degradation set in. The maximum degradation occurred at the lowest sink temperature that could be achieved in the test apparatus, which gave a condenser-end temperature of −51°C and a nearly completely gas-blocked condenser. The measured capacity, with the reduced effective length taken into account, was 29 W-m, and therefore the capacity degradation was $\dot{Q}L_{\text{eff}}/(\dot{Q}L_{\text{eff}})_{\text{isothermal}} = 0.35$.

Conclusions

Clearly, the simple theory presented shows that the Marangoni effect can produce the large capacity degradation observed in gas-loaded axially grooved heat pipes, and correctly predicts how the degradation increases with the surface-tension difference across the condenser.

The difference between the measured degradation (65%) and that predicted (44%) can be largely attributed to idealizations used in the theoretical model, such as a flat meniscus in the condenser, rectangular rather than rounded groove lands, neglect of liquid density variation with temperature, and a zero liquid contact angle. For example, a contact angle of 30 deg would alone increase the predicted degradation from 44% to 56%.

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Readers' Forum

Brief discussions of previous investigations in the aerospace sciences and technical comments on papers published in the AIAA Journal *are presented in this special department. Entries must be restricted to a maximum of 1000 words, or the equivalent of one* Journal *page including formulas and figures. A discussion will be published as quickly as possible after receipt of the manuscript. Neither the AIAA nor its editors are responsible for the opinions expressed by the correspondents. Authors will be invited to reply promptly.*

Velocity Coupling in Oscillatory Combustion of Solid Propellants

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THE phenomenon of oscillatory combustion instability in solid rocket motors results from the responsiveness of the combustion process to oscillations in the flow environment. Early studies have concentrated on response to pressure oscillations,[1-5] described as perpendicularly incident waves with alternate compression and expansion of the combustion zone. Analytical descriptions are one-dimensional models, which assume the propellant to be effectively homogeneous and isotropic. Such a model yields a "response function" relating the amplitude and phase of the "burning rate" oscillations to the pressure oscillations, which is dependent on oscillation frequency, propellant burning rate, and properties of the propellant. The combustion environment (mean or time-average properties) enters in primarily through the effect of mean pressure on mean burning rate, which "disappears" into a normalized frequency $\Omega = \alpha f/\bar{r}^2$ where f is frequency, α is thermal diffusivity of the propellant, and r is mean burning rate of the propellant. The central point to note here for the present objective is that the "pressure coupled response function" becomes viewed as a property of the propellant, not of location on the burning surface of a propellant charge. The weak dependence on pressure and limited change in mean pressure with location on the burning surface of the propellant charge are usually neglected in calculations of overall combustor stability, reinforcing the idea that the combustion response is a property of the propellant, rather than of location in the flowfield, on the surface of the propellant charge, or in the acoustic field.†

Now it has always been recognized that the nature of the gas flowfield adjoining the burning surface can affect mean burning rate,[6,7] and the effect (called "erosive burning") has been linked (by experiments and analytical models) to the mainstream flow velocity or mass flux. The erosive burning effect presumably depends on such detailed behavior as enhanced heat transfer, mixing in the combustion zone, and shearing stress at the propellant surface. Describing these effects analytically is a very formidable problem. However, for the present purpose it is sufficient to note that the erosive burning effect is a function not only of the propellant but also of some minimum set of flow variables descriptive of the flowfield near the burning surface (and encompassing the gas phase reaction layer). In a given combustor, this will correspond to a spatially nonuniform effect, which property is completely inescapable for erosive burning. As noted earlier, efforts have been made to simplify this complex problem by describing the flow dependence in terms of variables descriptive of the "mainstream" flow parallel to the burning surface, variables that are average values of the variable over a cross section of the flow channel. In other words, the combustor flow parallel to the burning surface is

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†Of course, the effect of the combustion response on the pressure waves is a function of position on the acoustic mode.

one-dimensionalized. This is an inherently contradictory step when dealing with erosive burning, because the burning involves processes explicitly eliminated by the assumption. However the essential qualitative attributes of spatial and flowfield dependence are retained, and the "impropriety" of one-dimensionalization of the flow can be minimized by use of experimental results or subsidiary modeling to yield plausible working relations in the one-dimensional context.

By now, the evidence is overwhelming that when the parallel flowfield is oscillating, the erosive burning oscillates, and that a substantial part of the oscillation is due to effects other than could be ascribed to the attendant pressure oscillations alone.[8-10] In other words, there is an "erosive coupling." In the framework of one-dimensional models, it is convenient to choose a single additional flow variable such as mainstream velocity, and call the effect "velocity coupling," and assume it is an effect that is locally additive to an independently definable pressure coupled response. Indeed, this is a widespread practice, and experiments have been designed to measure the velocity-coupled response function as some kind of counterpart to the pressure-coupled response function. As such, it is viewed as a propellant property, i.e., the magnitude and phase of a burning rate oscillation induced by a given oscillation in gas flow velocity.

Aside from the difficulties involved in falling back to a one-dimensional flow representation of a distinctly two- or three-dimensional problem, there is another serious difficulty in the velocity coupling function concept. It is not plausible to believe that a given flow perturbation in the combustor would produce the same combustion perturbation at each location along the wall flow, because the conditions near the wall change drastically with location. Thus the "velocity coupled response function" cannot be handled rigorously as a property of the propellant. This fact was recognized early by Hart and McClure[8] in connection with large amplitude oscillations where flow reversals might occur. The implications were examined further by Price and Dehority,[10,11] who explored the effect of flow-dependent response functions on combustor stability. Zinn and Srivastava[12] constructed a reacting boundary-layer model to explore the perturbation response without complete one-dimensionalization of the flow. In this latter work, the calculations were carried out for the case of a first axial mode.

It is premature to say at present how rigorous the flow-combustion model must be in order to yield a useful description of combustion response in the parallel flow (erosive) situation, or whether the response can be either 1) separated into independent parts, of which one is due to the local pressure oscillations and the other due to the local parallel flow situation, or 2) separated into independent parts that can be handled as properties of the propellant.

There is no doubt that case 2 has been helpful in exploring the role of parallel flow, and there is a great deal of evidence that a simple consideration of the parallel flow situation (as by Hart and McClure[8]) describes certain aspects of combustor instability at large amplitude that cannot be accounted for by case 1. However, results of Price regarding pulsed instability in center-vented motors[9] were not explained by the Hart-McClure model,[8] a situation that led to the adoption of a mean-flow dependent velocity coupled response function by Price and Dehority.[10,11] This adaptation (which still uses a one-dimensional representation of the parallel flow) provides a qualitative explanation of the center-vented motor results and possibly of certain development motor results that seem to conflict with the Hart – McClure erosive-coupled model. However, it may ultimately be necessary to abandon the one-dimensional flow representation, in spite of the greatly increased labor of computation of stability with more rigorous models.

The boundary-layer model of Zinn and Srivastava illustrates the problem of more rigorous models. Not only are they awkward to use, but this particular model still assumes a mainstream velocity (i.e., most of the stream is one-dimensional). While this and other assumptions limit the model's validity, it is a direct attack on even more simplistic assumptions of other erosive-velocity coupled models, most specifically the internal inconsistency of one-dimensional descriptions of a process that includes an explicitly two-dimensional process like erosive coupling.

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