Discussion

W. V. Hanzalek.[7] The authors are to be congratulated for conducting this study and preparing this paper in a manner such that the obvious applications to turbojet and rocket combustion chambers were evidently kept constantly in mind. Since the use of oscillations someday may lead to improved combustion systems, it is refreshing that this paper reports a study in a way calculated to speed the use of this information in future design and development procedures.

In view of the fact that the three combustion chambers used were designed to the same principles employed in industry, it should be pointed out that this study was carried out at 1200 R, a relatively low combustion-chamber discharge temperature compared with the modern turbojet values of 2000 R. One wonders therefore how these particular burner oscillations affected the combustion process which was an essential part of this test setup. It would appear to be in order to incorporate these observations in this paper if at all possible. Either at 1200 R or at some higher temperature where there is less excess air, a study of the effect of burner oscillations on flame structure, combustion efficiency, inflammability range, and total pressure loss across the combustion zone would be a significant extension of this paper.

Although the authors have made every attempt to simulate typical combustion-chamber systems, no provision was made to duplicate the introduction of excess air at right angles to the through-flow. Admittedly this would tend to destroy any organ-pipe-type oscillations set up but it also might provide some measure of the strength and action of these oscillations in a turbojet chamber. Similarly a study of the effect at the burner head of controlled turbulence, swirl or vortex flow on organ-pipe oscillations also would be a useful amplification of this work and tend to orient it within the operating regime of a more complex design.

The fact that this paper has stimulated these comments directed toward a broader use of its findings is a sign that it has filled a gap in the thinking concerned with the problem of oscillations in combustion-chamber systems. The number of practical suggestions for ways to effect a particular oscillation phenomenon, included in this paper, also testify to its value and contribution to the subject.

J. A. Johnson.[8] Recently the problem of suppressing burner oscillation has become more important for both military and industrial developments directed toward higher rates of heat release. The advantages of burner oscillation from the standpoint of the development of some types of wave machines and of the possibility of increased heat transfer represent another direction of endeavor. Greater urgency is attached to the problem of suppressing burner oscillation and a definite contribution has been made in the analysis of the organ-pipe type of oscillation by the authors.

In addition to oscillations of the organ-pipe type, to which the paper is limited, some remarks on the important type of oscillation associated with appreciable movement of the flame front may be interesting to those faced with a burner-oscillation problem. These frequencies in combustion units as shown in Fig. 1 (*b*) of the paper, are ordinarily much lower than the organ-pipe frequencies and are associated with high gas velocities in elongated confining tubes having small damping forces. It is known that this type of oscillation may be changed by variations in design. Simple corrective measures for unstable oscillations of this type have included the use of a flame-stabilizing baffle in the fuel-air mixture parallel with the direction of flow but terminating at the flame front. Vanes to cause a rotating flow at the point of flame holding and downstream of the burner also have been reported to improve combustion stability. Another device used with some success is a type of muffle about the burner discharge point.

However, apparently many unknown factors are involved in combustion stability. The authors' comments on the effect of the following factors on both types of burner instability would be interesting:

1 Inherent low-frequency combustion oscillations upon which recently developed electronic flame-failure devices are based and the cause of this oscillation.

2 Blower or air-source pressure-flow characteristics and the stability of flow due to this characteristic.

3 Size of flow passage at the point of flame holding.

4 Use of liquid fuel-burners in which the fuel is not vaporized at the point of flame holding.

The writer wishes to congratulate the authors on an able presentation of factors involved in the increasingly important burner-oscillation field of study.

Authors' Closure

Messrs. Hanzalek and Johnson have effectively pointed out the many complicating factors entering into the study of oscillations in combustion systems. It is clear that much work remains to be done, both in obtaining new information, and in extending results such as those reported in this paper. To obtain the desired answers, the efforts of many additional investigators will be needed, beyond the relatively small number presently engaged in work in this field.

In reply to Mr. Hanzalek's question regarding temperature, it might be mentioned that although tests on the burner configurations shown in Figs. 1(*a*) and 1(*c*) were conducted at about 1200 R, temperatures as high as 2000 R were attained with the burner shown in Fig 1(*b*). The results of these tests, as well as tests on other combustion systems over wide ranges of temperature, have shown that the hypothesis concerning the required phasing of the rate of heat release with the oscillating component of the pressure can be applied equally as well at temperatures of 2000 R or higher as at 1200 R, to explain flame-driven oscillations.

As for the effect of oscillations on such factors as flame structure and combustion efficiency, the following comments are offered: As a direct result of oscillations, the flame front of a laminar flame in a low-velocity stream changes in shape. This effect could be seen in the tests, since each time an oscillation started, the flames immediately became appreciably shorter and wider than the corresponding flames without oscillation. The change in shape for this type of flame can be explained by the fact that oscillations in the region of the flame tend to shift the flow pattern from a laminar type, with a parabolic velocity profile, toward a type of potential flow which has a relatively flat velocity profile. However, there has been no evidence that there is any change in fundamental variables, such as burning velocity, when an oscillation is imposed.[9,10,11]

For flow patterns in high-velocity streams, where the velocity profile tends to be flat, the oscillations do not affect the flow pattern directly. However, as a consequence of an increased mixing of

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[9] "The Effect of High-Frequency Sound Waves on an Air-Propane Flame," by C. J. Kippenhan and H. O. Croft, Trans. ASME, vol. 74, 1952, pp. 1151–1155.

[10] "The Effect of Sound on Laminar Propane-Air Flames," by S. Loshaek, R. S. Fein, and H. L. Olsen, *Journal of the Acoustical Society of America*, vol. 21, 1949, pp. 605–612.

[11] "Interaction of Flame Propagation and Flow Disturbance," by G. H. Markstein, Third Symposium on Combustion, Flame, and Explosion Phenomena, Williams and Wilkins, Baltimore, Md., 1949, p 162.

fuel and oxidant caused by oscillations, or an increased mixing of burned and unburned gases, an increase in apparent flame speed and flame thickness may be obtained, as also an increase in rate of heat transfer to the surrounding gas stream, and to the combustor walls. Therefore the oscillations not only may cause a change in flame structure and an increase in combustion-chamber discharge temperature, but also, indirectly, may cause a change in flow pattern. These effects would be similar to the effects obtained by increasing turbulence. Increased mixing might cause premature quenching of the outer mantle of the flames in the tube configuration of Fig. 1(*a*), where a large amount of excess air is present, but it is believed that the effect of this quenching on discharge temperature is insignificant, at least for the hydrogen-air flames used.

It should also be mentioned that oscillations may cause a decrease in flame holding ability,[10] in much the same way that increased turbulence may cause the flame to be less stable in some types of burners.[12]

It is difficult to give specific answers to the questions raised by Mr. Johnson. However, some broad general statements can be made. Several types of low-frequency oscillations have been observed in various combustion systems, the Helmholtz type being one of frequent occurrence. This oscillation can be obtained with a burner configuration similar to that shown in Fig. 1(*c*).

Another type of low-frequency oscillation has been observed in which the burning zone undergoes such violent changes in shape and size during a cycle that the region of combustion acts, in so far as frequency analysis is concerned, as an additional equivalent length of pipe. Because of this effective increase in the length of the system, the natural frequency of the pipe without combustion, computed using the nominal length, is higher than the observed frequency with combustion. This type of oscillation might occur in any of the three configurations used, as well as in many others.

The flame can also act as an amplifier, either for pulses from other components of the system, such as a blower, or for random pulses traveling from the surrounding atmosphere into the combustion zone. This amplification may give rise to a troublesome pulsation at low frequency.

In regard to the air-source pressure-flow characteristics of a system, some excellent information is available in a paper by Bailey[13] dealing with the surging, pulsation, and blowout of semistable and unstable flow and combustion systems. In this paper the principles of fluid dynamics are used to determine the conditions for instability in flow systems such as a furnace and stack and a blower discharging into a plenum chamber. Flow and entrainment instability and high-temperature dynamic instability in combustion systems are also discussed.

If the flow passage is not greatly restricted at the point of flame holding in a combustion chamber, there is little effect on the calculated natural frequency of the system. If a large restriction is imposed, the system will be effectively closed at this point, as far as oscillations are concerned, and the chamber will act as a quarter-wave tube.

The last question proposed by Mr. Johnson brings up some interesting possibilities regarding flame-driven oscillations. Since the evaporation rate of fuel droplets changes with their velocity, it is reasonable to expect that with an oscillation present, there might be a periodic change in evaporation rate, and a corresponding periodic change in the concentration of fuel vapor at the flame front. This can lead to the satisfaction of the requirement regarding phasing of the rate of heat release and of the pressure which must be fulfilled to drive an oscillation. Thus combustion systems, such as afterburners, may have oscillations driven by this mechanism as well as by other combinations of feedback cycles.

[12] "Flame Stabilization and Propagation in High-Velocity Gas Streams," by G. C. Williams, H. C. Hottel, and A. C. Scurlock, Third Symposium on Combustion, Flame, and Explosion Phenomena, Williams and Wilkins, Baltimore, Md., 1949, pp. 21–40.

[13] "Flow and Combustion Stability," by N. P. Bailey, ASME paper No. 51—A-83, presented at the Annual Meeting, Atlantic City, N. J., November 25–30, 1951.