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Discussion

G. H. Markstein.[4] The results presented in this paper appear to confirm a conclusion reached in previous work,[5–9] namely, that burning velocity is not affected by sound. The frequencies employed in these studies range from less than 100 cycles per sec to more than 50 kilocycles per sec, but leave wide bands of frequencies unexplored. Therefore the possibility that effects of sound on chemical kinetics and/or transport phenomena and thus on burning velocity may occur for other frequencies cannot be excluded; coupling phenomena between sound and chemical reactions have indeed been contemplated.[10]

No agreement seems to exist, however, with respect to the effects of sound on flame shape. It would seem desirable that in future studies of this nature visual and conventional photographic observation of the flame be supplemented by spark shadowgraph or schlieren photography, in order to ascertain whether the flame surface actually remains smooth and stationary in spite of the presence of high-frequency sound disturbances. Exploration of the flow field by means of particle or smoke traces may also help to understand the peculiar changes of flame shape observed in the present study and by Hannemann and Ehret,[5] as well as the lifting that occurred in the present work only for turbulent flames but which was observed by Loshaek[7,8,9] with laminar flames.

The conclusion reached by the present authors regarding the effect of sound on blowoff and flashback stability is at variance with the results of Loshaek, et al.,[7,8,9] that were obtained in very careful and quantitative work; moreover, it does not seem to be substantiated by their own experimental results.

It may be worth while to mention that although the effects of sound waves on burner flames appear to be of minor significance, flames burning in tubes were found to be affected by sound to a much larger extent, regardless of whether the sound was applied artificially[11] or whether it was generated spontaneously by the flame.[12,13] The essentially negative results of the work on burner flames would seem to confirm the writer's opinion[14] that the phenomena which occur in tubes should be ascribed primarily to variations of flame-surface area rather than of burning velocity.

A. A. Putnam.[15] An interesting question regarding these tests is brought up by the similarity between the shape of an acoustically disturbed flame front, as shown by Markstein's[16] photographs, and the shape of the turbulent flame front, as shown by Karlovitz, et al.;[17] the distortions of the fronts given by both workers are of approximately the same size. Since Markstein used frequencies below 1000 cycles, we may ask what distortion in flame front should be expected when an ultrasonic frequency is used.

If a value of jet velocity of about 4 fps, and a sound frequency of 50 kc are assumed, sound pulses will pass through the flame at a spacing of about $^1/_4$ in. However, these pulses will not affect the flame directly. The effect will occur through the production of vortexes, at the boundary of the stream, as shown by Markstein. The spacing of vortexes and their size will be not $^1/_4$ in., but about 0.001 in. Thus, whereas low frequencies produced disturbances large compared with the laminar-flame thickness of about 0.01 in., ultrasonic frequencies may produce vortexes much smaller than the laminar-flame thickness. This means that we should no longer use equations such as Shelkin's[18] large-scale equation

$$\frac{F_t}{F} = \sqrt{1 + \left(\beta \frac{u'}{F}\right)^2} \qquad [1]$$

for the prediction of the effect of the turbulent velocity, u', on the ratio of turbulent to laminar-flame speed, because this equation is based on the concept of a distorted flame front. We should use a relation such as that given by Shelkin for small-scale turbulence

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[4] Head of Combustion Section, Cornell Aeronautical Laboratory, Inc., Buffalo, N. Y.

[5] Reference (5) of paper.

[6] Reference (6) of paper.

[7] Reference (7) of paper.

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[15] Fuels Research Division, Battelle Memorial Institute, Columbus, Ohio. Jun. ASME.

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$$\frac{F_t}{F} = \sqrt{1 + \frac{\alpha u' \, l \, C_p \rho}{k}} \qquad [2]$$

which, it may be seen, includes a scale term l.

In tests at Battelle on an apparatus similar to that used by Kippenhan and Croft, but with the combustible mixture driven by the bottom plate of the resonator cavity, an intensity of 5 watts per sq cm was attained at 20 kc. Using the root-mean-square velocity corresponding to this intensity as the measure of turbulent intensity, and the scale previously estimated, Equation [2] becomes

$$\frac{F_t}{F} = \sqrt{1 + \sim 10} \cong 3.3 \ldots\ldots\ldots\ldots\ldots [3]$$

Although this indicates a large effect of the sound, not only is the estimate too large because of the assumption that all of the intensity appears in vortex generation and that there is no dissipation, but the effect is confined to a region of the flame of about the size of the vortex. Therefore the effect on average flame speed would be imperceptible.

Ultrasonics do have an effect on flow pattern, however, as many investigators have shown. This phase of the problem appears worthy of further investigation.

AUTHORS' CLOSURE

We wish to thank the discussers for their thoughtful and stimulating discussions. The authors agree with Dr. Markstein that more elaborate techniques for observing the flame fronts such as schlierer or shadograph are much needed in order to interpret the exact nature of the flame front under the influence of high-frequency disturbances.

An attempt was made to study quantitatively the stability limits. However, the experimental apparatus was not well suited for such a study; hence it was decided to place the main emphasis on normal flame velocity. The term stability is perhaps unopportunely chosen when suspended flames, lifted from the burner mouth, are discussed. Such suspended flames fall in the region between flashback and blowoff limits, but were not useful for study of normal burning velocity.

The phenomena qualitatively observed in combustion chambers, where high gas velocities require use of flame-holding devices, seem to indicate a much larger and more complex interaction between sound waves and the combustion front. The effects observed on burner flames fail to provide an answer to this most critical problem.