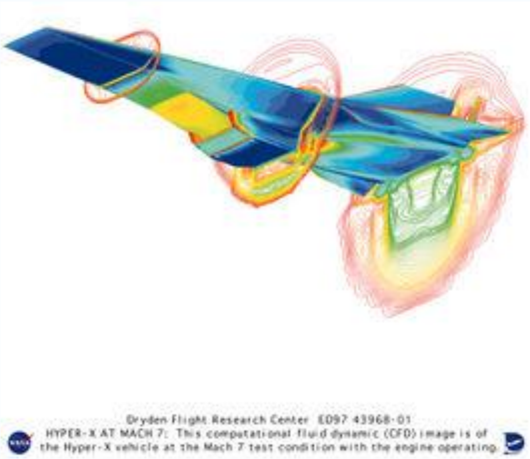
Scramjet



X-43A waverider with scramjet attached to the underside at Mach 7

A **scramjet** (**s**upersonic **c**ombustion **ramjet**) is a variation of a ramjet where the flow of the air and combustion of the fuel air mixture through the engine happen at supersonic speeds. This allows the scramjet to achieve greater speeds than a conventional ramjet which slows the incoming air to subsonic speeds before entering the combustion chamber. Projections for the top speed of a scramjet engine (without additional oxidiser input) vary between Mach 12 and Mach 24 (orbital velocity). By way of contrast, the fastest conventional air-breathing, manned vehicles, such as the U.S. Air Force SR-71, achieve slightly more than Mach 3.2. (Rockets achieved Mach 30+ during Apollo.)

Like a ramjet, a scramjet essentially consists of a constricted tube through which inlet air is compressed by the high speed of the vehicle, fuel is combusted, and then the exhaust jet leaves at higher speed than the inlet air. Also like a ramjet, there are few or no moving parts. In particular there is no high speed turbine as in a turbofan or turbojet engine that can be a major point of failure.

A scramjet requires supersonic airflow through the engine, thus, similar to a ramjet, scramjets have a minimum functional speed. This speed is uncertain due to the low number of working scramjets, relative youth of the field, and the largely classified nature of research using complete scramjet engines. However it is likely to be at least Mach 5 for a pure scramjet, with higher Mach numbers 7-9 more likely. Thus scramjets require acceleration to hypersonic speed via other means. A hybrid ramjet/scramjet would have a lower minimum functional Mach number, and some sources indicate the NASA X-43A research vehicle is a hybrid design. Recent tests of prototypes have used a booster rocket to obtain the necessary velocity. Air breathing engines should have significantly better specific impulse while within the atmosphere than rocket engines.

However scramjets have weight and complexity issues that must be considered. Whilst very short suborbital scramjets test flights have been successfully performed, perhaps significantly no flown scramjet has ever been successfully designed to survive a flight test. The viability of scramjet vehicles is hotly contested in aerospace and space vehicle circles, in part because many of the parameters which would eventually define the efficiency of such a vehicle remain uncertain. This has lead to grandiose claims from both sides, which have been intensified by the large amount of funding involved in any hypersonic testing. Some notable aerospace gurus such as Henry Spencer and Jim Oberg have gone so far as calling orbital scramjets 'the hardest way to reach orbit', or even 'scamjets' due to the extreme technical challenges involved. Major, well funded projects, like the X-30 were cancelled before producing any working hardware.

History

During and after World War II, tremendous amounts of time and effort were put into researching high-speed jet- and rocket-powered aircraft. The Bell X-1 attained supersonic flight in 1947, and by the early 1960s, rapid progress towards faster aircraft suggested that operational aircraft would be flying at "hypersonic" speeds within a few years. Except for specialized rocket research vehicles like the North American X-15 and other rocket-powered spacecraft, aircraft top speeds have remained level, generally in the range of Mach 1 to Mach 2.

In the realm of civilian air transport, the primary goal has been reducing operating cost, rather than increasing flight speeds. Because supersonic flight requires significant amounts of fuel, airlines have favored subsonic jumbo jets rather than supersonic transports. The production supersonic airliners, the Concorde and Tupolev Tu-144 operated at a financial loss (with the possible exception of British Airways that never opened the accounts). Military aircraft design focused on maneuverability and stealth, features thought to be incompatible with hypersonic aerodynamics.

In the United States, from 1986-1993, a reasonably serious attempt to develop a single stage to orbit reusable spaceplane using scramjet engines was made, but the Rockwell X-30 (NASP) program failed.

Hypersonic flight concepts haven't gone away, however, and low-level investigations have continued over the past few decades. Presently, the US military and NASA have formulated a "National Hypersonics Strategy" to investigate a range of options for hypersonic flight. Other nations such as Australia, France, Russia, and India have also progressed in hypersonic propulsion research.

Different U.S. organizations have accepted hypersonic flight as a common goal. The U.S. Army desires hypersonic missiles that can attack mobile missile launchers quickly. NASA believes hypersonics could help develop economical, reusable launch vehicles. The Air Force is interested in a wide range of hypersonic systems, from air-launched cruise missiles to orbital spaceplanes, that the service believes could bring about a true "aerospace force."

Simple description

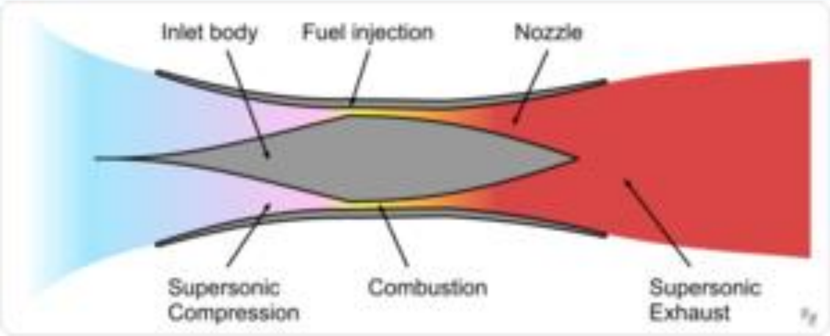


Diagram illustrating the principle of scramjet operation

A scramjet is a type of engine which is designed to operate at the high speeds normally associated with rocket propulsion. It differs from a classic rocket by using air collected from the atmosphere to burn its fuel, as opposed to an oxidizer carried with the vehicle. Normal jet engines and ramjet engines also use air collected from the atmosphere in this way. The problem is that collecting air from the atmosphere causes drag, which increases quickly as the speed increases. Also, at high speed, the air collected becomes so hot that the fuel doesn't burn properly any more.

The scramjet is a proposed solution to both of these problems, by modifications of the ramjet design. The main change is that the blockage inside the engine is reduced, so that the air isn't slowed down as much. This means that the air is cooler, so that the fuel can burn properly. Unfortunately the higher speed of the air means that the fuel has to mix and burn in a very short time, which is difficult to achieve.

To keep the combustion of the fuel going at the same rate, the pressure and temperature in the engine need to be kept constant. Unfortunately, the blockages which were removed from the ramjet were useful to control the air in the engine, and so the scramjet is forced to fly at a particular speed for each altitude. This is called a "constant dynamic pressure path" because the wind that the scramjet feels in its face is constant, making the scramjet fly faster at higher altitude and slower at lower altitude.

The inside of a very simple scramjet would look like two kitchen funnels attached by their small ends. The first funnel is the intake, and the air is pushed through, becoming compressed and hot. In the small section, where the two funnels join, fuel is added, and the combustion makes the gas become even hotter and more compressed. Finally, the second funnel is a nozzle, like the nozzle of a rocket, and thrust is produced.

Note that most artists' impressions of scramjet-powered vehicle designs depict waveriders where the underside of the vehicle forms the intake and nozzle of the engine. This means that the intake and nozzle of the engine are asymmetric and contribute directly to the lift of the aircraft. A waverider is the required form for a hypersonic lifting body.

Theory

All scramjet engines have fuel injectors, a combustion chamber, a thrust nozzle and an inlet, which compresses the incoming air. Sometimes engines also include a region which acts as a flame holder, although the high stagnation temperatures mean that an area of focused waves may be used, rather than a discrete engine part as seen in turbine engines. Other engines use pyrophoric fuel additives, such as silane to avoid such issues. An isolator between the inlet and combustion chamber is often included to improve the homogeneity of the flow in the combustor and to extend the operating range of the engine.

A scramjet is reminiscent of a ramjet. In a typical ramjet, the supersonic inflow of the engine is decelerated at the inlet to subsonic speeds and then reaccelerated through a nozzle to supersonic speeds to produce thrust. This deceleration, which is produced by a normal shock, creates a total pressure loss which limits the upper operating point of a ramjet engine.

For a scramjet, the kinetic energy of the freestream air entering the scramjet engine is large compared to the energy released by the reaction of the oxygen content of the air with a fuel (say hydrogen). Thus the heat released from combustion at Mach 25 is around 10% of the total enthalpy of the working fluid. Depending on the fuel, the kinetic energy of the air and the potential combustion heat release will be equal at around Mach 8. Thus the design of a scramjet engine is as much about minimizing drag as maximizing thrust.

This high speed makes the control of the flow within the combustion chamber more difficult. Since the flow is supersonic, no upstream influence propagates within the freestream of the combustion chamber. Thus throttling of the entrance to the thrust nozzle is not a usable control technique. In effect, a block of gas entering the combustion chamber must mix with fuel and have sufficient time for initiation and reaction, all the while travelling supersonically through the combustion chamber, before the burned gas is expanded through the thrust nozzle. This places stringent requirements on the pressure and temperature of the flow, and requires that the fuel injection and mixing be extremely efficient. Usable dynamic pressures lie in the range 20 to 200 kPa (0.2-2 bar), where

$$p = \frac{\rho v^2}{2}$$

where

p is the dynamic pressure of the gas
ρ (rho) is the density of the gas
v is the velocity of the gas

The minimum Mach number at which a scramjet can operate is limited by the fact that the compressed flow must be hot enough to burn the fuel, and of high enough pressure that the reaction is finished before the air moves out the back of the engine. Additionally, in order to be called a scramjet, the compressed flow must still be supersonic after combustion. Here two limits must be observed: Firstly, since when a supersonic flow is compressed it slows down, the level of compression must be low enough (or the initial speed high enough) not to slow down the gas below Mach 1. If the gas within a scramjet goes below Mach 1 the engine will "choke", transitioning to subsonic flow in the combustion chamber. This effect is well known amongst experimenters on scramjets since the waves caused by choking are easily observable. Additionally, the sudden increase in pressure and temperature in the engine can lead to an acceleration of the combustion, leading to the combustion chamber exploding.

Secondly, the heating of the gas by combustion causes the speed of sound in the gas to increase (and the Mach number to decrease) even though the gas is still travelling at the same speed. Forcing the speed of air flow in the combustion chamber under Mach one in this way is called "thermal choking". It is clear that a pure scramjet can operate at Mach numbers of 6-8 (e.g [1]), but in the lower limit, it depends on the definition of a scramjet. Certainly there are designs where a ramjet transforms into a scramjet over the Mach 3-6 range[5] (Dual-mode scramjets). In this range however, the engine is still receiving significant thrust from subsonic combustion of "ramjet" type.

The high cost of flight testing and the unavailability of ground facilities have hindered scramjet development. A large amount of the experimental work on scramjets has been undertaken in cryogenic facilities, direct-connect tests, or burners, each of which simulates one aspect of the engine operation. Further, vitiated facilities, storage heated facilities, arc facilities and the various types of shock tunnels each have limitations which have prevented perfect simulation of scramjet operation. The HyShot flight test showed the relevance of the 1:1 simulation of conditions in the T4 and HEG shock tunnels, despite having cold models and a short test time. The NASA-CIAM tests provided similar verification for CIAM's C-16 V/K facility and the Hyper-X project is expected to provide similar verification for the Langley AHSTF [1], CHSTF [2] and 8 ft HTT.

Computational fluid dynamics has only recently reached a position to make reasonable computations in solving scramjet operation problems. Boundary layer modeling, turbulent mixing, two-phase flow,

flow separation, and real-gas aerothermodynamics continue to be problems on the cutting edge of CFD. Additionally, the modeling of kinetic-limited combustion with very fast-reacting species such as hydrogen makes severe demands on computing resources. Reaction schemes are numerically stiff, having typical times as low as 10^{-19} seconds, requiring reduced reaction schemes.

Much of scramjet experimentation remains classified. Several groups including the US Navy with the SCRAM engine between 1968-1974, and the Hyper-X program with the X-43A have claimed successful demonstrations of scramjet technology. Since these results have not been published openly, they remain unverified and a final design method of scramjet engines still does not exist.

The final application of a scramjet engine is likely to be in conjunction with engines which can operate outside the scramjet's operating range. Dual-mode scramjets combine subsonic combustion with supersonic combustion for operation at lower speeds, and rocket-based combined cycle (RBCC) engines supplement a traditional rocket's propulsion with a scramjet, allowing for additional oxidizer to be added to the scramjet flow. RBCCs offer a possibility to extend a scramjet's operating range to higher speeds or lower intake dynamic pressures than would otherwise be possible.

Advantages and disadvantages of scramjets

Special cooling and materials. Unlike a rocket that quickly passes mostly vertically through the atmosphere or a turbojet or ramjet that flies at much lower speeds, a hypersonic airbreathing vehicle optimally flies a "depressed trajectory", staying within the atmosphere at hypersonic speeds. Because scramjets have only mediocre thrust-to-weight ratios, acceleration would be limited. Therefore time in the atmosphere at hypersonic speed would be considerable, possibly 15-30 minutes. Similar to a reentering space vehicle, heat insulation from atmospheric friction would be a formidable task. The time in the atmosphere would be greater than that for a typical space capsule, but less than that of the space shuttle.

Therefore studies often plan on "active cooling", where coolant circulating throughout the vehicle skin prevents it from disintegrating from the fiery atmospheric friction. Active cooling could require more weight and complexity. There is also safety concern since it's an active system. Often, however, the coolant is the fuel itself, much in the same way that modern rockets use their own fuel and oxidizer as coolant for their engines. Both scramjets and conventional rockets are at risk in the event of a cooling failure.

Half an engine. The typical waverider scramjet concept involves, effectively, only half an engine. The shockwave of the vehicle itself compresses the expanding gasses, forming the other half. Likewise, only fuel (the light component) needs tankage, pumps, etc. This greatly reduces craft mass and construction effort, but the resultant engine is still very much heavier than an equivalent rocket or convention turbojet engine of similar thrust.

Simplicity of design. Scramjets have few to no moving parts. Most of their body consists of continuous surfaces. With simple fuel pumps, reduced total components, and the reentry system being the craft itself, scramjet development tends to be more of a materials and modelling problem than anything else.

Additional propulsion requirements. A **scramjet** cannot produce efficient thrust unless boosted to high speed, at least Mach 5. Therefore a horizontal take-off aircraft could need conventional turbofan or rocket engines to take off, sufficiently large to move a heavy craft. Also needed would be fuel for those engines, plus all engine associated mounting structure and control systems. Turbofan engines are heavy and cannot easily exceed about Mach 2-3, so another propulsion method would be needed to reach scramjet operating speed. That could be ramjets or rockets. Those would also need their own separate fuel supply, structure, and systems. Many proposals instead call for a first stage of droppable solid rocket boosters, which greatly simplifies the design.

Testing difficulties. Unlike jet or rocket propulsion systems facilities which can be tested on the ground, testing scramjet designs uses extremely expensive hypersonic test chambers or expensive launch vehicles, both of which lead to high instrumentation costs. Launched test vehicles very typically end with destruction of the test item and instrumentation.

Lack of stealth. There is no published way to make a scramjet powered vehicle stealthy- since the vehicle would be very hot due its high speed within the atmosphere it should be easy to detect with infrared sensors.

Advantages and disadvantages for orbital vehicles

An advantage of a hypersonic airbreathing (typically **scramjet**) vehicle like the X-30 is avoiding or at least reducing the need for carrying oxidizer. For example the space shuttle external tank holds 616,432 kg of liquid oxygen (LOX) and 103,000 kg of liquid hydrogen (LH2). The shuttle orbiter itself weighs about 104,000 kg (max landing weight). Therefore 75% of the entire assembly weight is liquid oxygen. If carrying this could be eliminated, the vehicle could be lighter at takeoff and hopefully carry more payload. That would be a major advantage, but the central motivation in pursuing hypersonic airbreathing vehicles would be to reduce costs. Unfortunately there are several disadvantages:

Lower thrust-weight ratio. A rocket has the advantage that their engines have *very* high thrust-weight ratios (~100:1), whilst the tank to hold the liquid oxygen approaches a tankage ratio of ~100:1 also. Thus a rocket can achieve a very high mass fraction (Takeoff rocket mass:unfuelled rocket mass=fuel+oxidiser+structure+engines+payload:structure+engines), which improves performance. By way of contrast the projected thrust/weight ratio of scramjet engines of about 2 mean a very much larger percentage of the takeoff mass is engine (ignoring that this fraction increases anyway by a factor of about four due to the lack of onboard oxidiser). In addition the vehicle's lower thrust does not necessarily avoid the need for the expensive, bulky, and failure prone high performance turbopumps found in conventional liquid-fuelled rocket engines, since most scramjet designs seem to be incapable of orbital speeds in airbreathing mode, and hence extra rocket engines are needed.

Need additional engine(s) to reach orbit. Scramjets might be able to accelerate from approximately Mach 5-7 to around somewhere between half of orbital velocity and orbital velocity (X-30 research suggested that Mach 17 might be the limit compared to an orbital speed of mach 25, and other studies put the upper speed limit for a pure scramjet engine between Mach 10 and 25, depending on the assumptions made). Generally, another propulsion system (very typically rocket is proposed) is expected to be needed for the final acceleration into orbit. Since the delta-V is moderate and the payload fraction of scramjets high, lower performance rockets such as solids, hypergolics, or simple liquid fueled boosters might be acceptable. Opponents of scramjet research claim that most of the theoretical advantages for scramjets only accrue if a single stage to orbit (SSTO) vehicle can be successfully produced. Proponents of scramjet research claim that this is a straw man, and that SSTO vehicles are exactly as difficult to produce and bring the same benefits to rocket-powered and scramjet-powered launch vehicles.

Reentry. The scramjet's heat-resistant underside potentially doubles as its reentry system, if a single-stage-to-orbit vehicle using non-ablative, non-active cooling is visualised. If an ablative shielding is used on the engine, it will probably not be usable after ascent to orbit. If active cooling is used, the loss of all fuel during the burn to orbit will also mean the loss of all cooling for the TPS.

Costs. Reducing the amount of fuel and oxidizer, as in scramjets, means that the vehicle itself becomes a much larger percentage of the costs (rocket fuels are already cheap). Indeed, the unit cost of the vehicle can be expected to end up far higher, since aerospace hardware cost is probably about two orders of magnitude higher than liquid oxygen and tankage. Still, if scramjets enable reusable vehicles, this could theoretically be a cost benefit. Whether equipment subject to the extreme conditions of a scramjet can be reused sufficiently many times is unclear; all flown scramjet tests are only designed to survive for short periods.

The eventual cost of such a vehicle is the subject of intense debate since even the best estimates disagree whether a scramjet vehicle would be advantageous. It is likely that a scramjet vehicle would need to lift more load than a rocket of equal takeoff weight in order to be equally as cost efficient (if the scramjet is a non-reusable vehicle).

Applications

Seeing its potential, organizations around the world are researching scramjet technology. Scramjets will likely propel missiles first, since that application requires only cruise operation instead of net thrust production. Much of the money for the current research comes from governmental defence research contracts.

Space launch vehicles may or may not benefit from having a scramjet stage. A scramjet stage of a launch vehicle theoretically provides a specific impulse with 1000 to 4000 s whereas a rocket provides less than 600 s while in the atmosphere[23], potentially permitting much cheaper access to space. However, a scramjet's specific impulse decreases rapidly with speed, as the vehicle exhibits increased drag.

One issue is that scramjet engines are predicted to have exceptionally poor thrust to weight ratio- around 2 [4]. This compares **very** unfavourably with the 50-100 of a typical rocket engine. This is compensated for in scramjets partly because the weight of the vehicle would be carried by aerodynamic lift rather than pure rocket power (giving reduced 'gravity losses'), but scramjets would take much longer to get to orbit due to lower thrust which greatly offsets the advantage. The takeoff weight of a scramjet vehicle is significantly reduced over that of a rocket, due to the lack of onboard oxidiser, but increased by the structural requirements of the larger and heavier engines.

Whether this vehicle would be reusable or not is still a subject of debate and research.

An aircraft using this type of jet engine could dramatically reduce the time it takes to travel from one place to another, potentially putting any place on Earth within a 90 minute flight. However, there are questions about whether such a vehicle could carry enough fuel to make useful length trips, and there are obvious issues with sonic booms.

There are also questions as to how realistic such a proposal is that revolve around costs (capital and maintenance) of technology that is yet to be developed.

Recent progress

In recent years, significant progress has been made in the development of hypersonic technology, particularly in the field of scramjet engines.

US efforts are probably the best funded, and the Hyper-X group have claimed the first flight of a thrust-producing scramjet with full aerodynamic manouvering surfaces. The first to demonstrate a scramjet working in an atmospheric test was a shoestring project by an Australian team at the University of Queensland. The university's HyShot project demonstrated scramjet combustion in July 30, 2002. This demonstration was somewhat limited, however; while the scramjet engine worked effectively and demonstrated supersonic combustion in action, the engine was not designed to provide thrust to propel a craft. Both of these projects are ongoing. At least the following nations have active scramjet programs (by alphabetical order):

- Australia
- France
- Germany
- Great Britain
- India
- Italy
- Japan
- Russia
- South Korea
- Sweden
- Unites States of America

The US Air Force and Pratt and Whitney have cooperated on the Hypersonic Technology (HyTECH) scramjet engine, which has now been demonstrated in a wind-tunnel environment. NASA's Marshall Space Propulsion Center has introduced an Integrated Systems Test of an Air-Breathing Rocket (ISTAR) program, prompting Pratt & Whitney, Aerojet, and Rocketdyne to join forces for development.

To coordinate hypersonic technology development, the various factions interested in hypersonic research have formed two integrated product teams (IPTs): one to consolidate Army, Air Force, and Navy hypersonic weapons research, the other to consolidate Air Force and NASA space transportation and hypersonic aircraft work. Current funding levels are relatively low, no more than US $85 million per year in total, but are expected to rise.

The most advanced US hypersonics program is the US $250 million NASA Langley Hyper-X X-43A effort, which flew small test vehicles to demonstrate hydrogen-fueled scramjet engines. NASA is working with contractors Boeing, Microcraft, and the General Applied Science Laboratory (GASL) on the project.

The NASA Langley, Marshall, and Glenn Centers are now all heavily engaged in hypersonic propulsion studies. The Glenn Center is taking leadership on a Mach 4 turbine engine of interest to the USAF. As for the X-43A Hyper-X, three follow-on projects are now under consideration:

- X-43B: A scaled-up version of the X-43A, to be powered by the ISTAR engine. ISTAR will use a hydrocarbon-based liquid-rocket mode for initial boost, a ramjet mode for speeds above Mach 2.5, and a scramjet mode for speeds above Mach 5 to take it to maximum speeds of at least Mach 7. A version intended for space launch could then return to rocket mode for final boost into space. ISTAR is based on a proprietary Aerojet design called a "strutjet", which is currently undergoing wind-tunnel testing.

- X-43C: NASA is in discussions with the Air Force on development of a variant of the X-43A that would use the HyTECH hydrocarbon-fueled scramjet engine.

While most scramjet designs to date have used hydrogen fuel, HyTech runs on conventional kerosene-type hydrocarbon fuels, which are much more practical for support of operational vehicles. A full-scale engine is now being built, which will use its own fuel for cooling. Using fuel for engine cooling is nothing new, but the cooling system will also act as a chemical reactor, breaking long-chain hydrocarbons down into short-chain hydrocarbons that burn more rapidly.

- X-43D: A version of the X-43A with a hydrogen-powered scramjet engine with a maximum speed of Mach 15.

Hypersonic development efforts are also in progress in other nations. The French are now considering their own scramjet test vehicle and are in discussions with the Russians for boosters that would carry it to launch speeds. The approach is very similar to that used with the current NASA X-43A demonstrator.

Several scramjet designs are now under investigation with Russian assistance. One of these options or a combination of them will be selected by ONERA, the French aerospace research agency, with the EADS conglomerate providing technical backup. The notional immediate goal of the study is to produce a hypersonic air-to-surface missile named "Promethee", which would be about 6 meters (20 ft) long and weigh 1,700 kilograms (3,750 lb).

See also

- Rockwell X-30
- Hyper-X
- Single-stage to orbit
- X-43A
- HyShot
- Liquid air cycle engine
- Atmospheric reentry