydrogen peroxide have received renewed attention due to its low toxicity [37, 38, 85, 86, 178, 305, 352, 416, 501]. For the same reason, N_2O are being studied as oxidizer in some applications [124, 413, 502], as well as hydroxylammonium nitrate solutions [127].

3.4 Nozzle Design

3.4.1 2000

Erosion of material surfaces in a hot-gas valve designed to change thrust direction is a limiting design consideration. In the work presented in [44] a rhenium coating on carbon-carbon substrates was shown to be reasonable inexpensive while still providing good erosion character.

Work on defining tensile adhesion strength using various configurations are presented in [45].

3.4.2 2001

Vacuum Plasma Spray techniques (VPS) are covered in [112]. This technique makes it easier to make complex shapes of refractory metals and ceramics (e.g., Re, Hf, HfC and W/Re alloys), attractive for their high melting temperature and chemical stability.

The work by Snecma to develop a new carbon fabric for use as ablative or insulator materials in nozzles in solid rocket motors are described in [113].

In another paper from Snecma, [114], the use of carbon/carbon materials in nozzles are discussed, but here the focus is on cost reduction.

In [115] hotfire testing of epoxy adhesives in flame surface bondlines in subscale solid-rocket motor to evaluate heat-affected depth, char depth and ablation rate are described.

Side load phenomenon is caused by flow separation in the nozzle, experimental studies were this area were studied are presented in [128, 129, 130, 145, 146].

Axisymmetric Navier-Stokes simulations were used to study transient flow characteristics in compressed truncated perfect (DTP) nozzles. The results are presented in [143], and a mechanism which possibly causes serious side-load during the start-up transient were identified.

The plug nozzle offers a continuous altitude adaption up to its design pressure ratio, but is sensitive to contour deviations from the ideal one, resulting in performance losses. In [144] a review of the subject is presented.

The internal pressure distribution in a 20° thrust vectored nozzle for various pressure ratios were measured in the work presented in [166]. The data were visualized as pressure contours, and the side force were evaluated for the different nozzle pressures.

3.4.3 2002

This year there were one session dedicated to plug nozzles, [225, 226, 227, 228, 229].

Another session were concerned with high temperature materials. In the work presented in [252, 253] optical techniques were used to quantify erosion on jet vanes for thrust vector control. In [254] CFD were used to study the same subject.

3.4.4 2003

Two sessions were dedicated to liquid rocket engine nozzles, were among other things the side force in overexpanded nozzles were studied, [310, 311, 312], size effects was studied in [309] and plug nozzles were addressed in [334, 335, 336].

3.4.5 2004

Two sessions were dedicated to liquid engine rocket nozzles where the following subjects were treated:

- Side load in overexpanded nozzles are addressed in [396, 397, 398, 399].
- A project leading to a laser welded sandwich wall for use in regeneratively cooled nozzle extension are described in [395].
- Plug nozzles are treated in [430, 431].
- Resonance phenomena were described in [429], and advanced ceramic matrix composite materials are described in [432].

Another session was titled “Exhaust Systems”, and in [423] the use of fluidic injection to reduce drag were studied.

Under the assumption that the flow is isentropic, the authors of [424] managed to obtain an asymptotic solution to Stodola’s area Mach number relation, i.e. given the area relation this method makes it possible to calculate the exit Mach number without having to rely on numerical root finding or tabulation.

The exhaust plume of a tactical missile were simulated in the work presented in [425]. A combination of Parabolized Navier-Stokes and Navier-Stokes were used in the simulations, and according to the authors this was the first time simulations of the total configuration under angle of attack conditions were simulated.

3.5 Solid Rocket Case Design

It appears that the JPC series is not the correct forum for this topic. During the period 2000–2005 there were only two sessions: “Composite Motor Cases, Pressure Vessels and Structures” (in 2001) and “Materials and Component Technology — Composite Cases” (in 2005). The papers [154, 155, 156, 157, 465, 466, 467, 468] consider composite cases, while [469] treats qualification.

3.6 Solid Rocket Plumes

In 2000 there were four contributions to the JPC; all concerning numerical simulations. Prediction of base flow/plume interaction including 3D and real gas effects are considered in [3], an analytical approach to determine plume-heating effects is found in [8], flowfield and radiation simulations of exhaust plume of a generic booster in [25], and a new space-marching technique for exhaust plume simulations was given in [26].

In 2002 there was only one contribution in this area. This paper, [263], treated simulations of particulate dispersion in exhaust plumes.

Also in 2005, there was only one contribution in this area. This paper, [506], presented the development and evaluation of a modeling capability for assessing rocket plume damage to launch vehicles.

During 2001, 2003, and 2004 no papers pertaining to solid rocket plumes was presented.

3.7 Gas Turbines

3.7.1 2000

The efforts can be divided into experimental work, computational work and analysis. The subjects treated can loosely be divided in the following areas:

- Emission and noise.
- Stability and combustion control.
- Evaluations of system performance, where all components are considered.
- Studies of single components, e.g., inlets, compressors, injectors, combustors, turbines.

Quite a few papers were using different numerical methods to study different aspects of turbine engines. In one paper, [1] the authors used LES to study combustion dynamics in a liquid fuel combustor. Other used Navier-Stokes and Euler solvers, and different types of turbulence models, e.g., see [9, 10, 11, 12, 13, 14, 24, 30, 32].

Hardly any of the papers dealt with innovative designs, but were instead studying methods, either numerical or experimental, which can be used in the quest for improvements (be it performance, reliability or cost).

In the work presented in [31] an array of synthetic jets were used to control the mixing of fuel and air, in order to improve entrainment and mixing.

Regarding optimization of the complete engine, genetic algorithms were used in the work presented in [70], and reported to work quite well.

3.7.2 2001

This year the following sessions dealt with subjects of interest in gas turbines:

- CFD-Turbomachinery.

  In this session among other things validation of a Navier Stokes code with different turbulent models, [79], mesh generation [80], and a 3-D streamline approach and a quasi 3-D approach, [81] with the purpose of reducing the computational time required to analyze transonic rotors, were treated.

- Gas Turbine Combustion and Heat Transfer.

  Here among other things the influence of distribution of swirl on the global flame behavior, [91], were treated.

In [92] a methodology of calculating the temperature of the liner in the combustor, and in [93] different arrays of injectors, and various orifice sizes were used in flame tubes, and the effect of NOx emission were studied.

- Combustion.

  In [104] the flow field in a two-stage turbine flow meter were studied using a Navier Stokes code, one million cells were used in the calculations.

  Combustion instability control, and the use of an adaptive stable controller was studied in the work presented in [105]. The purpose of such a device is to prevent flame extinction under stringent emission requirements.

  In an effort to reduce NOx emissions an LPP (lean premixed prevaporized) combustor was studied in [106]. The particular burner suffers instability problems, and a control mechanism was used to relax these problems.

- Gas Turbine Combustion.

  In [108] a "Problem Solving Environment" (PSE) was used for creating reduced kinetic mechanisms for combustion systems.

  The generation of a flamelet library for nonpremixed flames in syngas/air is described in [109]. These flamelets were parameterized both by the scalar dissipation rate and the "enthalpy defect" (the difference between the actual enthalpy and the enthalpy of an adiabatic flamelet with the same elemental composition).

  Spray combustion in a gas turbine combustor was studied using Large Eddy Simulation in the work presented in [110]. The results of this work show that droplets accumulate in low vorticity regions.

  In [111] a lean direct injection (LDI) combustor was analyzed with a Reynolds Stress Turbulence Model. The results from these simulations were compared with results from experiments using laser-Doppler velocimetry data and with results from the National Combustion Code using a cubic non-linear k-ε model. The results of this study confirmed the inadequacies of the k-ε model when treating complex flow fields where separation, strong anisotropy and high swirl are present.

- Fuel Injectors and Fuel/Air Preparation.

The structure of the internal two-phase flow inside an aerated-liquid injector was studied in [131]. Among other things it was found that improved spray atomization can be achieved for aerated-liquid that have co-annular two-phase flows inside the discharge passage.

In [132] a new "sheet breakup model" were evaluated in a swirl coaxial injector.

A 3-D analytical model to predict the instability of a swirling annular liquid sheet between swirling air streams is described in [133]. This model was used to evaluate the atomization process under different conditions.

In [134] the effects of swirlers in a MultiPoint Lean Direct Injection burner were studied. To this end the National Combustion Code (NCC) was used, and the cubic non-linear k-ε model was used. Two to three million computational cells were used in the computations.

- Gas Turbine Combustion and Fuels.

  In [148] eight different coherent flame models were evaluated in simplified ramjet calculations where a flamelet model was used to simulate the combustion.

  A study were experimental data from CARS measurements were compared with results from numerical simulations with different models for turbulence and combustion are presented in [149]. One of the conclusions from the study were that the standard k-ε model yields similar results as the much more expensive Reynolds-Stress-Model.

  JP-10 is a complex fuel, and in [150] a procedure for measuring the initial products in the thermal decomposition is described. This technique is based on a high-speed UV absorption kinetic spectrograph.

  When utilizing hydrocarbon fuels as a cooling medium the added heat has the unwanted effect of starting chemical reactions in the fuel, which in turn leads to solid deposit formation along the heated surface. Results from numerical simulations where this problem was addressed are presented in [151].

  The US Air Force traditionally uses a special, expensive fuel for long duration high-altitude flights. In the work presented in [152] a simulator was used to evaluate a less expensive alternative.

- Fuel Injection Systems.

  Planar imaging techniques were used to study swirlers, used to improve flame stability, of different geometries in the work presented in [160].

3.7.3 2002

This year the sessions related to gas turbines were:

- Turbomachinery Compressor Aerodynamics and Design.

  The results of an optimization tool for multistage compressors are described in [172]. An multiobjective evolutionary algorithm was used for the optimization, and an streamline curvature method was employed to calculate the performance of the candidate compressor.

  In the work presented in [173] the Lattice Boltzmann (LB) method were successfully used to simulate the fluid dynamics of cascades. The authors claim this is the first time LB simulation of turbomachinery has been reported.

  In [174] the results of validations of the CFD code EURANUS on NASA Rotor 37 are reported. Three fan configurations were used, and improvements were suggested to the blade profile leading to elimination of flow separation at the design point

- Turbomachinery Forced Response.

  In [175, 176] work on off-design unsteady aerodynamics including dynamic stall due to the interaction of rotor-generated wakes with a downstream vane row are presented. Experimental data from a low-speed axial flow compressor were obtained using PIV measurements.

  In [177] results from time-marching multistage CFD analyses were validated against experimentally obtained multi-blade row flow environment data. The code used was TURBO, an advanced three dimensional Navier-Stokes multi-blade row turbomachinery CFD code.

  Different aspect of inlet guide vanes (IGV) and their effect on transonic compressors were addressed in [255, 256, 257, 258]

- Turbomachinery Hot Section Aerodynamics and Heat Transfer.

  In [188] a new transition model to predict the onset of transition is presented. The model has been validated against a large number of experiments.

  In the work presented in [189] the boundary layer development on the suction surface of a low pressure turbine blade were studied. The focus were on the relationship between the boundary layer behavior and hot-film data.

  Today's engines are designed at increasingly higher turbine inlet temperatures, and it is therefore important to be able to evaluate the effect of the hot streak migration through the turbine stages. In [190] results from simulations of this problem using a three dimensional, viscous, unsteady code (ADPAC) is presented.

An electrically dissipative capillary injector was studied in the work reported in [191]. This injector does not require atomizing gas, and the influence of the quality of the spray (n-heptane was used in this case) on emissions and combustion instabilities was studied both numerically and experimentally. Large Eddy Simulation were used in the numerical work, and it was found that droplet vaporization and flame temperatures were well predicted by the simulations

- Combustion Measurements and Modeling.

  The National Combustion Code (NCC) is an integrated system of computer codes being developed by an industry-government team in the US for the design and analysis of combustion systems. In [192] an effort to minimize the number of cells along the different domains in the domain decomposition is described. The method used was shown to improve the parallel scalability of the code.

  In [193, 194] the mixing of primary air and fuel, as well as the effect of perpendicularly injected secondary air jets were studied both experimentally and through various CFD-codes.

  A computational analysis using an Arbitrary Lagrangian–Eulerian (ALE) method of flow in simplex fuel atomizers (pressure-swirl atomizers) is presented in [195]. The effect of the geometry on performance, here evaluated by film thickness, spray cone half angle, and discharge coefficient, was studied.

  The propagation of detonations in lean and rich hydrogen-air mixtures are treated in [196]. A one dimensional inviscid code with detailed finite rate chemistry and with a dynamically adaptive grid was used in the study. The occurrence of “galloping” detonations near the detonability limits were obtained.

- Air Breathing Combustion

  An experimental study on the effect of geometry on the flow structure of experimental swirl-stabilized gas turbine burners is presented in [217]. The measurements were conducted without combustion and PIV measurements were made.

  In [218] work regarding the transport Probability Density Function (PDF) is presented. It was concluded that this method can be used in practical combustor designs.

The PDF method is also treated in [219], but here a Lagrangian method was used. The conclusion is the same though, namely that Lagrangian Monte-Carlo PDF method can reliable be used in simulations of practical gas turbine combustors.

- Turbomachinery Active and Passive Control.

  Flutter and vibrations are common problems in the development of compressor blading for gas turbine engines. Instead of redesigning the blades the concept of active/passive vibration control is considered in [231]. Here feedback control using piezo-ceramic sheets applied to stator vanes of an axial flow compressor was studied.

  In [232] an experimental investigation of the performance of the adaptive control scheme for active control of combustion instabilities is presented. The controller was investigated in a gaseous fuel, high-pressure combustor simulator that incorporates an industrial pre-mixer. It is claimed that this study demonstrated for the first time the effective control of large pressure oscillations with amplitudes larger than 7 bar and a frequency of 400 Hz in a high-pressure combustor.

  In [233] it was shown that by using the continuous wavelet transform, instead of a traditional FFT to analyze the acoustic signature, it is possible to detect the development of rotating stall and surge 40 to 50 revolutions earlier.

- Turbomachinery Flow Instabilities.

  Wavelet analysis is also treated in [234]. Here the signals from pressure sensors located on the casing of axial compressors were evaluated. Guidelines for selection of suitable wavelet bases are presented in the paper.

  A CFD based model (3 D Euler equations) for the prediction of aerodynamic instabilities like rotating stall and surge in axial flow compressors are presented in [235]. The results in the study were compared to experimental data.

  Results from a numerical and experimental study of flow instabilities in a high-speed multi-stage axial compressor is presented in [236]. A diagnostic tool based on Chaos theory was used to evaluate the dynamic behavior or the results from the numerical calculations.

- Spray Combustion.

Models to simulate atomization process based on "first principles" are described in [247]. The authors claim that their model is capable of providing reasonable predictions of liquid volume flux, droplet velocity, and droplet size at different locations and different liquid/gas momentum flux ratios.

In the work presented in [248] the effect of spray combustion upon combustion instabilities were studied.

A coupled level set and Marker and Cell method was developed in the work described in [249]. Results from simulations on the impact of liquid droplets onto solid surfaces using this model is also presented.

Atomization and combustion of droplets are treated in [250, 251].

3.7.4 2003

Sessions related to gas turbines:

- Turbine Engine Concepts.

  Work on the Constant Volume Combustor (CVC) is presented in [266]. In contrast to an conventional turbine engine combustor, the CVC creates a pressure rise in addition to the temperature rise. The analytical results in the paper indicate benefits in fuel burn and direct operating cost, at the expense of higher production cost.

  In [267] it was shown that significant performance gains can be obtained if gas turbine engines are topped with wave rotors.

- Turbine Engine Combustor Performance/Control.

  In the work presented in [280] the influence of spray quality on combustion dynamics in a liquid-fueled turbulent combustor was studied. A novel electrical capillary injector capable of generating droplets from 100 microns down to sub-micron range were used in the tests.

  Active control of instabilities in a high-pressure combustor by means of fuel injection was also treated in [281].

  The problem of obtaining the lean blowout (LBO) fuel/air ratio is an important design requirement. In [282] both Unsteady Reynolds Averaged Navier Stokes (URANS) and combustion Large Eddy Simulations (LES) calculations were used to model this problem. The results were promising, but improvements on spray modeling is said to be required.

LES was also used in the study presented in [283]. Emissions in liquid-fueled combustors were studied, and experimental data were used to evaluate the model.

- Spray Combustion.

  A review of the state of the art of spray combustion modeling is presented in [318].

  In [319] tests on a novel swirling injector capable of controlling the spreading rate and mixing in high speed flows is presented.

  The influence of the droplet size on the flame features of a liquid-fueled swirl combustor was studied in the work presented in [320]. The computational scheme was based on a stochastic separated flow model, and a strong correlation between the droplet size and the heat release was observed.

  The effect of cavitation on sprays are reported in [321, 322].

3.7.5 2004

The relevant sessions this year were:

- Spray Combustion.

  Measurements of spray characteristics produced by effervescent atomizers were made in the work presented in [364].

  In order to increase performance it can be advantageous to increase the chamber pressure of gas turbine engines. As a result it is of interest to understand supercritical jet behavior. In the work presented in [365] this problem was studied both through Direct Numerical Simulation (DNS) and Large-Eddy Simulation. It was found that LES with the subgrid mixing model approach gives results in good agreement with DNS data whereas conventional eddy diffusivity closure does not.

  An experimental investigation of sub- and supercritical liquid fuel injection and combustion in a high-pressure combustor is presented in [419]. It was found that a change in spray quality in the subcritical regime affects combustor dynamics causing various regimes of stable and unstable combustor operation. Supercritical injection of heptane resulted in gradual decrease in combustor oscillatory pressure amplitude.

- Turbomachinery Technology - Gas Turbine Performance and Modeling.

  Performance prediction of axial compressors is important, and although multi-row CFD is an important tool it has several drawbacks (meshing is complicated leading to long turn around times). In [372] a method using a combination of single-row CFD and Streamline Curvature codes is presented. The method was tested on several multistage compressors and predictions well within measurement accuracy were obtained.

Results using the CE/SE, Space-time Conservation Element/Solution Element, framework to model viscous flow problems are presented in [373]. The model was tested on "simple" problems, e.g., laminar flow over a flat plate, driven cavity, and external flow over a circular cylinder.

An attempt to simulate the flow path of an entire gas turbine engine is presented in [374]. In order to reduce the computational time both LES and Reynolds Averaged Navier-Stokes (RANS) were used, and the problem of matching the boundary conditions between domains were the different methods are used was studied.

The same subject, the interaction of RANS and LES, is also covered in [375].

- Arthur H. Lefebvre Memorial Session.

  Empirical expressions for estimating the spray Sauter Mean Diameter (SDM) were evaluated in the work presented in [381]. Both airblast and pressure swirl atomizers were addressed in this effort.

  In the study presented in [382] the benefits of lateral jet injection into swirling crossflow were addressed.

  As inlet temperatures increase there is a tendency for the flame to anchor on perturbations on the wall. This problem was addressed in the work presented in [383].

  A review of combustor stability and lean blowout is presented in [384].

- Turbomachinery Component Technology - Gas Turbine Engine Hot Section Research.

  In the work presented in [385] the effect of dimples on turbine blades were studied. Three different configurations were investigated, and their relative effectiveness in reducing boundary layer separation were ascertained.

  A new method of turbine blade cooling, based on potassium evaporate cooling is described in [386].

  The use of plasma discharges to control boundary layers on turbine blades is treated in [387].

- Turbomachinery Component Technology - Unsteady Aerodynamics of Gas Turbine Engines.

  The effect of geometrical uncertainty of compressor blades on modal response was studied experimentally in the work presented in [407]. High resolution measurements of frequency response were performed, and it was found that there were significant variations between the different blades in the study.

  In [408] flow-induced blade vibration of compressor blades is addressed. The objective of the research was to explore the feasibility of vibration control methods for application to blades in gas turbines.

  The problem of mistuning of bladed disks, and their consequence on high cycle fatigue, is treated in [409].

  Three-dimensional, time-accurate, Reynolds-averaged Navier-Stokes simulations of IGV-rotor aerodynamics interactions in a transonic compressor for two IGV trailing-edge profiles and IGV-rotor axial spacings are presented in [410].

  In [411] an unsteady aerodynamic model was used to study flutter. The mathematical method used in the computations was tested against controlled experiments, and it was concluded that the method is able to account for the variations in airfoil oscillation frequency that do occur in experiments.

  Small pulsed jets can stabilize the boundary layer and keep the flow over turbine blades attached. In [426] Particle Image Velocimetry (PIV) was used to study this phenomenon.

  Another paper dealing with secondary flow to keep the flow attached is [427]. In this paper 3D CFD simulations were used to study several internal duct designs.

  In [428] the results from numerical simulations of a rotating stall in a subsonic compressor are presented.

- Active Combustion Control and Low-Emission Technology.

  The use of a true non-thermal transient plasma actuator in a swirl-stabilized gas turbine combustor are described in [433]. The purpose of the actuator is to reduce emissions by generating radicals for enhanced combustion in high temperature environments in the combustor.

  Lean-burning, low emission combustors are often plagued by high frequency thermo-acoustic instabilities. A method to reduce these instabilities named the Adaptive Sliding Phasor Averaged Control was tested on a combustor rig, and the results presented in [434] show a dramatic reduction of the instabilities.

In the work presented in [435] the instabilities in the combustor were studied (and reduced) by using an array of injectors where the operating conditions of each individual injector could be adjusted (while keeping the overall operating conditions the same).

Severe combustion instabilities were studied in the work presented in [436]. It was found that when the temperature of the injected liquid fuel (n-heptane) were varied over a range from room temperature to well over supercritical severe instabilities developed. It was further found that the behavior were not only dependent on the actual temperature, but also on the direction in which the fuel temperature varied.

The dynamics of a LPP system (Lean Premixed Prevaporized) is addressed in [437]. These systems are attractive since they minimize emission, but they are on the other hand very sensitive to couplings leading to unstable behaviors. In this study planar laser induce fluorescence were used to monitor OH radicals and acetone vapor.

3.8 Liquid Fuel Ramjets

3.8.1 2000

Nothing of relevance from this year.

3.8.2 2001

Two computational and two experimental studies were reported this year.

A computational study of the combustion dynamics of ramjet operation is reported in [77] and automated design optimization of supersonic inlets is presented in [103].

On the experimental experimental side there is a study of a compact ram combustor in [101] and on free jet testing in [102].

3.8.3 2002

Experiments on the usage of a geometrically movable "throat" is considered in [204], in order to design a ramjet/scramjet dual-use configuration.

Development of low-cost ramjet technology, mainly oriented towards modularity of components, is the topic of [205].

3.8.4 2003

Nothing of relevance from this year.

3.8.5 2004

The effect of inlet dump angle on the performance of a ramjet combustor was numerically investigated in [418].

3.8.6 2005

Nothing of relevance from this year.

3.9 Ducted Rockets

During the period 2000–2005 there were only three papers directly considering ducted rockets [23, 78, 403]. The subjects of these papers were measurements of mixing, numerical simulation of the propulsion system, and combustion and ignition characteristics of a solid fuel where Zr was added, respectively.

Even though the JPC is the correct forum for this propulsion system, the small number of contributions during these years is probably caused by the fact that ducted rockets can be considered a mature technology.

3.10 Solid Fuel Ramjets

Only two contributions to JPC was found for the selected time period.

A numerical study of the performance of solid fuel ramjets was reported in [139] and a description of a free jet test facility that can be used for experimental investigations of solid fuel ramjet propulsion [487]. The experimental rig is, however, focused on the propulsion of gun-launched projectiles.

3.11 High Mach Number Applications: Combined Cycles

3.11.1 2000

Nothing of relevance from this year.

3.11.2 2001

In [82] a new high Mach engine concept is studied. The "SteamJet" is based on existing turbojets, and employs a simple modification to reduce the high incoming air stagnation temperature at high Mach number. It is claimed to permit vehicle acceleration with a single engine from sea-level static conditions up to Mach 6+. The innovation in the concept is a flow conditioning device consisting of a water-injection system in front of the compressor with the purpose of reducing the high incoming air stagnation temperature.

The Ejector Scramjet (EJR), the Supercharged Ejector Ramjet (SEJR), and the Supercharged Ejector Scramjet (SEJS) are described in [83]. They are all derivates, with different additions, of the ejector ramjet.

Analytical and experimental results, as well as results from CFD on Rocket-Based Combined Cycle (RBCC) engine performance are presented in [116, 118, 119, 120]. RBCC is a term which includes (but is not limited to) ejector ramjets.

Another system, the Integrated Rocket Ramjet, is studied in [117]. This system combines a rocket booster and a ramjet sustainer in one propulsion system with a common combustion chamber for the two phases. In the study a numerical approach was used to analyze both the transition from the booster, as well as the sustained ramjet phase.

3.11.3 2002

RBCC systems are addressed in [182, 183].

3.11.4 2003

Different aspects of RBCC systems are treated in [355, 356, 357, 358, 359].

3.11.5 2004

A one dimensional compressible flow model was used to analyze RBCC in the work presented in [388]. The method was used to optimize the specific impulse of a concept engine.

The ATR is addressed in [389]. A thermodynamic cycle analyses were performed, and showed, among other things, that the performance of the ATR degrades greatly above Mach 3.

Ignition limits of a ducted rocket were studied experimentally in the work presented in [390]. It was found that ignition was favored by lower rocket equivalence ratios, but that among the cases that ignited higher thrust and specific impulse were seen when higher equivalence ratios were used.

In the work presented in [391] it was, by the use of CFD, shown that the compression ratio in an ejector ramjet can be increased by increasing the area of an axisymmetric ejector. This in turn leads to an increased thrust.

3.12 Scramjets

3.12.1 2000

This year there were three sessions dealing with scramjets and supersonic combustion:

- Supersonic Combustion Systems
  The following was presented:
  - The combustion of liquid JP-7 in a scramjet combustor [47]
  - Fuel distribution about a cavity flame-holder [48]
  - Effect of plasma torch feedstock on ignition characteristics [49]
- Supersonic Combustion
  The following was presented:
  - Design analysis of the combustor flowfield [55]
  - Analysis of unsteady cavity flow [56]
  - Supersonic mixing control using cavities; especially the effect of fuel injection location [57]
  - Reforming and pyrolysis of liquid hydrocarbons and partially oxidized fuels [58]
  - Combustion characteristics of kerosene-hydrogen dual fuel [59]
- Scramjet Propulsion Systems
  The following was presented:
  - Real-gas calculations of the performance of an MHD/bypass scramjet [62]
  - A fuel injector for scramjet applications was assessed [63]
  - Three-dimensional effects in the modeling of dual-mode scramjets [64]
  - An airframe-integrated scramjet [65]
  - The thermal choking process was numerically studied in [66]
  - A fuel-injector that is streamlined and pressure-matched [67]

  - The performance of an aerodynamic ramp fuel injector [68]
  - The mixing and combustion when using a raised and relieved ramp in the combustor [69]

3.12.2 2001

- Supersonic Combustion
  The most noteworthy of the presentations in this session were the following:
  - Fuel injection and flame-stabilization [140]
  - Effect of notches on circular jet mixing [141]
- Supersonic Combustion II
  The most noteworthy of the presentations in this session were the following:
  - Passive mixing control via lobed injectors [158]
  - Two-stage plasma torch ignition [159]

3.12.3 2002

- RTO Working Group 10–1: Scramjets
  The most noteworthy of the presentations in this session were the following:
  - A review of experiments on ignition and flameholding [212]
  - Fundamental mixing and combustion experiments [213]
  - A review of air vitiation effects on ignition and flameholding [214]
- Scramjet Design, Analysis, and Test
  The most noteworthy of the presentations in this session were the following:
  - CFD analysis of the NASA/CIAM scramjet [237]
  - Experiments with a ramp-compression inlet at Mach 8 condition [238]
  - Experiments of the internal compression inside a hypersonic intake [239]
  - Initial flight tests of the NASA Dryden F-15B [240]

- Development of a cooled CMC combustor structure [241]

- Scramjet Combustion Research
  - Pilot injection and flame characteristics [259]
  - The use of cavities for thermal and momentum mixing of dual streams [260]
  - Numerical study of a scramjet combustor with a backward-facing step [261]
  - Effervescent atomization of liquid hydrocarbon fuel [262]

3.12.4 2003

- Hypersonic Propulsion Experiments
  - Axisymmetric cavity-based flameholding concepts [300]
  - Suppression of combustor–inlet interaction at Mach 4 flight condition [301]
  - Effect on ingested boundary layer on thrust and combustion characteristics [302]
  - Injection and combustion in divergent section [303]
  - Comparison between CFD simulation and experiment of sidewall-compression [304]
- Hypersonic Propulsion — Analysis & CFD
  - Numerical study of unsteady shock-induced combustion [342]
  - Suppression of premature ignition [343]
  - Numerical study of injection into a Mach 5 stream through diamond orifices [344]
  - Minimum-mass heat exchanger design [345]
  - Sonic injection into a Mach 5 stream through diamond orifices at various incidence [346]
  - Starting and unstarting of high Mach number air inlets [347]
  - Evaluation of the X-43A controller performance with Monte Carlo simulation [348]

3.12.5 2004

- Ramjet/Scramjet Engine System Analysis Design & Test
  - Gas-sampling from exhaust flow at Mach 6 flight condition [360]
  - Optimization for maximum off-design performance [361]
  - Status of LEA flight test program [362]
  - Comparison of HEG and flight test data for HYSHOT [363]
- Hypersonic Engine Component Design Evaluation & Test
  The most noteworthy of the presentations in this session were the following:
  - Performance of supersonic combustors with fuel injection in the diverging section [379]
  - Investigation of hydrocarbon fuel combustion [380]
- Hypersonic Propulsion Experiments and Other Related Topics
  The most noteworthy of the presentations in this session were the following:
  - Mixing in high-speed flows with thick boundary layers [392]
  - The function of a cavity in supersonic combustion using OH-PLIF [393]
  - Blowout limits of supersonic cavity-stabilized flames [394]
- Hypersonic Propulsion CFD, Plasma & MHD
  - Analysis of a kerosene-fueled MHD scramjet [447]
  - CH production in a pulsed DC discharge for ignition enhancement [448]
  - Plasma aerodynamic flow control for hypersonic inlets [449]
  - Flow starting in high compression hypersonic inlets [450]
  - LES of supersonic combustion of hydrocarbon spray [451]

3.12.6 2005

- Hypersonics I
  - The scramjet as a solution for hypersonic propulsion [460]

  - Self-ignition using supercritical kerosene injection [461]

- Hypersonics II
  - Independent stage control of a cascade injector [471]
  - Flowfield behavior when using an upstream mixing cavity in conjunction with a downstream flameholding cavity [472]
  - Temperature and H_2O concentration measurements using a wavelength-multiplexed tunable diode laser sensor [473]
  - Characterization and optimization of off-design performance [474]
  - Compressibility effects in propulsive shear flows [475]
  - Measurements of mixing when injecting transverse and oblique sonic jets in supersonic crossflow [476]
  - Characterization when using vaporized kerosene injection [477]

- Air Breathing Propulsion for High Speed Flight
  - Firing test of a liquid hydrogen-cooled engine [483]
  - A method for design, integration, and analysis [484]
  - Thermoacoustic flow instability [485]
  - Numerical simulation of combustion in a dual-mode combustor [486]

- Hypersonics III
  - Mixing effects of a pylon placed upstream a cavity flameholder [493]
  - Compact heat exchangers for air liquefaction [494]
  - Waverider design for inward-turning inlet flows [495]
  - Use of additives to increase fuel heat sink capacity in heat exchanger [496]

- Hypersonics IV
  - Transformation of the United States DoD aerospace capability [503]
  - Three-component particle image velocimetry (PIV) in a dual-mode scramjet [504]
  - Effects of fuel-air injection location in cavity flameholder [505]

- Panel Session: Current and Future States of Hypersonic Propulsion
  In this panel session the renewed interest in hypersonic propulsion was considered. The panel consisted solely of people from the US; working for the Office of Secretary of Defense, ATK GASL, Boeing Phantom Works, Pratt & Whitney, Raytheon, and ONR. All panel members presented their ongoing efforts, and discussions (including the audience) were held afterwards.

- Hypersonics VI
  - Numerical simulation of supersonic combustion [512]
  - CFD modeling using a variable geometry [513]
  - Dynamic combustion characteristics when using transverse fuel injection [514]

3.13 Pulse Detonation Engines

3.13.1 2000

This year there were two sessions dealing with pulse detonation engines:

- A procedure for evaluating the performance of an idealized, air breathing PDE is described in [33]. The procedure is based on the assumption of constant volume combustion, and hence disregards all issues regarding the dynamics of the detonation (e.g., the initiation of the detonation).

- Detonation diffraction were numerically studied in the work presented in [34]. The work were concerned with the transition of the detonation when moving from a pre-detonator to the main chamber where the diameter of the pre-detonator is smaller than that of the main chamber. It was concluded that a oxygen enriched mixture were required in the pre-detonator in order for a successful transition of the detonation to the main chamber.

- Results from a multidimensional CFD analysis where the use of a pulse detonation device were used as instead of an afterburner in a generic turbofan engine are presented in [35]. It was found that thrust could be nearly doubled by using the pde-device instead of the conventional afterburner.

- The chemistry of ethylene (C_2H_4) were addressed in [36]. A detailed kinetic mechanism were identified, and under consideration of conditions applicable in a PDE this mechanism were reduced substantially.

- In [50] soot diagnostics were used obtain information on the progress of burning during a cycle. JP-10 were used as fuel, and among other things it was revealed that the combustion continued even after the passage of the detonation.

- The performance of a "rocket pde" (one which uses oxidizer carried on board, and not oxygen from the air) is compared with an ordinary rocket in [51]. Analyses were made both in zero, one and two dimensions. It was found that the PDE outperforms the rocket IF the combustion pressure rise from the detonation is added to the chamber pressure in the rocket. On the other hand, if the peak pressures are the same the rocket performance is higher.

- Deflagration to detonation in different ethylene/oxygen/nitorgen mixtures were studied in [52].

- Results from operation of a JP10/air pde is presented in [53]. Oxygen were added in the pre-detonator, and in order for the mixture to detonate, it was found that a Sauter Mean Diameter below approximately 3 microns were required. Alternatively, the mixture would detonate with larger droplets if a large fraction of fuel vapor were present.

- In the work described in [54] a diode laser sensor system was used to measure multiple performance critical flow properties in PDEs.

3.13.2 2001

This year there were four sessions devoted to PDEs. Among the contributions the following can be noted:

- Results from numerical and experimental studies on diffraction from pre-detonator to the main chamber are reported in [121]. Again it was shown that the detonation failed to transmit unless oxygen were used in the pre-detonator.

- In [122] the effect of DDT (Deflagration to Detonation Transition) on the impulse was studied. It was shown that as long as the DDT occured within the tube, and no fuel was spilled prior to detonation, the impulse of a DDT process was not lower than that of a direct initiation.

- In [142] the CE/SE, Space-time Conservation Element/Solution Element method was used to analyze the plume dynamics of a PDE.
- A simple analytical model for PDE performance based on elementary gas dynamics and dimensional analysis is presented in [161].
- In the work presented in [162] direct impulse measurements were carried out for detonations and deflagrations in tubes by using a ballistic pendulum arrangement.
- A review of the research regarding nozzles on PDEs is presented in [167].
- In [168] results from a numerical study is presented. Among other things the effects of partial fuel-fill on the pressure histories of a ethylene-air driven PDE are presented. The data are also shown to compare quantitatively with data from experiments.

3.13.3 2002

There were four sessions dedicated to PDEs this year. Some of the papers are covered in the items below.

- A novel initiation system is presented in [184]. A system generating a collapsing toroidal detonation wave front were built. The purpose of the device were to use the high pressures and temperatures at the focal region of the collapsing detonation to initiate a detonation in the main chamber.
- In the work presented in [185] PDE nozzles were evaluated both numerically and experimentally. The impulse were found to be linearly dependent on the fraction of the tube volume filled with the explosive mixture. An analytical method to account for the effect of diaphragms was also presented. Further on a thermodynamic cycle analysis were conducted to evaluate the efficiency of the PDE.
- In [186] results from a cycle analysis for hydrogen fueled air-breathing PDEs are presented. It was found the high temperature dissociation can quite substantially reduce the performance under certain circumstances.
- The effects of ejectors were addressed in the work presented in [187]. It was found that ejector systems can utilize the energy stored in the

strong shock wave leaving the tube to augment the impulse of the detonation tube alone.

- In [197] work on "splitting" detonations are reported. The purpose of the study was to utilize part of the detonation (split it) in one tube to initiate the detonation in another tube. A dual tube system, with only one spark plug, was built and successfully tested.

- Different transition enhancing devices were tested in the study presented in [198]. High-speed digital imaging was used to track flame propagation, and pressure transducers were used to record the progress of the shock structure.

- The use of a hot turbulent jet to initiate a detonation were studied in the work presented in [215]. Propane-oxygen diluted with varying amount of nitrogen were used in the main chamber, and propane oxygen were used in the smaller chamber where the hot jet were generated. Only when the nitrogen content were below 40% did detonations evolve in the main chamber.

- Zero-, one-, and two-dimensional performance models of a rocket PDE were evaluated in the work presented in [216].

- A one-dimensional method of characteristics code was developed in the work presented in [230]. The method was compared against experiments and two-dimensional CFD codes and a reasonable agreement was verified. The method was then used to evaluate different configurations, e.g., detonation initiation location, filling velocity, and partial fills. The configurations were also evaluated both with and without nozzles.

3.13.4 2003

Three sessions were devoted to PDE technologies, and some of the topics are briefly described below:

- A review of recent developments is presented in [276]. Among the subjects covered are subsonic and supersonic air-breathing missiles and hybrid PDE-turbine engines. Detonation initiation, performance enhancement and performance prediction are also covered in the paper.

- An analytical model for predicting the performance of a single-tube air-breathing PDE was developed in the work presented in [277]. The model is based on a single tube engine, and an inlet manifold large enough to dampen pressure transients is assumed between the inlet and the actual detonation tube. Two of the conclusions from the study were that: the engine is capable of generating thrust up to a flight Mach number of about 4, and when operated on JP10-air the PDE has a higher specific impulse than the ramjet below a flight Mach number of 1.35.

- Work on simulations of the flow-field interaction between the different tubes in a multi-tube PDE with common inlet and nozzle is presented in [278].
- Nozzles and the efficiency of partial fill were analyzed in the work presented in [279].
- The subject of multiphase detonation is covered in [296]. A review of previous work is supplied, and one of the conclusions from this review were that if the droplets are fine enough (less than about 10 microns) detonations can propagate in various fuel-oxygen systems at about the equivalent gas-phase Chapman-Joguet detonation velocity. At the time of the writing the minimum droplet size required for fuel-air mixtures was not determined.
- A diode-laser-based sensor was developed in the work described in [297]. The sensor was put to use in a PDE in order to monitor and control the charging of fuel.
- OH concentration and gas temperature were measured using UV absorption in the study presented in [298].
- In an effort to make JP-10 easier to detonate thermal cracking, catalytic cracking and pre-mixed partial oxidation of JP-10 were studied in the work presented in [299].
- The work on the collapsing toroidal detonation wave front presented last year, [184], were continued and is described in [330]. In the paper the adoption of the device for use in an ethylene-air and propane-air PDE is described. Oxygen was still used in the initiator, but the device is claimed to require less than what is needed in a "conventional" initiator tube.
- In the work described in [331] characteristics of electrostatic inkjet technology were studied. It was shown that droplets sizes less than 10 microns could be produced with very little pressure drop.

- A cyclic PDE was built and tested in the work described in [332]. Infrared spectroscopy was used for emission and absorption measurements at the exit of the PDE. Fuel leakage was observed due to stratification between fill and purge gases during the filling process. Combustion products left-over in the detonation tube after the purge process was also observed.

- The use of overdriven detonations in a pre-detonator as a mean to initiate the detonation in the main chamber was studied in the work presented in [333].

3.13.5 2004

Three sessions were of relevance to PDE research this year.

- The work from the last year, on the use of overdriven detonations in a pre-detonator as a mean to initiate the detonation in the main chamber presented in [333], were continued and presented in [368].

- The use of ejectors in combination with PDEs were examined in the work presented in [369]. The authors obtained an 40% increase in thrust on their research engine.

- The use of detonation "branching" (or "splitting") of the detonation as a mean to shorten the initiation of the next pulse in the second tube is described in [370]. The DDT distance in a stoichiometric heptane-air mixture were reduced from 1.0 m (using spark ignition) to 0.83 m.

- The use of the PDE in a Mach 2.5 strike missile application were evaluated in the study presented in [371]. In the same paper a PDE performance analysis methodology is also described.

- In the work presented in [404] the performance of an idealized PDE were obtained using a analytical model. It was shown that when compared to a ramjet the PDE driven system had a superior specific impulse, in contrast to the conclusions from [186, 277]. The two systems were evaluated at Mach 2.5.

- A novel method to speed up the DDT process is described in [405]. As is commonly used the authors applied a sequence of orifice plates in the detonation tube. But in contrast to what is ordinary done, spark plugs were placed in connection to the orifice plates, and these spark plugs were fired at the same time as the arrival of the flame front. A slight reduction (about 10%) in DDT distance were observed.

- The operation of a valveless PDE is described in [406]. The engine used hydrogen as fuel, and added oxygen in a "initiator" section.
- An experimental investigation on nozzles of different shapes were performed in the work presented in [420]. The ballistic pendulum technique were used to measure the impulse.
- The effect of turbulence on the distance to complete the DDT were studied in [421]. The intake valves of an automobile cylinder were used to inject a propane/oxygen/nitrogen mixture in smooth tube. Turbulence were introduced by the motion of the intake valves. The results indicated that the distance to complete the DDT were decreased by as much as 6 times as a result of the induced turbulence.
- Experiments on a ethylene-oxygen single-tube rocket PDE were performed in the work presented in [422].

4 Conclusions and Outlook

A large part of the contributions to JPC were dedicated to further the understanding of basic combustion processes, both through numerical simulations and experimental studies. Of these papers, the largest numbers were related to turbine engines, with a lesser number focusing on combustion processes in PDEs, scramjets, ramjets, rockets and various combined cycles.

It should also be mentioned that some of the methods used to study this field represented the forefront of their respective technologies, be it numerical or experimental methods.

Turbine engines represent a mature technology, but there is a constant quest for increased performance, as well as a drive to produce engines with a lesser impact on the environment. Being a mature product, production costs of the engine has been driven down, which is another fact which will make it difficult for competing, new technologies to replace it. There has to be a distinct advantage, be it cost or performance, before competing systems will be considered to replace it.

The PDE were covered in several sessions each year, and even though the technology is immature, a steady trend toward a working air-breathing engine can be discerned. The rocket PDE have not received the same amount of interest in this forum, but it certainly has advantages which merits continued research.

The renewed interest in hypersonic propulsion has resulted in a number of new national and international (and even intercontinental) research programs on scramjets. That scramjets, again, has become a “hot” research area is also clear from the increasing number of contributions to the JPC and the special panel session on hypersonics at JPC in 2005.

The topics of solid rocket plumes, liquid fuel ramjets, solid fuel ramjets, and ducted rockets were not extensively considered at the JPC during the period of study. Concerning solid rocket plumes there are still fairly large areas of incompleteness in, e.g., modeling of the phenomena. The other topics are of a more mature nature; the technology needed to build such systems is to a large extent known. It should, however, be possible to try to increase the performance of these systems. Recent research and development along this line is clearly not reported at the JPC.

Large efforts are being made in both the US and in Europe (predominantly in France) on building numerical simulation frameworks for accurate prediction of the flow in solid rocket motors. These simulation capabilities aim at catching the inherently three-dimensional and unsteady effects that are impossible to compute with more traditional computational tools.

A tremendous part of the JPC is devoted to testing of liquid rockets and their subsystems. The main reason for this is the various ongoing space programs around the world, resulting in a perpetual quest for higher reliability and lesser expenses. A large part of this research is obviously also applicable to tactical missiles.

Variable thrust rocket propulsion systems enables missiles to be more flexible by providing the possibility of multi-platform and multi-target capability. Rocket propulsion systems that can provide variable thrust are hybrids, monopropellants, bipropellants and to some extent dual or multi pulse solid rockets, or solid rockets with variable nozzle. These types of propulsion systems have thus gained renewed attention for tactical missile applications and hence research on hybrid rocket fuels, monopropellants and liquid and gelled bipropellant have increased.

Toxicological concerns about current liquid propellants, such as hydrazine based fuels and dinitrogen tetroxide, has intensified the effort of finding non-toxic or green alternatives. Hydrogen peroxide has thus received new interest as liquid oxidizer in hybrid and bipropellant systems, as well as in monopropellant systems. Due to its low stability, hydrogen peroxide is not likely to be used for tactical missile applications, but might find its way to space applications. Another way to improve the handling safety of current toxic propellants is to transform them in to a gel. Gelled propellants provide lower toxicity and fire hazards, reduced leakage, spillage, and slosh problems. Energetic ionic liquids based on ADN or HAN might be used as benign liquid oxidizers, or as advanced monopropellants. These types of monopropellants have a density-impulse up to 70% higher than the current state of the art monopropellant hydrazine.

For hybrid propulsion systems the emphasis is to improve the regression rate of the solid fuel by adding nano-sized metal powders, solid oxidizers or metal hydrides, or by using new binders such as energetic polymers or paraffin based fuels. The past years have seen many significant development programs in the field of hybrid rocket propulsion and it is likely that hybrid rocket propulsion systems will find its way to tactical missile applications within a couple of years.

The development of new solid rocket propellants are mainly focused on minimum smoke propellants, by using solid oxidizers such as AN, ADN or HNF, or on high performance smoky propellants, containing nano-sized aluminum powder. Minimum smoke requirements are becoming more important since the capability of detecting plumes has become more sophisticated. It is expected that new high performance minimum smoke composite rocket propellants based on ADN will be available in future man-portable anti-tank weapons. AN and HNF is however not expected to be used due to, respectively, poor performance and poor thermal stability. Nano-sized aluminum powder can increase the combustion rate and the combustion efficiency, thus leading to a higher specific impulse, but on the expense on the formation of dense smoke. It might however find its way to applications were performance are more important than low signature, as in long range interceptor missiles.

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