Heat Transfer in Solid-Propellant Motors

ANTHONY SAN MIGUEL* AND ROBERT M. MCCARTEN†
Naval Weapons Center, China Lake, Calif.

Theme

FURTHER evidence is presented that a serious discrepancy exists between measured transient temperatures in solid-propellant motors as obtained from embedded thermocouples, and those predicted by the classical Fourier heat conduction equation using independently-measured (laboratory) thermal properties. A consequence of such poor predictions is that a viscoelastic stress analysis is significantly limited in accuracy,[1] since an accurate temperature history is a prerequisite for predicting stress history and eventual mechanical failure.[2]

Contents

A solid-propellant motor very similar to the structural test vehicle previously studied[1] was instrumented and subjected to a step temperature change from 82.4°F to −44.1°F on the entire outer surface of the motor case. The 7.0-in.-i.d. × 33.0-in.-long case bonded motor tested consisted of a 0.065-in.-thick steel case, a 0.040-in.-thick liner (LP-4), and a cast CTPB propellant grain incorporating a 2.0-in. bore. Rigid end caps with seals were attached to each end. Thermocouples (0.010-in. bead) were located at the longitudinal center at $r = 1.0$, 1.5, 2.1, 2.5, 3.1, 3.4, and 3.5 in. as well as at the ¼-length at $r = 2.5$ and 3.4 in. The objective was to accurately measure the transient temperatures along several radii at both the longitudinal center and ¼ length of the motor, and to test previous conclusions.[1]

The principal dissimilarities between this experiment and that of Ref. 1 are given in Table 1. Of particular significance was the use of a bath as an environmental chamber, with the motor case surface temperature controlled by the boiling point of Freon 22. The use of miniature thermocouples minimized heat conduction losses and proved the feasibility of imbedding such small thermocouples using general purpose production (propellant) casting facilities.

Table 2 presents measured temperature-dependent thermal conductivity (k), specific heat (c_p), and density (ρ), for the CTPB solid propellant, LC-4 liner, and AISI 1015 case used in this experiment. Although the precision of this data is better than 5%, its accuracy has not been determined because of the inherent scatter of properties from batch to batch for solid propellant as well as the uncertainties related to the measurement of k for poor conductors.

The measured transient temperature data and radial locations of the thermocouples are given in Fig. 1 by the dashed curves and parentheses, respectively. At the radii $r = 3.4$ and 2.5 in., the temperature measurements were the same at both the longitudinal center and ¼ length. The deviation of this data with respect to the NBS platinum resistance thermometer standard is less than ±1.5°F, with a plausible maximum of ±4°F being attributed to uncertainties associated with using equilibrium calibration data in a transient experiment and conceivable thermocouple leakages. Also shown in Fig. 1 are the best fit theoretical predictions which were obtained by using the thermocouple data at $r = 3.5$ as the boundary condition, together with the temperature-sensitive thermal properties in Table 2.

A comparison of theory and experiment (Fig. 1) is given in Fig. 2. An explanation for the discrepancy cannot yet be made until other controlled experiments are performed. The significant discrepancy between theory and experiment is similar in all respects to that reported elsewhere.[1] The general observations made based on both this study and that reported elsewhere[1] are as follows. 1) Transient temperature gradients (greater than 4°F/min) cannot be accurately predicted by using classical theory and constant-temperature measured properties. 2) Classical theoretical predictions

Table 1 Major dissimilarities between two experiments

	New experiment	Experiment from Ref. 1
Case thickness	0.065 in.	0.375 in.
Bore	2.0 in.	2.62 in.
Environment	Freon 22	Air chamber
Test surface temperature	−44.1°F ± 0.2 after 2 min	0°F ± 7 after 0.4 hr
No. thermocouples/size	11/0.010 in.-bead	6/0.1 in.-bead
Thermocouple lead wire diameter	0.004 in.	0.040 in.
Transducer positioning wires	0.002 guide wires	None
Transducer lead wire positioning	Longitudinal	Radial
Instrumentation	NWC-Skytop multichannel IBM 1800 data acquisition system (0.002 sec sampling time)	Leeds & Northrup single channel thermocouple recorder (30 sec sampling time)
Reference temperature	Deionized ice bath and quartz thermometer	Electronic reference junction

Table 2 Temperature-dependent thermal properties for CTPB propellant, LC-4 liner and AISI 1015 Case

	T, °F	
CTPB propellant	−50	100
k, Btu/ft-hr-°F	0.32	0.28
c_p, Btu/lb-°F	0.28	0.30
ρ, lb/in.³	0.063	0.063
LC-4 liner		
k	0.14	0.10
c_p	0.12	0.25
ρ	0.063	0.063
AISI 1015 case		
k	28	27
c_p	0.09	0.11
ρ	0.28	0.28

Received January 18, 1971; synoptic received May 3, 1971; revision received November 12, 1971. Full paper available from National Technical Information Service, Springfield, Va. 22151, as N712-11831 at the standard price (available upon request).
Index categories: Heat Conduction; Thermal Modeling and Experimental Thermal Simulation; Thermal Stresses.

* Research Mechanical Engineer.
† Aerospace Engineer. Member AIAA.

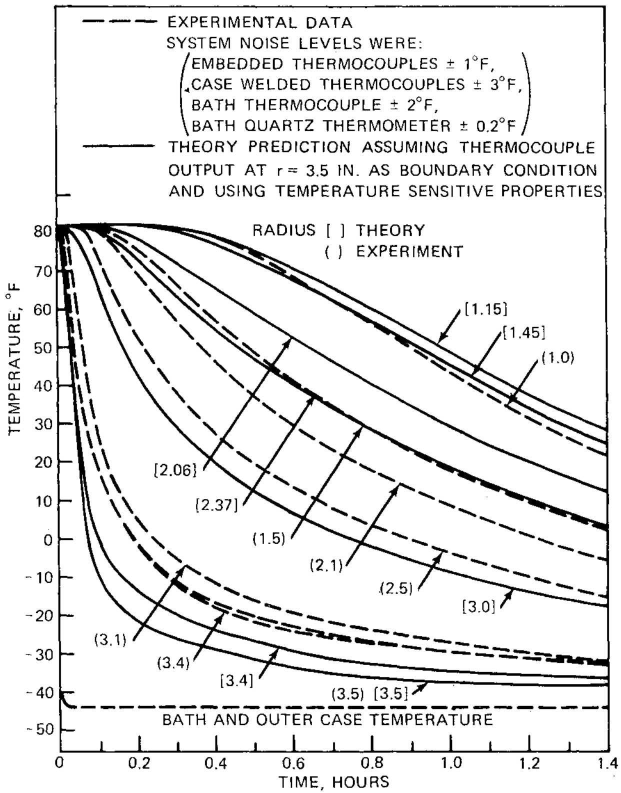

Fig. 1 Experimental and best-fit theoretical predictions for transient cooldown test.

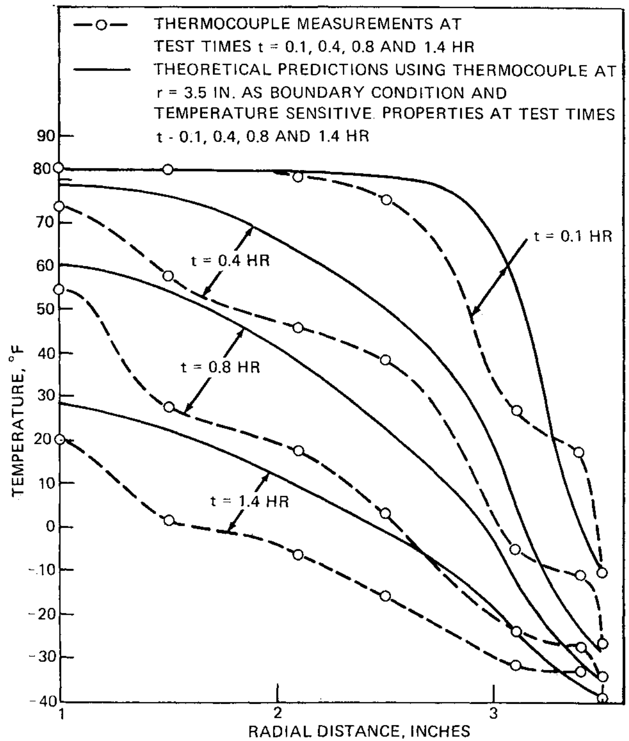

Fig. 2 Comparison of experimental and best-fit theoretical predictions for transient cool-down test.

result in smaller transient temperature gradients than actually exist. 3) Outer case boundary temperature measurements alone, when used with the classical theory, predict transient temperature gradients which are unacceptable[1] for the viscoelastic stress analysis of solid-propellant motors.

References

[1] San Miguel, A., "Prediction of Temperature Gradients in Solid Propellants," *Journal of Spacecraft and Rockets*, Vol. 7, No. 5, May 1970, pp. 533–538.

[2] Bills, K. W. et al., "Development of Criteria for Solid Propellant Screening and Preliminary Engineering Design," 1159-81F, Dec. 1968, Aerojet General Corp., Sacramento, Calif.