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EXPERIMENTS ON METHODS FOR IMPROVED FUEL IGNITION IN SCRAMJET COMBUSTION SYSTEMS

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EXPERIMENTS ON METHODS FOR IMPROVED FUEL IGNITION IN SCRAMJET COMBUSTION SYSTEMS

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Abstract

Experimental results concerning the ignition characteristics of high velocity hydrogen diffusion flames are presented where ignition of the primary fuel flow is achieved by pre-burning small mass fractions of secondary hydrogen. The secondary combustion is catalytically induced by platinum surfaces. The experimental data indicate that conditions for self-ignition of the diffusion flames can be extended to very low temperature levels. Applied to ramjet and scramjet combustion systems at supersonic and moderate hypersonic aircraft velocities this technique may eliminate losses of flame stabilizers as well as the danger of flame-outs.

I. Introduction

Aircraft operating at hypersonic velocities with airbreathing propulsion will be exposed to severe aerodynamic heating. Hence active cooling of the structure and the engine will be necessary. Today it is generally assumed that liquid hydrogen as fuel will offer the required cooling capacity. Hydrogen is also very attractive because of it's high specific impulse.

The present paper deals with another property of hydrogen which makes it well suited for application in the hypersonic aircraft speed range, namely it's capability for thermal self-ignition at relative low static combustor entrance temperatures. From extensive ignition studies (1) it can be said that thermal self-ignition of supersonic hydrogen-air diffusion flames may be expected at aircraft Mach-numbers greater than 5.7. In a ramjet with subsonic combustion the limiting Mach-number would be 5.0.

However, in many cases it will be desirable to extend scramjet or ramjet propulsion into the range of relatively low aircraft Mach-numbers in order to provide a transition between the turbojet application range and hypersonic velocities. This paper will describe an experimental method by which thermal self-ignition of hydrogen-air diffusion flames can also be guaranteed in the transitional Mach-number range.

II. Apparatus and Procedure

A more detailed description of the test facility (2) has been given in an earlier publication. The required stagnation enthalpy of the test air is achieved by means of a pebble heater to which an expansion nozzle is directly connected.

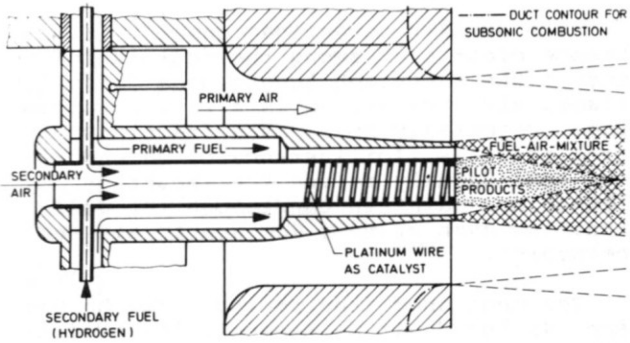


FIG. I SCHEMATIC GRAPH OF FUEL INJECTOR FOR PILOT STABILIZED SUPERSONIC AND SUBSONIC COMBUSTION

Figure 1 shows a schematic graph of the axisymmetric nozzle configuration with a cylindrical duct. The nozzle is equipped with a contoured fuel injector in a concentric position which has an outer exit diameter of lo mm. The outer shape of the injector provides the cross section distribution required for Laval-expansion to a Mach-number of 1.5. The shape of the cylindrical duct can be varied as indicated in Figure 1 in order to get subsonic exit Mach-numbers.

In the nozzle the air is expanded to pressure, Mach-number and static temperature conditions which can be expected at the entrance of a scramjet or ramjet combustor. Downstream of the injector exit, mixing of air and fuel occurs and the development of a diffusion flame can be observed within the free jet downstream of the nozzle configuration. If the static temperature is high enough, a diffusion flame is stabilized by thermal self-ignition.

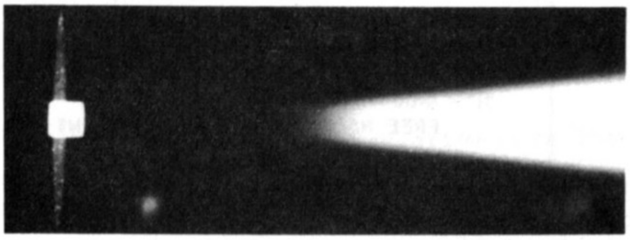


FIGURE 2. HYDROGEN DIFFUSION FLAME AT CONDITIONS FOR SPONTANEOUS IGNITION

Figure 2 shows a typical hydrogen diffusion flame at conditions for spontaneous ignition. Due to the ignition delay of the hydrogen-air system (3), a certain gap can be observed between flame front and injector edge. This gap may be called "induction length" which is a typical quantity characterizing the ignition properties of the system. If the static air temperature drops to lower values, the induction length will rapidly increase thus indicating a limit for the range of thermal self-ignition.

From earlier investigations (1) it has become clear that among the factors influencing the induction length of a diffusion flame, air composition is a very important one. Especially small mass fractions of free radicals (for instance O, OH and H) can considerably reduce the induction length and maintain conditions for self-ignition even at very low static air temperatures.

The mentioned free radicals may be present in humid air as dissociation products. If, for instance, air is at equilibrium composition upstream of the Laval-nozzle (Fig. 1), a certain amount of water vapor and oxygen is dissociated, according to the respective stagnation temperature. In the considered temperature range the composition will almost exactly be preserved during the rapid expansion through the Laval-nozzle.

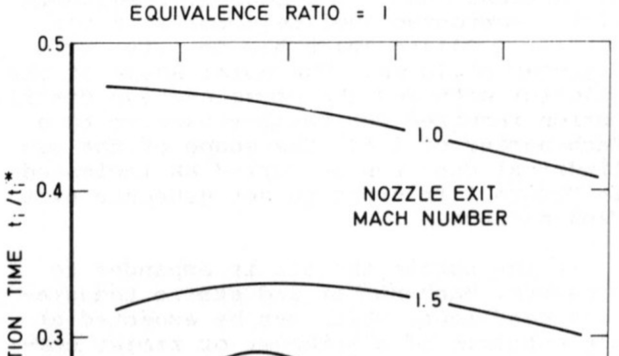


FIG. 3 REDUCTIONS OF INDUCTION TIME DUE TO PRESENCE OF FREE RADICALS O, OH AND H

AFTER APPROXIMATE CALCULATIONS BY F. SCHMALZ (3)

Due to the presence of the dissociation products O, OH and H, ignition of the diffusion flame downstream of the nozzle is promoted as shown in Fig. 3 where reductions of induction time are plotted vs. static temperature of a stoichiometric mixture for the Mach-numbers 1.o/1.5/1.8. At Mach 1.5, for example, the induction time is reduced roughly to one third of the time which would be observed without initial concentrations of free radicals. The results in Fig. 3 were obtained using an approximate kinetic calculation procedure as proposed by SCHMALZ (3).

A simple way to introduce additional free radicals into the induction zone of a diffusion flame is by pre-burning a small mass fraction of hydrogen. Pre-burning does not only provide species for chemical exertion of the induction mechanism but it simultaneously produces thermal energy by which the elementary induction reactions will be accelerated. Thus pre-burning can be expected to influence the ignition characteristics of a diffusion flame considerably.

The scheme in Fig. 1 demonstrates how fuel pre-burning was achieved in the considered test arrangement. Secondary air and secondary hydrogen was fed into a separate pre-burner placed at the axis of the injector having an outer diameter of 7 mm. The mass flow of the secondary hydrogen could be varied independently of the primary mass flow. Thus the optimum fuel/air ratio of the pre-burner could be chosen in all cases.

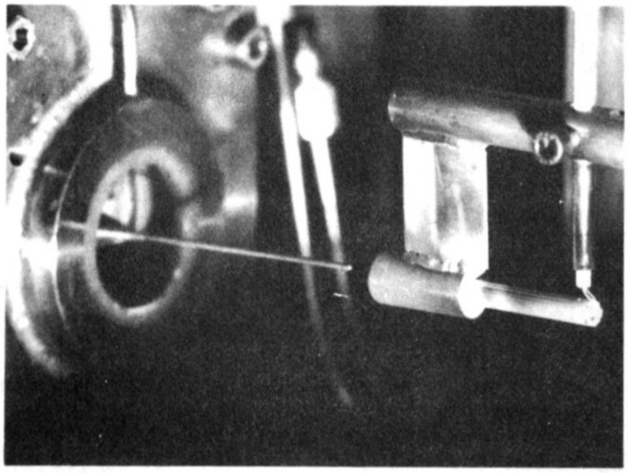


FIGURE 4. TEST ARRANGEMENT FOR OPTIMIZATION OF PRE-BURNER LENGTH.

In the course of several preliminary experiments it was found that catalytic influences can help very much to amplify the range of stable combustion in the pre-burner. Simple platinum wire was used as catalyst. The length of the platinum winding was optimized in an arrangement as shown in Fig. 4. A thin hollow lance could penetrate to variable positions within the pre-burner and eject the secondary hydrogen at it's tip. The tip position was recorded together with the exit wall temperature of the pre-burner.

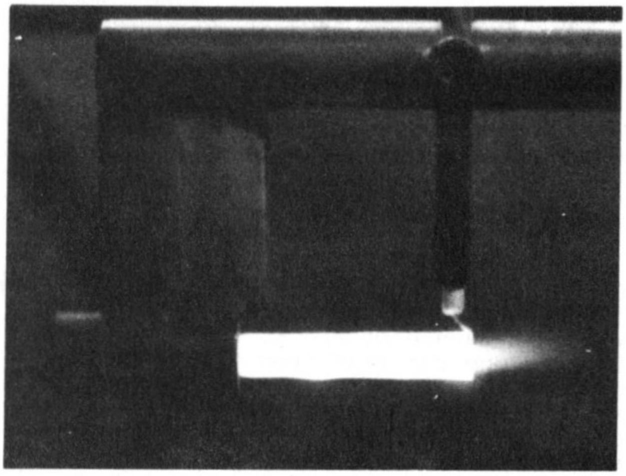
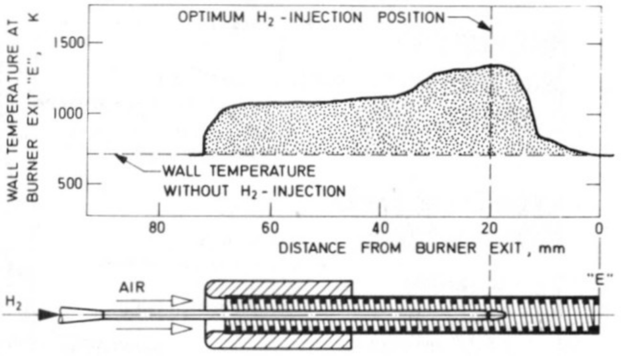


FIGURE 5. PRE-BURNER AS SHOWN IN FIGURE 4 IN OPERATION



AIR STAGN. TEMPERATURE : 870 K , MACH NO. : 0.65 , STAT. PRESSURE : 1 BAR
H_2-MASS FLOW = 2 PERCENT OF PRIMARY MASS FLOW WHEN Q = 0.1
(Q = H_2 MASS FLOW DENSITY / AIR MASS FLOW DENSITY)

FIG.6 TYPICAL PRE - BURNER EXIT WALL TEMPERATURE DISTRIBUTION VS. H_2 - INJECTION POSITION

Figure 5 shows the pre-burner during such an experiment. A typical exit wall temperature distribution as a function of the lance tip position is given by Figure 6. It was found that in the considered range of air temperatures and secondary hydrogen mass flows, a winding length of about 2o mm yields the highest exit wall temperatures of the pre-burner and hence presumably the highest exit temperature of the pre-burner products.

As shown in Figure 1, the pre-burner products penetrate into the primary fuel-air-mixture downstream of the exit and hence may act as a pilot to accelerate the reactions in the phase of the ignition delay.

III. Results

It was found that such an arrangement is very effective and may reduce the temperatures necessary for thermal self-ignition be several hundred degrees. This can be seen from Fig. 7, where induction lengths of Mach - 1.5 diffusion flames have been plotted over the static air temperature.

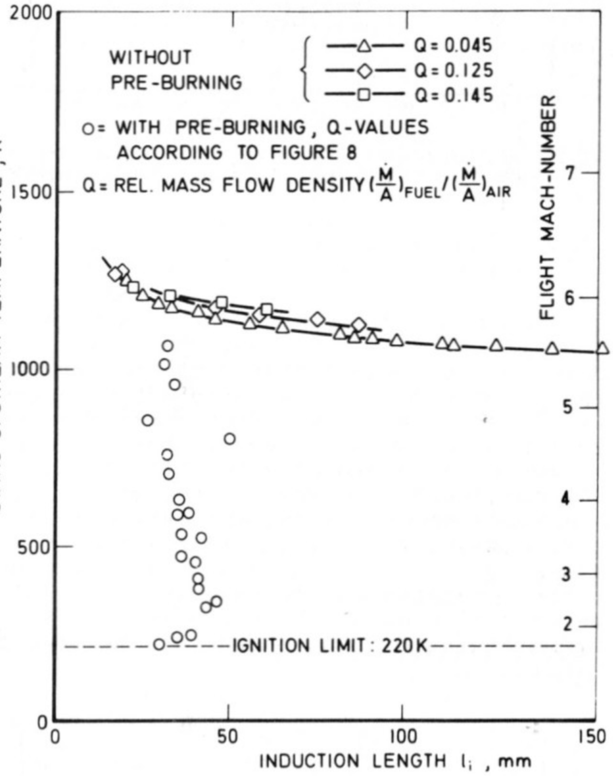


FIG. 7 INDUCTION LENGTHS WITHOUT AND WITH CATALYTICALLY INDUCED PRE-BURNING
MACH-NO. : 1.5 STAT. PRESSURE : 1 BAR

Some of the measured data are connected by lines. They indicate induction lengths without pre-burning. There is a rapid increase of the lengths below air temperatures of about 12oo K. As indicated, the lower temperature limit depends slightly on the hydrogen mass flow, measured by the relative mass flow density Q (=mass flow of hydrogen through injector exit unit area/ air mass flow through nozzle exit unit area). The circular symbols in Fig. 7 mark data which were measured in the case with pre-burning small mass fractions of hydrogen. It was possible to maintain induction lengths below 5o mm down to a burning limit of 22o K static air temperature.

On the other hand, the relative mass flow density Q had to be reduced in order to keep the induction lengths below the 5o mm limit. Figure 8 shows, for the conditions of Fig. 7, the Q-values as well as the pre-burned mass fractions of hydrogen, related to the total hydrogen mass flow. If a Q-value of o.1 is accepted as the lowest mass flow density of practical interest,

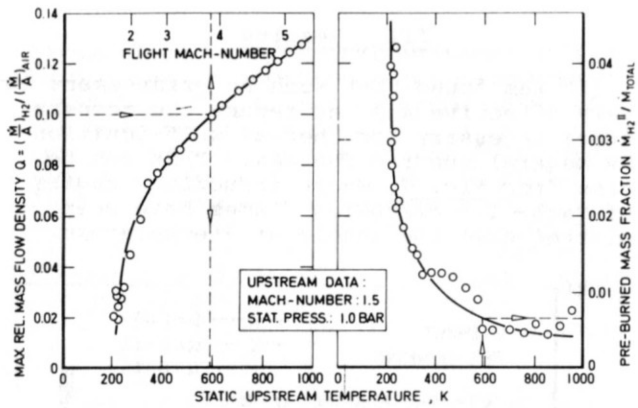


FIG. 8 MAXIMUM PRIMARY H_2-MASS FLOW DENSITIES AND MASS FRACTIONS OF CATALYTICALLY IGNITED SECONDARY HYDROGEN

one can conclude from Figure 8 that self-ignition at Mach 1.5 should be possible down to about 6oo K static air temperature, which corresponds to an aircraft Mach number of about 4. Here, from thermodynamic reasons, it would already be advantageous to apply the subsonic combustion mode. The described gain can be achieved by pre-burning less than 1 percent hydrogen, as indicated by the right hand diagram in Figure 8. During the experiments the pre-burner operated at equivalence ratios of about o.3 to o.25. So the burner exit temperatures did not exceed the structural limit.

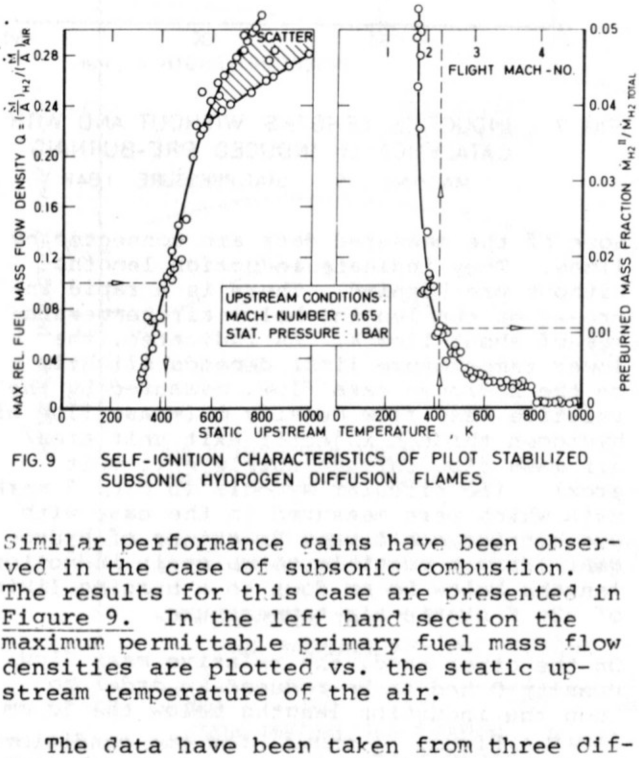


FIG. 9 SELF-IGNITION CHARACTERISTICS OF PILOT STABILIZED SUBSONIC HYDROGEN DIFFUSION FLAMES

Similar performance gains have been observed in the case of subsonic combustion. The results for this case are presented in Figure 9. In the left hand section the maximum permittable primary fuel mass flow densities are plotted vs. the static upstream temperature of the air.

The data have been taken from three different test runs and indicate that they can be reproduced satisfactorily. If, for example, in a practical case the relative fuel mass flow density must not fall short

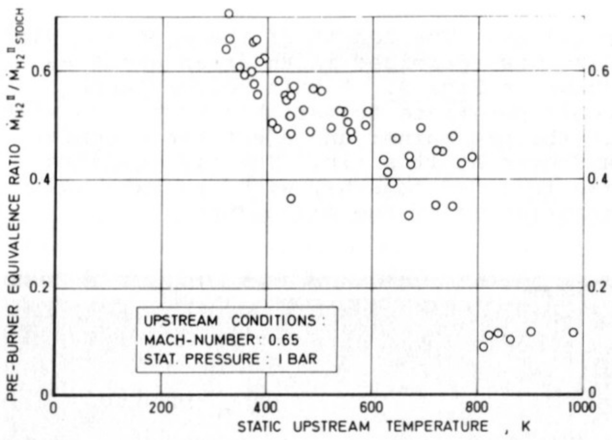
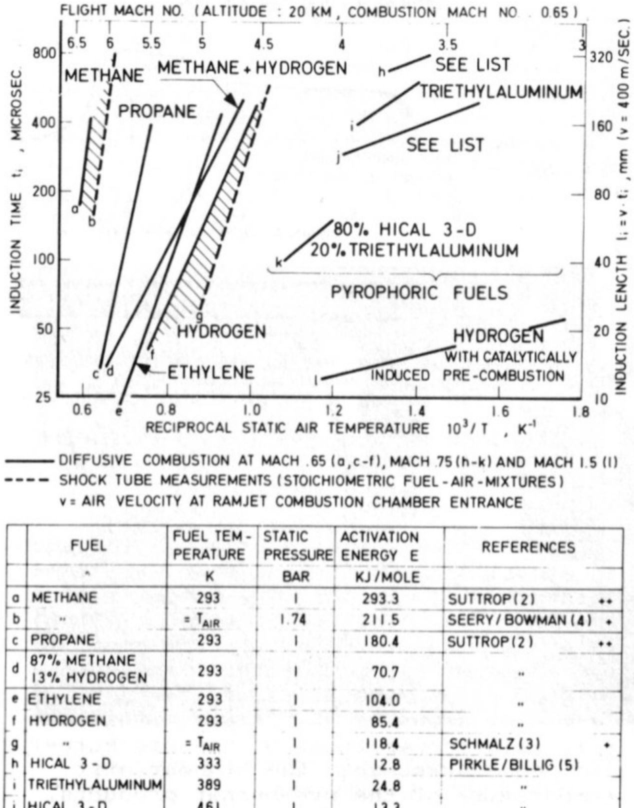


FIG. 10 PRE-BURNER EQUIVALENCE RATIOS FOR THE CONDITIONS SHOWN IN FIGURE 9

of Q = o.1, the left hand diagram of Figure 9 indicates a minimum permittable static air temperature of 42o K. For this temperature, one can read from the right hand diagram that a hydrogen mass fraction of about 1 percent must be pre-burned in order to ignite the primary fuel. The corresponding aircraft Mach-number in this special case is about 2.3. Typical pre-burner equivalence ratios for the conditions of Figure 9 are shown by Figure lo.



	FUEL	FUEL TEMPERATURE	STATIC PRESSURE	ACTIVATION ENERGY E	REFERENCES
	"	K	BAR	KJ/MOLE	
a	METHANE	293	1	293.3	SUTTROP (2) ++
b	"	= T_{AIR}	1.74	211.5	SEERY/BOWMAN (4) +
c	PROPANE	293	1	180.4	SUTTROP (2) ++
d	87% METHANE 13% HYDROGEN	293	1	70.7	"
e	ETHYLENE	293	1	104.0	"
f	HYDROGEN	293	1	85.4	"
g	"	= T_{AIR}	1	118.4	SCHMALZ (3) +
h	HICAL 3-D	333	1	12.8	PIRKLE/BILLIG (5)
i	TRIETHYLALUMINUM	389	1	24.8	"
j	HICAL 3-D	461	1	13.3	"
k	80% HICAL 3-D + 20% TRIETHYLALUM.	394	1	28.9	"
l	HYDROGEN	293	1	8.8	THIS PAPER +++

+) SHOCK TUBE DATA, ++) RELATIVE MASS FLOW DENSITY $Q = (\rho v)_{FUEL}/(\rho v)_{AIR} = 0.185$
+++) WITH CATALYTICALLY INDUCED PRE-COMBUSTION, Q-VALUES SEE FIG 8

FIG. 11 CORRELATION OF MEASURED INDUCTION TIMES ACCORDING TO THE RELATION $t_i = N \cdot \mathrm{EXP}(E/RT)$

Figure 11 relates the results to other ignition delay data on the basis of induction times which are plotted vs. the reciprocal static air temperature. Lines a through g present the self-ignition characteristics of the fuels methane, propane, ethylene and hydrogen, where the full lines correspond to diffusive combustion and the dashed lines symbolize shock tube results. Line h through k comprise induction times of pyrophoric fuels as derived from experiments with diffusion flames carried out by PIRKLE and BILLIG (5). The above described results obtained with catalytically induced pre-combustion are represented by line l in Figure 11. The graph clearly indicates the effectiveness of pre-burning (notice the difference between curves f and l) which makes hydrogen even more inflammable than the pyrophoric fuels. This becomes also evident when the apparent over-all activation energies of the different fuels are compared (see list, Figure 11).

IV. Conclusions

Pre-burning a small amount of hydrogen proved to be a very effective ignition aid both in subsonic and supersonic diffusive combustion. Best results are obtained when the pre-combustion is induced catalytically.

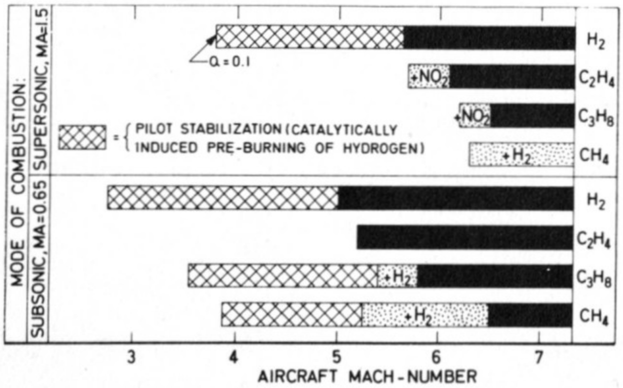


FIG. 12 OPERATIONAL RANGES OF THERMAL SELF-IGNITION IN RAMJET AND SCRAMJET COMBUSTION SYSTEMS
INDUCTION LENGTHS ≤ 50mm, STATIC IGNITION ZONE PRESSURE : 1 BAR
RELATIVE FUEL MASS FLOW DENSITY : $Q = (\dot{M}/A)_{FUEL} / (\dot{M}/A)_{AIR} \geq 0.185 \, (0.1)$

Figure 12 which was taken from an earlier publication (2) summarizes the results indicating the application ranges of diffusive hydrogen combustion with thermal self-ignition at subsonic and supersonic burner velocities. The ranges (full beams) are compared with the respective ranges of several hydrocarbons as investigated earlier (2). The ignition performance deteriorates in the sequence hydrogen, ethylene, propane, methane.

The cross-hatched beams in Figure 12 indicate the gains in aircraft Mach-number which can be obtained by application of the described piloting system. As far as hydrogen is concerned as primary fuel, the aircraft Mach-number limits are extended to very low values. Thermal self-ignition can be applied to ramjet and scramjet combustion throughout the interesting application ranges. It would also be applicable to hydrogen fuelled turbojet combustion, for instance in the NASA Space Shuttle landing engines.

If the same technique is applied to hydrocarbon combustion, substantial range extensions are possible too. As shown in Figure 12, hydrocarbon fuelled ramjet operation with pilot induced ignition is possible at aircraft Mach-numbers above and slightly below 4. Especially methane may become more interesting in the future since it is a major constituent of natural gas. It may be expected that the described technique can also be applied in supersonic turbojets which are fuelled with liquid natural gas. However, further research and development work is required to answer this question.

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