The "Delta p" Approach from Nike Combustion Instability

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Preliminary

Abstract

A malfunction study of a first stage Nike solid propellant motor has led to the "delta p" approach to the combustion instability problem. To bypass this problem, a sufficiently large enthalpy change is assumed necessary to provide adequate mixing of combustion gases within the combustion chamber. By providing an adequate pressure drop across the combustion chamber, that level of turbulent flow is reached to reduce both undesirable effects of nozzle swirl flow and excessive heat flow back to the propellants' burning surface. A few experimental objectives are suggested.

On 24 November 1964 (1), a first stage Nike M-5 malfunctioned after approximately 1.4 seconds of flight of a Nike-Javelin at Eglin AFB. This failure was significant for two reasons. The first obviously reflected on the unreliability of reputedly reliable motors (2). The other raised concern over the intended Nike boosted flight of an Aerobee 350 vehicle with sustainer engine which was under development at the time by the Space General Corporation for the Goddard Space Flight Center.

In the investigation (1) that followed, it was concluded on the basis of rippled grain surface evidence that unstable burning had occurred in some of the channel chambers of the multi-channeled single grain. Speculation at the time assumed the loss or improper installation of the resonance rods running down each of the grain channels.

Prior to the successful launch of the Aerobee 350 sounding rocket by NASA on 18 June 1965, (3), a functional sequence study had been conducted along the lines suggested by (2). This study, touching on many things, stressed the need to avoid leakage at the aft end of the motor to prevent the flow of combustion gases past the seam sealing compound. Proper installation of this sealing compound was therefore highlighted as one of the critical steps of assembly of the Nike unit employed on the first Aerobee 350 flight.

It was apparent that gas leakage past this seal would reduce the pressure drop across the motor. This pressure drop diminution would not presumably adversely affect combustion in the smaller cross sectional area channels but would do so in the channels with larger cross-sectional areas. This could explain why all the grain channels did not ex[illegible]t combustion instability.

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Proceeding along these lines in preference to the loss of or improper installation of resonance rod failure mode has led to the "delta p" approach to combustion instability (19, 20). It begins with the concept of stagnation enthalpy and proceeds to tie in applicable intuitive insights of other workers in the field.

The "delta p" approach to combustion instability in solid and liquid propellant engines stems directly from the concept of total enthalpy as applied to one-dimensional steady adiabatic flow within the combustion chamber.

Assume a central stream tube in an internally burning cylindrical solid propellant grain with a constant total or stagnation enthalpy along its length from the forward end of the motor to upstream of the throat.

$$H = h_1 + \frac{V_1^2}{2gJ} = h_2 + \frac{V_2^2}{2gJ} \qquad (4)$$

$$\text{where } h_2 - h_1 = \int_1^2 \nu \, dp \qquad (16)$$

The change in enthalpy is assumed to be largely dependent on the differential pressure across the chamber which performs three functions:

1. Accelerates the combustion gases within this tube toward the nozzle. (2)
2. Overcomes frictional flow. (21)
3. Provides improved mixing of the combustion gases within the combustion chamber. (11, p. 351)

It is the last effect which is assumed to be most significant in bypassing the combustion instability condition.

The fast flowing central stream tube can be imagined to be a central core jet mixing stream flowing past concentric flow streams (11, p. 334). As its velocity increases, so does the general turbulent mixing pattern (22).

At low turbulence levels, supporting combustion instability, heat transfer back to the grain surface (in the case of solid propellant motors) is excessive and the surface temperature is raised accordingly. This in turn increases the pressure dependent burning rate. ( )

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Swirl flow at the throat is also assumed to be associated with low turbulence levels (5). The effect of nozzle swirl is to reduce the effective area of the throat and also increase the chamber pressure (8).

As the combustion chamber pressure is increased simultaneously by excessive heat transfer back to the grain surface and reduced throat area, the differential pressure across the chamber also increases assuming that the pressure upstream of the nozzle throat remains fairly constant.

This increment in differential pressure is then assumed to increase the velocity (12, p. 1097, p. 1099) of the central core jet and in turn the general turbulence level.

At this stage, the increased turbulence tends to eliminate nozzle swirl to bring the throat area back to the design value and also to reduce heat transfer back to the grain surface. The amount of heat transmitted back to the grain surface is obviously a function of the distance of the partially combusted gas particles from the grain surface (7). Turbulence tends to increase this distance so that the further away from the grain surface that the combustion process is completed, the less the heat transfer to this surface. At a threshold distance, the heat transfer back to the grain surface will maintain the surface at an equilibrium temperature (9).

Chamber pressure again falls because of the increase in throat area and reduced burning rate due to reduced heat transfer back to the surface. The differential pressure also falls (17) and the pressure oscillation cycle is now ready to recur.

In effect, one has a pulsating central core drive a swirl pattern of flow into the throat where it degenerates into smaller turbulent eddies, again and again. It may very well be that the central core, fluctuating in strength, with the pulsating differential chamber pressure causes the acoustic complexities under such diligent study nowadays (8, 24).

The fix of inserting an extension tube between the aft end of the chamber arc throat to eliminate unstable burning (2, p. 20) may be explained by the above mechanism. A pulsating central core drives a pulsating swirl flow into the extension tube and the reduced effective throat area position moves to and fro in the tube to maintain a constant (though reduced) throat area.

At high turbulence levels, adequate to bypass the combustion instability condition, heat transfer back to the grain surface is sufficient to maintain an equilibrium surface temperature and the nozzle swirl has sufficiently degenerated (23) so that the throat area remains at the design value.

Similar reasoning would apply to liquid propellant rocket combustion instability.

In summary, the above "delta p" approach to combustion instability assumes that a sufficiently high pressure drop across the combustion chamber provides the necessary turbulence level (10) to suppress unstable burning in two ways--by reducing the effect of swirl on nozzle flow (8) - and by reducing the heat flow back toward the burning surface (9).

This approach offers a common denominator explanation for the diverse instability fixes developed in the past, points to promising new design concepts, and suggests new experimental objectives. A discussion of instability fix explanations and new design concepts will be bypassed in favor of enumerating new experimental objectives with appropriate references in the area of combustion instability.

Test programs are envisaged which will:

1. Test the assumption that the pressure upstream of the throat does indeed remain constant as the pressure drop across the combustion chamber is increased.

2. Characterize combustion chambers in terms of their longitudinal and transverse pressure differential profiles (6) (12, p. 1092).

3. Compare pressure differential profiles of combustion chambers with and without their combustion instability fixes:

    a. Throat extension tube

    b. Baffles (12, p.1084, p. 1097, p. 1095)(13)(14)

    c. Resonance rods

    d. Solid propellant containing aluminum

    e. Holes radially drilled into the solid propellant grain

    f. Acoustic liners

    g. Other fixes

4. Undertake the study of methods to increase the longitudinal pressure differential within a combustion chamber.

a. Use of tapered grains (15)

b. Use of grains with conical chambers ( )

c. Use of the diverging rocket engine ( )

d. Use of reduced volume at head of combustion chamber (25)

5. Study the contribution of transverse pressure differentials to combustion instability (6).

6. Seek to evaluate the critical pressure drop time trace for selected solid (and liquid) propellant rocket engines (18).

7. Seek to correlate average differential pressure across a combustion chamber with the area of the envelope of the oscillating chamber pressure time trace (17).

8. Study the applicability of sonic and supersonic fluid ejector theory to the combustion instability problem.

NOMENCLATURE

g	acceleration due to gravity
H	stagnation or total specific enthalpy, Btu/lb
h_1	static specific enthalpy of fluid at aft end of combustion chamber
h_2	static specific enthalpy of fluid at forward end of combustion chamber
J	778 ft-lb/Btu = mechanical equivalent of heat
p	absolute static pressure, psf
	specific volume, cu ft/lb
V_1	fluid velocity at aft end of combustion chamber, ft/sec
V_2	fluid velocity at forward end of combustion chamber, ft/sec

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