Sensitivity of Premixed Compression-Initiated Supersonic Combustion to Small Perturbations in Inlet Flow Variables

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An analysis of the sensitivity of a scramjet combustor to small perturbations in the inlet flow variables is presented. The analysis is limited to a combustor having perfectly premixed fuel and air at the inlet with combustion being initiated with a compression process, a shock wave for example. Flow in the combustor is taken to be inviscid, one dimensional, and adiabatic with the fuel being hydrogen gas in stoichiometric proportions. Both constant pressure and constant area combustion processes are considered. Numerical results are presented for combustor inlet conditions corresponding to a wide range of flight conditions. The major conclusion is that the combustion process can be quite sensitive to small perturbations in the inlet flow variables.

Nomenclature

h = combustor height at inlet
L_{id} = ignition delay length
M = Mach number
p = static pressure
T = static temperature
V = velocity
δ = inlet wedge angle
θ_{M_3} = Mach line angle corresponding to M_3

I. Introduction

For several years, considerable controversy has centered around the feasibility of premixing fuel with air at low temperature on the inlet of a supersonic combustion ramjet engine (scramjet) and igniting the combustible mixture with a compression process, a shock wave for example. There is considerable experimental evidence to indicate that stationary stable heat release in a flowing combustible mixture that is ignited with a shock is possible.[1–5] It is also reasonable to assume that this condition can be achieved with other compression processes. Some of the merits of premixing are discussed at length by Rubins and Bauer[6]; however, four possible merits may be simply stated as follows: reduction in combustor length, reduction in skin fraction drag on the inlet if a low molecular weight fuel is used, cooling of the inlet, and control of the effective inlet contour. Ferri[7] pointed out the sensitivity of shock-initiated combustion under premixed conditions but in the absence of any analysis or experimental verification.

This paper is primarily concerned with a theoretical study of the sensitivity of the combustion process in a scramjet combustor, using premixed compression-initiated combustion, to small perturbations in the inlet flow variables. Some of the results apply to other combustion schemes in which mixing is essentially complete before appreciable chemical reaction occurs. For example, for flight at very high altitudes and velocities, mixing may be complete before combustion begins even when fuel is injected directly into the combustor and not premixed on the inlet.

When the fuel and air are premixed upon entering the combustor, the rate of heat release is controlled by the kinetics of the chemical reactions in the combustion process. This is in contrast to the mixing-controlled method of combustion in which, as the term implies, the rate of heat release is controlled by the rate at which fuel and oxidizer can be brought into contact by mixing. The compression-initiated combustion process differs from the conventional detonation wave in that chemical reaction and the attendant heat release do not necessarily affect the compression process.

II. Sensitivity of the Combustion Process to Small Perturbations in the Inlet Flow Variables

During flight through the atmosphere, perturbations in the flow variables at the inlet of a combustor are to be expected from, for example, small variations in angle of attack and variations in atmospheric temperature. For a fixed geometry engine, it can be shown that there is only one free-stream Mach number that will yield precisely on-design conditions at the entrance of the combustor. In general, a small variation in angle of attack or atmospheric temperature will result in simultaneous perturbations in all inlet variables. However, for this study, a perturbation in only one variable at the time is considered while all other variables are held fixed. It should be emphasized that this analysis treats the quasi-steady behavior of the combustor and not the transient behavior.

It might be expected that some of the problems associated with sensitivity of the combustion process to variations in the inlet flow variables can be attributed to the interaction of the heat release from combustion with the compression process. A quantitative analysis of this problem is beyond the scope of this paper; however, some qualitative aspects of the problem are discussed later. For purposes of analysis, it is postulated that the compression process is entirely a gas dynamic phenomenon which acts to heat the combustible mixture above ignition conditions and that heat release occurs without affecting the compression process. Additional postulates for purposes of analysis are the flow in the

Presented as Paper 68-995 at the AIAA 5th Annual Meeting and Technical Display, Philadelphia, Pa., October 21–24, 1968; submitted October 28, 1968; revision received July 16, 1969. The work described in this paper was performed under the provisions of United States Air Force Contract F40600-69-C-0001 with ARO Inc., the operating contractor of the Arnold Engineering Development Center for the Air Force Systems Command with partial financial support provided by the Air Force Office of Aerospace Research under Air Force Project 6952. Further reproduction is authorized to satisfy the needs of the U.S. Government. The author acknowledges the helpful suggestions of R. P. Rhodes, R. C. Bauer, and C. E. Peters and the efforts of W. J. Phares, K. W. Allen, and I. T. Osgerby with regard to the chemical kinetics computer program. The data presented in Fig. 13 were based on unpublished calculations performed by J. Garner.

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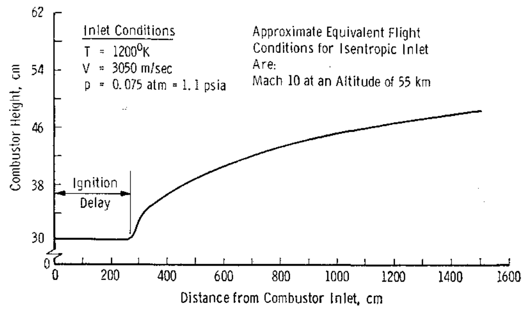

Fig. 1 Schematic of a planar constant pressure combustor.

combustor is inviscid, one dimensional, quasi-steady and adiabatic, the fuel is hydrogen gas and the equivalence ratio is unity, and the fuel is completely premixed with the air at the inlet of the combustor.

On the basis of these postulates, the problem has been reduced to that of analysis of a one-dimensional chemically reacting stream tube. The equations governing the flow are given by Ferri et al.[8] A computer program was written to solve these equations for the hydrogen air system. The solution techniques used in the program are discussed by Osgerby.[9] The model for chemical kinetics used in this study is the one proposed by Strehlow and has been shown to be in good agreement with experiments conducted in subsonic combustion of hydrogen with air.[10]

The mass fractions of all species except N_2, O_2, and H_2 were taken to be 10^{-16} at the entrance of the combustor. In all cases, the static pressure distribution is taken to be indicative of the sensitivity of the combustion process to perturbations in the inlet flow variables. In general, however, any influence on the static pressure distribution is accompanied by corresponding effects on temperature, velocity, and species concentration distributions in the combustor.

Constant Pressure Combustion

To study the behavior of a constant pressure combustor for given inlet conditions, it is necessary to know the combustor geometry, that is, the variation of cross-sectional area with distance from the combustor inlet. The computer program previously mentioned has the option of prescribing constant pressure or area variation along the combustor. Thus, the constant pressure version was used to calculate a corresponding combustor contour, and for this contour, the prescribed area version was used subsequently to determine the behavior of the combustor for inlet conditions perturbed from the design values. Figure 1 illustrates schematically a typical constant pressure combustor. It can be noted that the combustor is comprised of a constant area section, corresponding to the period of ignition delay, followed by a diverging section corresponding to the period of recombination and heat release.

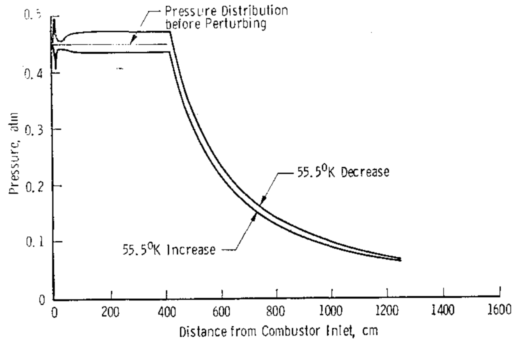

Fig. 2 Effect of perturbing inlet static temperature, case 1.

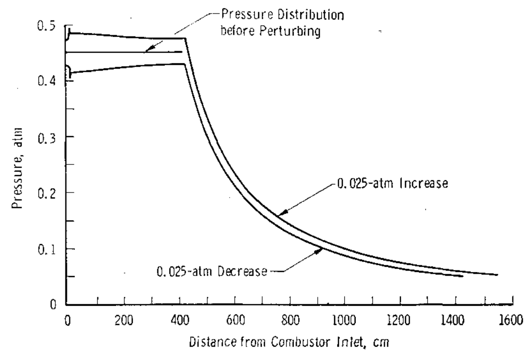

Fig. 3 Effect of perturbing inlet static pressure, case 1.

The first set of combustor inlet conditions considered is as follows: $V = 3050$ m/sec, $p = 0.45$ atm, and $T = 1504.1°K$. Isentropic compression to these conditions corresponds approximately to flight at Mach 10.5 at an altitude of 47.8 km. Figure 2 shows that a 55.5°K (3.7%) perturbation in the inlet temperature results in a 10% peak change in the static pressure distribution in the combustor. The distance beyond 400 cm in this figure, as well as in Figs. 3 and 4, corresponds to a nozzle whose cross-sectional area increases linearly with distance. Figure 3 shows that a 5% perturbation in inlet static pressure will cause a peak change of 5% from the inlet pressure and a total change of 10% from the design pressure. In Fig. 4, it can be noted that changing the mass fraction of atomic hydrogen from 10^{-16} to 10^{-8} produces a pressure spike of approximately 20%. Thus, although concentrations of free radicals may be small, the concentrations are quite important in establishing the ignition delay distance for flow in the combustor.

In the next four sets of combustor inlet conditions considered, the inlet velocity and temperature are 3050 km/sec and 1200°K, respectively. Only the static pressure level is varied, and only the static temperature is perturbed. The corresponding flight conditions for an isentropic inlet are given for each pressure on the respective figure.

Figure 5 shows that positive and negative perturbations of 60°K (5%) in the inlet temperature cause, respectively, 20.4 and 25.3% peak changes in static pressure in the combustor for an inlet static pressure of 0.075 atm. The combustor contour shown in Fig. 1 is for this set of inlet conditions.

For an inlet static pressure of 0.1 atm, Fig. 6 shows that a positive perturbation of 5% in inlet temperature causes a peak increase of 23.5% in the static pressure, whereas a negative perturbation of the same magnitude causes a peak decrease of 29.5% in the pressure.

As shown in Fig. 7, positive and negative 5% perturbations in inlet temperature produce maximum changes in static pressure in the combustor of 39.8 and 46.2%, respectively, for an inlet pressure of 0.25 atm.

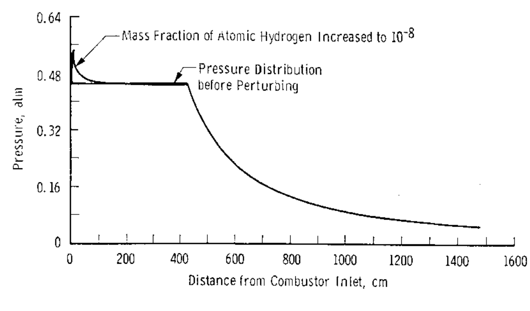

Fig. 4 Effect of changing atomic hydrogen concentration, case 1.

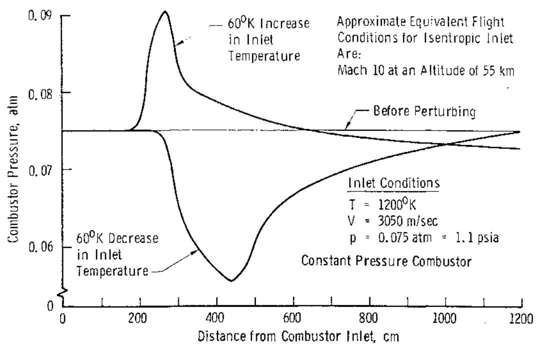

Fig. 5 Effect of perturbing inlet temperature, case 2.

For an inlet static pressure of 0.75 atm, a positive perturbation in inlet temperature of only 5% causes a 76% peak increase in static pressure inside the combustor. This is shown in Fig. 8.

A comparison of the pressure distributions for the preceding four sets of inlet conditions shows that the recombination distance decreases rapidly with increasing pressure. This implies that the rate of cross-sectional area increase, after the ignition delay section, must increase rapidly with increasing pressure in order to accommodate the increase in the rate of heat release. It can be further concluded that sensitivity of the combustion process, based on the peak pressure change in the combustor, to perturbations in the inlet temperature increases with increasing pressure. This is shown in Fig. 9 where the peak change in static pressure in the combustor has been plotted vs the static pressure level for a 5% perturbation in inlet temperature. No explanation is offered for the nearly straight line behavior of the curves on logarithmic coordinates.

To determine the effect of static temperature level on the sensitivity of the combustion process, a constant pressure combustor was designed for an inlet pressure of 0.075 atm, an inlet temperature of 1300°K, and a velocity of 3050 m/sec. For this combustor, it was found that a positive perturbation of 5% in the static temperature caused a peak increase of 13.3% in the static pressure in the combustor. As mentioned previously, a 5% perturbation in temperature for inlet pressure, temperature, and velocity of 0.075 atm, 1200°K, and 3050 m/sec, respectively, results in a 20.4% peak increase in combustor pressure. Thus, the sensitivity of the combustion process decreases with increasing temperature at the inlet of the combustor.

With the exception of the first set of combustor inlet conditions considered, perturbations in the inlet temperature have been taken to be 5%. Figure 10 illustrates the effect of the magnitude of the perturbation in inlet temperature on peak pressure increase in the combustor for inlet conditions identical to the second set considered previously. It is interesting to note that the rate of change in peak pressure increase is greatest for no perturbation in temperature.

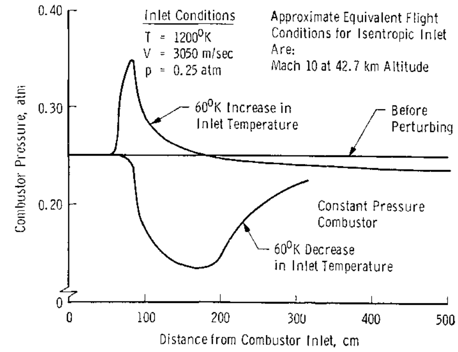

Fig. 7 Effect of perturbing inlet static temperature, case 4.

Within the framework of the postulates made in the analysis, it can be concluded from the results given earlier that the constant pressure combustion process can be quite sensitive to small perturbations in the inlet flow variables. To a large degree, the sensitivity can be attributed to the rapid area change after the period of ignition delay in the constant pressure combustor. The constant area combustion process is now investigated.

Constant Area Combustion

Unlike the constant pressure combustor, the constant area combustor does not have an area change after the period of ignition delay. It follows that perturbations in the temperature and pressure at the inlet of a constant area combustor will merely shift the position of the heat release zone with relatively little effect on the level of the pressure distribution in the combustor. Of course, the inlet Mach number must be high enough so that the perturbations will not cause the flow to thermally choke. For an inlet pressure, temperature, and velocity of 0.075 atm, 1200°K, and 3050 m/sec, respectively, Fig. 11 shows that a 5% increase in inlet temperature moves the heat release zone forward by approximately 30%. Clearly, there is no spike in the pressure distribution as occurred for the corresponding constant pressure case shown in Fig. 5. One can conclude that constant area combustion can be much less sensitive to perturbations in inlet flow variables than constant pressure combustion. However, if the inlet Mach number is low enough for the flow in the combustor to be on the verge of thermally choking, constant area combustion may be much more sensitive than constant pressure combustion. Moreover, Fig. 11 shows that there is a strong adverse pressure gradient associated with constant area combustion, and there is reason to doubt that such adverse pressure gradients can be tolerated in an actual engine. A strong adverse pressure gradient may not allow the boundary layer to stay attached to the walls of the combustor. It is worthy to note that the pressure gradient increases with increasing combustor pressure just as the

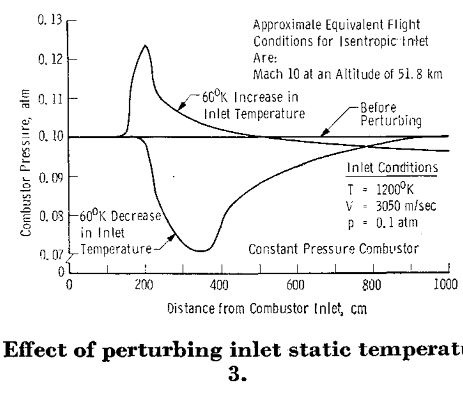

Fig. 6 Effect of perturbing inlet static temperature, case 3.

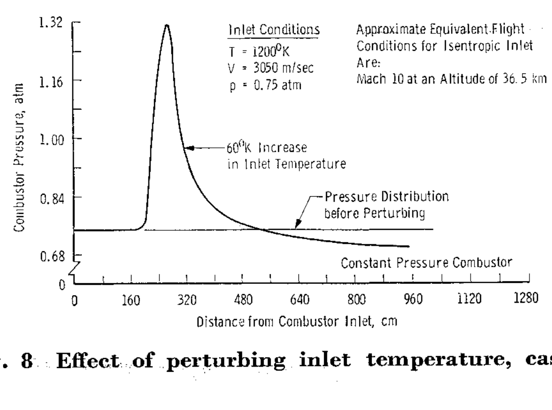

Fig. 8 Effect of perturbing inlet temperature, case 5.

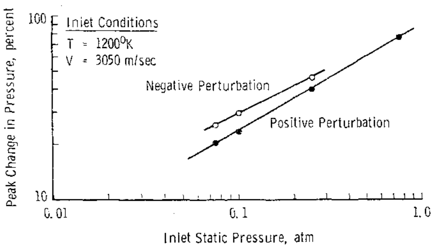

Fig. 9 Effect of static pressure level on maximum change in pressure in combustor for 5% perturbation in inlet temperature.

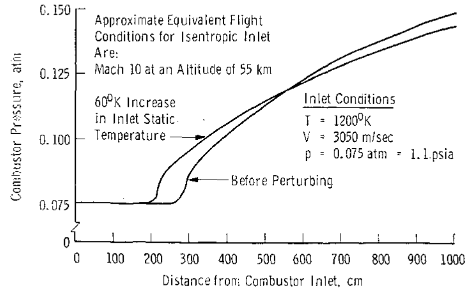

Fig. 11 Effect of perturbing inlet temperature on pressure distribution for constant area combustion.

sensitivity of the constant pressure combustor increases with increasing pressure.

III. Possible Amplification of Disturbances in the Combustor

It has been shown how perturbations in the flow variables at the inlet of the combustor can give rise to disturbances in the combustor. Now the possible amplification of these disturbances will be discussed.

There are at least two primary mechanisms of amplification of disturbances in the combustor. The first can be attributed to the wave-like nature of the supersonic flow in which disturbances are propagated along Mach lines through regions of the flow where they may affect the combustion process in a nonlinear manner. The second mechanism is that of boundary-layer separation in the combustor.

A rigorous treatment of the first mechanism of amplification would require an analysis of the flow, using the rotational method of characteristics including effects of finite rate chemistry and heat release. However, one aspect of the problem can be illustrated by referring to Fig. 12 which shows schematically a constant pressure combustor using an oblique shock wave for ignition and having uniform flow properties at the inlet. If a small compression disturbance originates at the upper surface in the zone of ignition delay, it will propagate along a Mach line into the flowfield and shorten the ignition delay time for adjacent streamlines. The farther away from the upper surface a streamline is, the more its ignition delay time is shortened. Thus, the beginning of the heat release zone will be curved as indicated in Fig. 12. It follows that more heat will be released in the constant area section than would be the case if the ignition delay were shortened uniformily for all streamlines by the same amount as the streamline along the upper surface. Figure 13 shows the results of a "worst case" analysis made to determine the flight condition at which combustion of hydrogen would just start to affect the ignition-producing shock wave. The calculations were based on the following propositions: 1) the ignition delay distance was calculated from an approximate formula for ignition delay time,[6] 2) combustor inlet conditions were determined from two shock inlet calculations, and 3) the fluid is air alone and was treated as a perfect gas. The cross plot in the figure for combustor inlet air temperature at 1111°K shows that interference will result for altitudes below about 40 km if the two-dimensional combustor height exceeds 30.5 cm. Increasing the inlet temperature and pressure will lower the minimum altitude for the given height since both of these effects shorten the ignition delay distance.

The possibility of boundary-layer separation exists whenever there is an adverse pressure gradient in the combustor. Therefore, it is important to consider that the pressure rise in the combustor caused by perturbations in the inlet flow variables can possibly cause the flow to separate from the walls of the combustor. For a fully developed turbulent boundary layer at high supersonic speeds, the separation ratio is approximately two.[11] Figure 9 shows that small perturbations in the inlet flow variables can cause pressure spikes having a ratio of this magnitude. Moreover, the boundary layer entering the combustor is probably ill conditioned from the standpoint of withstanding separation since it has a history of unfavorable pressure gradient from its development along the inlet and may even be laminar. Thus, it probably will not withstand nearly as large a pressure rise as would a fully developed turbulent boundary layer. If the flow separates from the wall, the entire flowfield in the combustor would be drastically altered because the resulting shocks would accelerate the rate of chemical reaction and heat release.

IV. Concluding Remarks

Within the framework of the postulates made in the analysis, the following conclusions concerning premixed compression-initiated supersonic combustion of hydrogen gas and air can be enumerated. 1) Because of the rapid area change which must follow the ignition delay section in a constant pressure combustor, the combustion process is quite sensitive to perturbations in the inlet flow variables. 2) The sensitivity of constant pressure combustion decreases with increasing temperature and increases rapidly with increasing pressure. 3) Constant area combustion is much less sensitive to perturbations in the inlet flow variables than constant pressure combustion if the inlet Mach number is sufficiently high. 4) Constant area combustion is accompanied by strong adverse pressure gradients which may induce

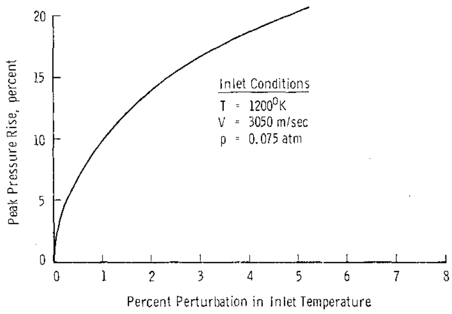

Fig. 10 Effect of magnitude of temperature perturbation on maximum pressure change in combustor.

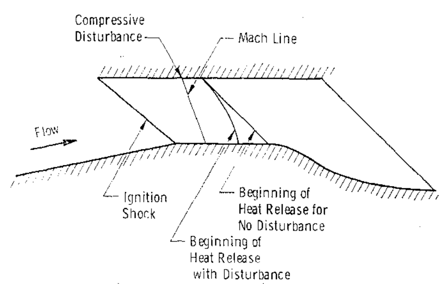

Fig. 12 Schematic illustrating wave interactions.

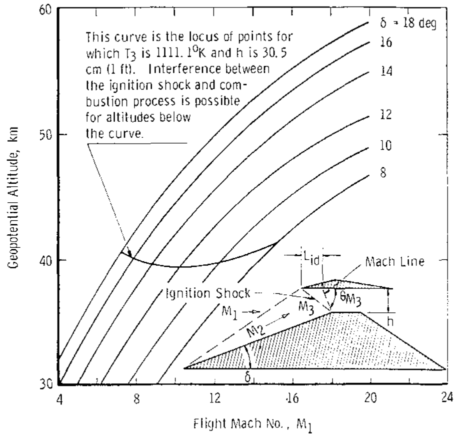

Fig. 13 Altitude vs Mach number for possible interference between ignition shock and combustion process.

boundary-layer separation. 5) Small disturbances in the combustor can be amplified by wave interaction phenomena and boundary-layer separation.

It should be emphasized that these conclusions depend to a great degree on the proposition of one-dimensional flow and the choice of fuel. In an actual engine, one would expect a large degree of nonuniformity in fuel concentration and velocity profiles entering the engine. Moreover, if a fuel is used whose reaction kinetics are slower and less dependent on initial conditions than hydrogen, a reduction in combustion sensitivity may be expected.

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