[6]Bohn, W.L., Hügel, H., Schall, W.O., and Schock, W., "Vorrichtung zur Anregung und/oder Ionisierung eines fließenden Gases," FRG Patent Application DE 29 40 627, 1979.

[7]Mayerhofer, W., Hügel, H., and Novack, R., "Pulsed E-beam Stabilized Supersonic CO-Laser," *Gas Flow and Chemical Lasers, 1984 Proceedings of 5th GCL Symposium*, Institute of Physics Conference Series, No. 72, Adam Hilger Ltd., Bristol, England, and Boston, 1985, pp. 319-324.

Experimental Verification of Temperature Fluctuations During Combustion Instability

H. F. R. Schöyer,*
ESTEC, Noordwijk, The Netherlands
and
R. T. M. de Bont†
Delft University of Technology
Delft, The Netherlands

Introduction

IN a recent paper[1] it was hypothesized that certain types of combustion instability might be caused by incomplete combustion. A consequence of this hypothesis is that for such oscillatory combustion, temperature fluctuations may be of the same order of magnitude as the pressure fluctations and may display the same behavior. It has also been suggested that for such oscillatory combustion, there are similar fluctuations in the composition of the combustion products. Eisel et al.[2] reported both fluctuations in the temperature and composition during L^* oscillations; Price[3] has reported variations in the composition of the exhaust during L^* instability, while Strand[4,5] and Kumar and McNamera[6] observed the occurrence of fluctuations in light intensity accompanying the pressure fluctuations during L^* instability. This note deals with the simultaneous measurement of temperature and pressure fluctuations during L^* instability.

Experiments

Disks of propellant, with a diameter of 10 cm and a thickness of about 1 cm, were burned in a variable volume, end-burning rocket motor. This L^* burner has been described elsewhere[7]. The nozzle end plate was made of two perspex disks to allow for the transmission of light and the visual observation of the combustion process. Different-size nozzles may be mounted. Ignition was achieved by means of a hot wire in combination with a pyrotechnic lacquer.[7] The combustion pressure was measured continuously by a Kistler piezoelectric transducer, mounted behind the propellant disk. Good contact between the transducer and the propellant was ensured by means of vaseline or silicon grease. The composition of the propellant was roughly: AP 74% (by weight), polyurethane 19.4%, aluminum 6%, and additives 0.6%. The theoretical flame temperature is about 2740 K. The Al and Al_2O_3 particles and droplets will act as blackbody radiators.

Temperature has been measured optically. To this end a 1-cm^2 United Detector Technology PIN-10 DF photocell was mounted in an SLR Hasselblad camera at the film position. The combination photocell-Hasselblad camera has been calibrated for various distances and apertures with the help of a tungsten-band lamp. In the region between 450 and 950 nm the light intensity is directly related to the blackbody temperature by a polynomial that may be obtained from Planck's radiation equation and a curve-fitting procedure.

The output of the photocell was amplified and subsequently digitized. The voltage output turned out to be very linear for light intensity ratios between 0.1 and 100. In applying this type of temperature measurement, the main uncertainty is the absorption of light by the perspex end plate.

Although the end plate remains transparent during combustion, particles and dirt are collected on the inner surface, while some perspex evaporates. To estimate the transparency of the end plate, a plate has been taken after a test run and the inner surface has been subsequently "wiped clean," after which it was determined that the transmissivity of the end plate was only 6.25% of the transmissivity of a "clean" end plate. This reduction in transmissivity has been assumed to be applicable during the major part of the test runs. As there is considerable uncertainty in this value, the measurements of the absolute temperature should not be regarded as fully reliable. On the other hand, the measurements of the relative temperature fluctuations $T'/\bar{T}$ do not suffer from this systematic error and may be regarded as being much more reliable.

During the actual experiments, a black screen was positioned between the camera and the L^* burner, preventing stray light from falling on the photocell. A small aperture in the screen ensures that only a small, well-defined portion of the nozzle end of the L^* burner is projected on the photocell.

The Hasselblad SLR camera allows for the precise determination of the dimensions of this area, so that it is known what portion of the photocell was actually covered. The outputs of the photocell and pressure transducer were recorded simultaneously on analog and digital magnetic tape and by a UV oscillograph for quick-look analysis. The voltage output of the photocell amplifier is in fact, a measure for the light intensity.

Results

According to Schöyer's hypothesis,[1] low-frequency combustion instability may be caused by incomplete combustion. Incomplete combustion itself should be accompanied by flame temperatures lower than the adiabatic flame temperature at complete combustion. The results indicate that the measured blackbody temperature is indeed lower than the theoretical adiabatic flame temperature. As mentioned previously, the measured value of the blackbody temperature may not be ac-

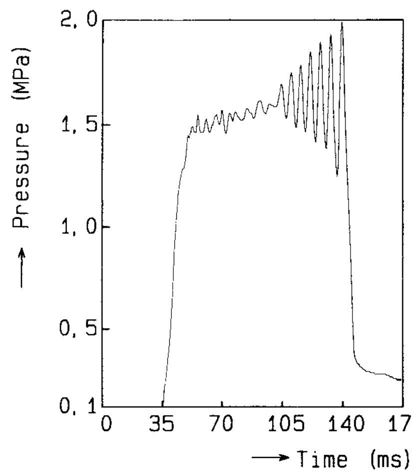

Fig. 1 A typical pressure record during L^* instability.

Received Dec. 17, 1984; revision received March 20, 1985.

*Propulsion Engineer, Mechanical Systems Division. Member AIAA.

†Graduate Student, Department of Aerospace Engineering.

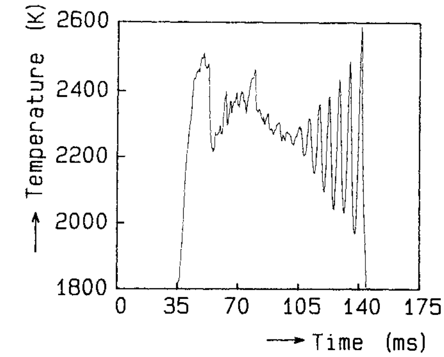

Fig. 2 Observed temperature oscillations during the pressure oscillations displayed in Fig. 1.

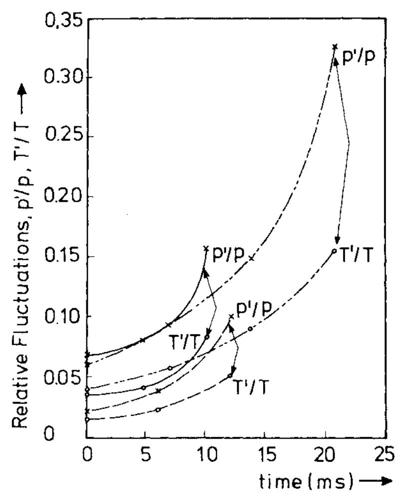

Fig. 3 Observed relation between relative pressure and temperature fluctuations during L^* instability.

curate. On the other hand, in case of pressure oscillations, large temperature oscillations are predicted and, according to Schöyer,[1] may be expected to be of the same order of magnitude as the pressure oscillations. We report here two test runs during which L^* instability occurred and which also yielded reliable data. During a few other test runs, which showed a similar behavior, test conditions were such that no valuable and accurate information could be obtained for either the temperature or the pressure history.

During all test runs dp/dt extinguishment occurred, followed by reignition. In some earlier test runs, with the same propellant and at the same pressure but at larger L^* values, only steady combustion without oscillations was observed. The first test run about which we report here yielded three successive periods of pressure buildup during which oscillations occurred.

The second test run yielded two successive periods of pressure buildup together with oscillations. The amplitude of the oscillations during the last period of pressure buildup in the second test run was negligible.

Figure 1 shows a typical pressure history during one sequence. The mean pressure was around 1.5 MPa while the initial $L^* = 0.093$ m. Shortly after pressure buildup, periodic pressure fluctuations with a rapidly growing amplitude occur, followed by dp/dt extinguishment. The frequency of the oscillations is 171 Hz. Figure 2 shows the accompanying temperature fluctuations. These show exactly the same behavior as the pressure fluctuations; i.e., after some initially erratic fluctuations, periodic fluctuations appear with a rapidly growing amplitude, also with a frequency of 171 Hz. This behavior has been observed during all test runs and appears to be characteristic of L^* oscillations. It should be noted that the maximum peak-to-peak temperature variation in Fig. 2 is more than 600 K. During the other L^* oscillations, maximum peak-to-peak temperature fluctuations were between 210 and 660 K.

Such large variations cannot be explained by adiabatic expansion and compression but are in agreement with the hypothesis that incomplete combustion[1] causes combustion instability. Figure 3 shows the relative pressure and temperature fluctuations as these have been observed during L^* instability for three test firings. From Fig. 3 it is observed that $T'/\bar{T} \approx p'/\bar{p}$ and, hence, that the relative temperature and pressure fluctuations are indeed of the same order of magnitude and that they display the same behavior.

Conclusions

Simultaneous pressure and temperature measurements confirmed that relative pressure and temperature fluctuations can well be of the same order of magnitude. Both fluctuations display the same behavior, while peak-to-peak temperature fluctuations have been observed as large as 660 K. These observations experimentally confirm the hypothesis that incomplete combustion may cause combustion instability.

Acknowledgments

This work was performed when the senior author belonged to the faculty of the Department of Aerospace Engineering of Delft University of Technology. The authors are indepted to the Prins Maurits Laboratory TNO, Rijswijk, where all experiments were performed, and which provided them with much help. Finally the authors are grateful to Mr. Zwi Nadler, from Technion—Israel Institute of Technology, who, as a graduate student at Delft University of Technology, painstakingly and patiently calibrated the Hasselblad SLR camera-photocell combination.

References

[1]Schöyer, H. F. R., "Incomplete Combustion: A Possible Cause of Combustion Instability," *AIAA Journal*, Vol. 21, Aug. 1983, pp. 1119-1126.

[2]Eisel, J. L., Ryan, N. W., and Baer, A. D., "Combustion of NH_4CLO_4-Polyurethane Propellants: Pressure, Temperature, and Gas-Phase Composition Fluctuations," *AIAA Journal*, Vol. 10, Dec. 1972, pp. 1655-1661.

[3]Price, E. W., Rice, D. W., and Crump, J. E., "Low-Frequency Combustion Instability of Solid Rocket Propellants, May 1, 1963 - May 31, 1964," U.S. Naval Ordnance Test Station, China Lake, CA, Technical Progress Rept. 360. NOTS TP 3524, 1964.

[4]Strand, L. D., "Studies of Unstable Combustion in a Transparent Solid Rocket Motor," Space Programs Summary 37-25, Vol. IV, Supporting Research and Advanced Development, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Feb. 29, 1964, pp. 60-63.

[5]Strand, L. D., "Summary of a Study of the Low-Pressure Combustion of Solid Propellants," Tech. Rept. 32-1242, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, April 15, 1968.

[6]Kumar, R. N. and McNamera, R. P., "Some Experiments Related to L-Star Instability in Rocket Motors," AIAA Paper 73-1300, Nov. 1973.

[7]Schöyer, H. F. R., "Results of Experimental Investigations of the L^*-Phenomenon," *Journal of Spacecraft and Rockets*, Vol. 17, May-June 1980, pp. 200-207.