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SUMMARY

Methane, the principal constituent of liquefied natural gas, is an attractive fuel for advanced airplanes. In particular, the commercial supersonic transport derives considerable benefit from methane's improved heating value and cooling capacity compared to conventional kerosene. Potential increases of about 30 percent in payload and a like reduction in direct operating cost have been predicted. However, the characteristics of liquid methane, such as its low boiling temperature and relatively low density, cause practical problems in airplane design and operation. Research is being conducted by NASA in an attempt to illuminate and solve these problems. The work includes such areas as fuel tanks and insulation, engine fuel systems, combustors, and turbines.

RÉSUMÉ

Le méthane, élément constitutif principal du gaz naturel liquéfié (LNG), est un combustible intéressant pour les avions avancés. Particulièrement, en comparaison avec le kérosène ordinaire, l'avion commercial de transport supersonique tire un bénéfice considérable de la valeur de chauffage et de la capacité de refroidissement perfectionnées du méthane. Des augmentations potentionnelles du poids utile d'environ 30% et une baisse des prix directs d'opération ont été prédites. Toutefois, les caractéristiques du méthane liquide, telles que son point d'ébullition bas et sa densité relativement basse, par exemple, entraînent des problèmes pratiques dans les domaines du dessin et de l'opération des avions. La NASA se trouve en train de rechercher ces problèmes afin de les éclairer et de les résoudre. Le travail comprend des domaines tels que les réservoirs de carburant et l'isolement, les systèmes de combustible à moteur, les combusteurs et les turbines.

INTRODUCTION

During its comparatively short existence, air travel has revolutionized military warfare and the movement of both people and cargo. Its great success in achieving high-speed, long-range, economical transportation has been largely due to striking advances in the technology of aerodynamics, airframe structures, and propulsion systems. Further advances will no doubt continue to be made. Nevertheless, it is becoming more difficult to envision major gains in these areas, while at the same time new concepts for air vehicles are being proposed that are hard to implement with current technology. Such concepts range from vertical-takeoff airplanes, through supersonic transports, to airbreathing boosters that place payloads into orbit about the Earth.

A common characteristic of most of these concepts is the demand for unusually large amounts of propulsive thrust and/or fuel. In an effort to satisfy this demand, attention in recent years has been directed to a component of the airplane that has heretofore been comparatively neglected. In most airplanes the single heaviest component is the fuel. And yet most designers have accepted without challenge the use of the traditional, conventional fuel that has been available since the first flight of the Wright Brothers nearly 70 years ago, viz., kerosene or slight variants thereof (e.g., gasoline or JP).

In the 1950's considerable effort was expended in the United States to derive alternative fuels that did not suffer from the limitations of kerosene. The effort was primarily aimed at military applications and, with the advent of the space age and ballistic missiles, was terminated without having achieved any significant success.

In the 1960's serious studies began in several countries on the subject of the commercial supersonic transport (SST). Despite significant achievements since then in aerodynamics, structures, and propulsion, it has proven extremely difficult to design a vehicle with an economically attractive combination of long range and adequate passenger capacity. In 1964 the author and his associates at the National Aeronautics and Space Administration (NASA) "re-discovered" the idea of improving this situation through the use of an alternative fuel. Because the intended application was a commercial one, fuel cost, availability, and safety were of prime importance. The selected fuel was liquid methane, the principal constituent of liquefied natural gas (LNG). Much work has been performed since that time concerning the concept and has been extensively reported in the literature. It is the purpose of this paper to briefly review the merits of methane as a potential aircraft fuel, the major problem areas that have been identified, and the research at NASA that is attempting to solve these problems. Primary emphasis will be placed on the SST application, since it has received the most attention and thus far appears to derive the most benefit from methane.

I. AIRPLANE PERFORMANCE

There are two major attributes of liquid methane that make it a desirable fuel for aircraft:

(1) It possesses a heat of combustion approximately 13-percent higher than that of kerosene. As a result, an airplane could fly about 13-percent farther, all other things being equal. Alternatively, the range could be held constant and either the airplane gross weight reduced or the payload increased. This last case (variable payload) yields the most spectacular improvement, but it is not necessarily best suited to the requirements of the airline operator.

(2) It has a cooling capacity some 4 to 6 times greater than kerosene. This is partly because the liquid methane starts out from such a low temperature (-162° C), but mostly because it can be raised to a high temperature (perhaps 700° C) before it decomposes to a significant extent. This high cooling capacity is employed to cool the turbine blades of the jet engines, either by passing the cold fuel through passages within the blades or by cooling with fuel a small amount of air bled from the compressor, which in turn is passed through the hollow blades. In either case it then becomes possible to raise the combustion temperature without overheating the metal of the blades. The thermodynamic benefit of higher combustion temperature is a significant reduction in engine weight plus a more modest reduction in fuel consumption.

The net effect of improved heating value and higher temperature on airplane performance is shown in figure 1. The vehicle assumed is a hypothetical SST designed to cruise at a Mach number of 3 with a specified range and takeoff gross weight. Passenger-carrying capacity is then used as the figure of merit. At a fixed value of turbine-inlet gas temperature (1200° C), the methane-fueled version can carry 17 percent more passengers than the kerosene version. To this can be added the benefit of higher temperature. If, for example, methane cooling allows a temperature of 1500° C, the total improvement over kerosene is 27 percent.

The SST is a commercial device, so economics must also be considered. A common measure of efficiency in aircraft is direct operating cost (DOC), which indicates the operating expense of carrying one passenger over a unit distance. The relative DOC's of methane and kerosene are compared in figure 2. (As in the previous figure, range and gross weight are equal for the two airplanes. Other means of comparison are not quite so favorable for illustrating the advantage of methane.) The results are quite dependent upon the unit cost of the fuel delivered onboard the airplane. For an estimated methane cost of 3.5 cent/kg vs. 4.0 cent/kg for kerosene, methane offers a possible reduction in DOC of about 30 percent. Such a saving would be of great significance to an airline operator.

II. PRACTICAL PROBLEMS

The preceding section presented a bright view of the potential of methane as a fuel. This section makes a more sober appraisal of the various difficulties that interfere with the realization of that potential.

Some of the problems are associated with the low density of methane. Liquefying the gaseous fuel reduces its volume by more than 600 times. But even then it occupies almost twice the volume of an equal weight of kerosene. Finding sufficient storage space within the airplane to contain the bulky methane can be troublesome. It may become necessary to redesign the airframe in order to provide more volume. This can increase the structural weight and aerodynamic drag by an appreciable amount.

In order to minimize such redesign, a study has been made of pressurized fuel tanks that are specially shaped to utilize efficiently the space that is available. Figure 3 indicates that these tanks are expected to be quite light, even when constrained to other than the optimum, circular cross section. (Nevertheless, these tanks are heavier than those for kerosene, which is normally contained within the existing wing structure with essentially no weight penalty.)

Other tankage problems with methane arise from its low temperature. Insulation is required to minimize fuel losses due to heat transfer. Protection is required for only rather short times but is complicated by the high surface temperatures associated with supersonic flight (in the order of 300° C). Only a few centimeters of insulation are required, so that the weight penalties appear acceptable. The main problems are such practical ones as installation, inspection, and reliability through many wide temperature cycles.

A more unusual boiloff problem is unique to airplanes. During takeoff and climb the ambient pressure drops from 1 atmosphere at the ground to only about 1/20 of an atmosphere at cruising altitude. If a saturated liquid is exposed to such a pressure drop, large amounts of vapor are flashed off. In the case of methane, more than 10 percent of the fuel would be boiled away in this fashion. Possible solutions include using pressurized, high-strength tanks that do not permit the internal pressure to drop, pumping the evolved vapor into the engines, or subcooling the fuel prior to flight. Each of these approaches incurs difficulties that require more study.

The preceding problems involve the airframe and fuel tanks. Another class of problems concerns modifying the jet engines in order to operate properly with methane fuel. Figure 4 schematically illustrates the principal components of the type of engine presently proposed for the SST, the afterburning turbojet. Air enters the inlet, is compressed by an axial-flow compressor, is mixed with fuel and burned in the combustor, expands through a turbine (which powers the compressor), is reheated by further combustion in the afterburner, and finally is expanded through the exhaust nozzle to generate a high-velocity jet. The fuel is pumped from the tank through one or more heat exchangers (to cool engine oil, turbine blades, and the passenger cabin) and is finally injected into the combustors. The components that are affected by the use of methane instead of kerosene are the pump, heat exchanger, combustors, turbine, and the fuel control system.

III. NASA RESEARCH PROGRAM

The preceding section identified a number of problem areas associated with the use of methane in aircraft. This section briefly describes the research projects currently underway at the Lewis Research Center that are pertinent to these problems.

Engine fuel system. - The proper control of a jet engine during both steady-state and transient operation is a delicate and complicated procedure. The different characteristics of methane cause concern that difficulties may arise when an engine is operated on this fuel. To investigate this area a project has been initiated to test the dynamic behavior of a methane fuel system of the type that might be used in the SST. As indicated in figure 4, the experiment will integrate a pump, two heat exchangers, and a small turbojet engine, plus the necessary valves, sensors, and controls (not shown). Thermal inertia, trapped volumes, etc., of the components will be similar to those for a real airplane system.

One of the major design difficulties concerns the pump. Current aircraft pumps are constructed to always deliver excess fuel; when the engine fuel demand is low, the unneeded kerosene discharged by the pump is recirculated back to the pump inlet. With methane fuel, however, this would cause undesirable heating and aggravate the boiloff problem. Instead, it is desired to have the pump deliver only the amount of fuel required by the engine - a quantity that varies during different parts of the flight by a ratio of about 25 to 1. Required discharge pressure on the other hand remains fairly constant - about 4.8 MN/m^2 (700 psi). Being considered for this duty are positive-displacement pumps having either a variable-speed drive or a variable displacement.

In the tests some of the operating problems that will be studied are: possibility of delivering slugs of liquid into the combustor, coking, local hot spots, freezing of fluids in the heat exchanger, instability of two-phase flow, and off-design performance.

High-temperature engine design. - One of the virtues claimed earlier for methane was its allowing of higher turbine-inlet temperatures. The initial estimates of what this does to the engine are being refined by more detailed studies. Two deleterious effects have thus far been revealed. Firstly, the cooling capacity of methane does not appear to yield as high a temperature gain as was originally hoped. Secondly, it has been found that higher temperatures tend to generate undesirable increases in engine noise, which can be avoided only by accepting significant performance penalties. Research in techniques of turbine cooling and noise alleviation is being performed.

Fuel management. - An experimental investigation (under contract to the Martin-Marietta Corporation) was made of the behavior of methane in fuel tanks subjected to conditions to be expected in the SST. Four types of tanks were fabricated and tested in the rig sketched in figure 5. Both saturated and subcooled methane was exposed to representative combinations of external heating, shaking, internal pressure, filling, and emptying. Testing has been completed, but results are still being evaluated. It appears, however, that no major problems were encountered in pumping, sloshing, heat transfer, or pressure variations. Storage and handling have thus been successfully demonstrated in a simulated flight environment using flight-weight hardware based on present-day cryogenic technology.

Tank insulation. - An experimental program has been started with the goal of developing a rugged, lightweight insulation with a temperature range from -176° to 371° C. This project, also under contract to Martin-Marietta, will include evaluation of candidate materials, installation on representative tanks, and heat transfer tests. Both internal and external installations are being considered. At this time small segments of insulation panels have been built, fit on double-curved surfaces, and exposed to both high and cryogenic temperatures. A full-size tank is under construction.

Combustion. - From the standpoint of combustor design methane is an attractive fuel for several reasons. Injection as a heated vapor should promote high combustion efficiency and therefore allow greater freedom of design. Also, the combustion flame emits less radiant heat than does kerosene, which will tend to lower wall temperatures. Consequently a methane combustor is potentially lighter, simpler, and more durable than a kerosene combustor.

On the other hand, the flammability limits of methane are much narrower than those of kerosene. This could cause difficulties in securing efficient combustion over the wide range of fuel-air ratios demanded during engine operation. Furthermore, the gaseous injection is apt to be disadvantageous if it is necessary to relight the burner at high altitudes. In this situation the air velocity is high, its temperature and pressure are low, and rapid diffusion of the fuel make it difficult to attain the rich fuel-air ratio needed for ignition.

An extensive experimental program has been undertaken to study these combustion characteristics. Figure 6 pictures one of the designs currently being tested. Preliminary results of the program show that good efficiency is obtainable at most normal operating points, but tends to be poorer than for kerosene at low air temperatures and pressures. Heating of the fuel is very beneficial. Blowout and relight limits have thus far been poorer than with kerosene.

IV. CONCLUDING REMARKS

Liquid methane or LNG is potentially a desirable fuel for various future aircraft such as the SST. However, its unusual characteristics relative to conventional fuel pose many problems in the design and operation of engines, airframes, and fuel systems. To explore these problems an extensive research program has been initiated by NASA. Other problems also exist in such areas as availability, ground handling, cost, safety, and acceptability to the airline operator. Near-term use in aircraft is not anticipated, but it is hoped that continued research and development will lead to successful applications of this fuel to flight.

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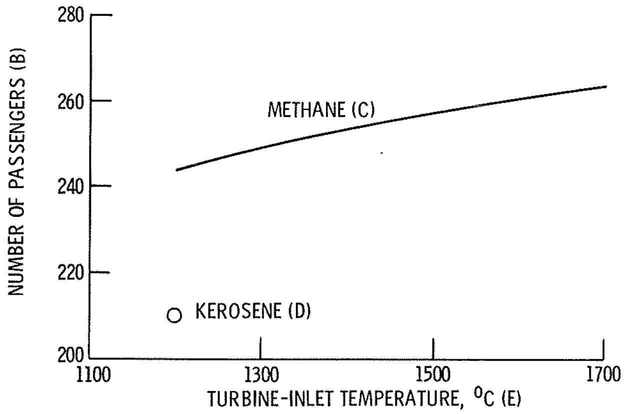

Figure 1. - Effect of turbine-inlet temperature. M3 SST; range, 6400 km; gross weight, 219 000 kg; no noise limits (A).

A - Effet de température à l'entrée de la turbine; M3 Avion de Transport Supersonique; portée = 6.400 km; poids brut = 219.000 km; pas de limite de bruit; B - Nombre de passagers. C - Méthane; D - Kérosène; E - Température à l'entrée de la turbine.

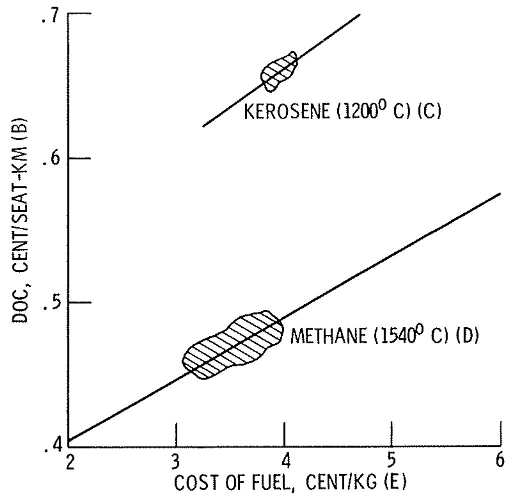

Figure 2. - Effect of fuel cost. M3 SST; range, 6400 km; gross weight, 219 000 kg; no noise limits. (A)

A - Effet du coût des combustibles; M3 Avion de Transport Supersonique; portée = 6.400 km; poids brut = 219.000 kg; pas de limite de bruit; B - PDO (prix directs d'operation), $.01 (US)/sièges-km; C - Kérosène (1.200° C); D - Méthane (1.540° C); E - Côut des combustibles, $.01/kg.

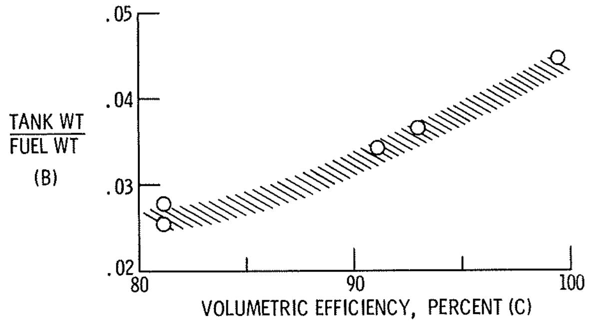

Figure 3. - Non-integral wing tanks. Titanium; 20.6 N/cm^2 internal pressure (A).

A - Réservoirs d'aile non-intégraux; Titane 20.6 N/cm^2 de pression interne; (B) Poids du réservoir/ Poids des combustibles; (C) Efficacite volumétrique, pourcentage.

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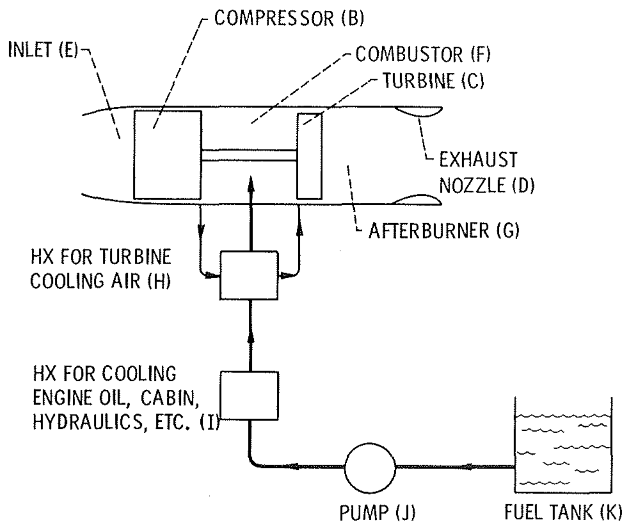

Figure 4. - Turbojet engine components (A).

A - Eléments constitutifs du turbo-réacteur; B - Compresseur; C - Turbine; D - Ajutage d'échappement; E - Entrée; F - Combusteur; G - Brûleur-arrière; H - Echangeur de temperature pour l'air de refroidissement de la turbine; I - Echangeur de température pour refroidir l'huile de moteur, la cabine, le système hydraulique, etc. J - Pompe; K - Réservoir de carburant.

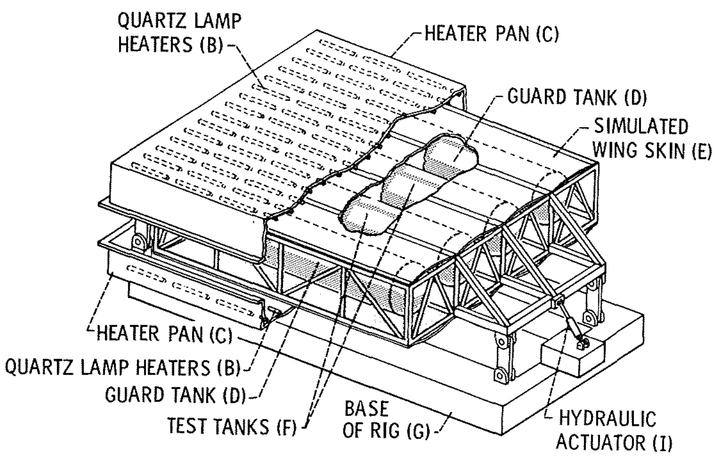

Figure 5. - Methane tank test rig (A).

A - Plateforme d'essai pour réservoirs de méthane. B - Lampes chauffantes a quartz; C - Enveloppe des lampes; D - Reservoir de garde; E - Revêtement de l'aile simulé; F - Réservoirs d'epreuve; G - Plateforme; I - Activateur hydraulique.

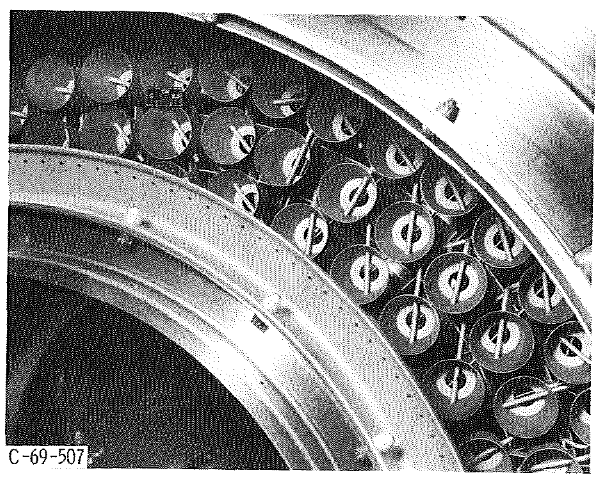

Figure 6. - Modular combustor designed for natural gas fuel (A).

A - Schéma d'un combusteur à module employant des combustibles au gas naturel.