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Experimental Study on Liquid Quench of Solid Rocket Motor

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This article proposes a physical model for liquid quench of solid rocket motor and presents the results of experimental study. It is found that there is a critical value of injection pressure drop during liquid quench of solid rocket motor. The critical value of injection pressure drop increases with propellant energy (Q_f). The additive selected appropriately added in liquid is able to reduce significantly the liquid quantity required (LQR) *Ws*, for extinction of solid rocket motor. LQR reduced by the addition of 0.5% CE by weight in water are about 35 and 25% for double base propellant and nonmetalized polyurethane-ammonium perchlorate composite propellant, respectively. LQR is mainly dependent upon the propellant energy, i.e., it increases with increasing propellant energy. For pure water, $Ws \propto 0.1Q_f$ and for water + 0.5% CE, $Ws \propto 0.76Q_f$. The variation of LQR with the chamber pressure is related to pressure exponent of propellant (n). If $n > 0$, it increases with increasing chamber pressure; and if $n < 0$, it decreases with increasing chamber pressure. With the injection pressure drop increasing, LQR decreases and the depressurization rate of solid rocket motor increases, respectively. The experimental results and the analysis indicate that the theoretical study on liquid quench of solid rocket motor should include the coupling effects of transient burning of propellant, heat transfer of liquid jet impinged on burning surface, evaporation of liquid droplets, and internal ballistics of rocket motor.

Introduction

THE extinction of a solid rocket motor by liquid injection as a kind of technical method for stop/restart of solid rocket motor has attracted much attention of a great number of researchers for the past 30 yr.[1-3] Understanding the mechanism of liquid quench of solid rocket motor, and determining and reducing liquid quantity required for extinction of solid rocket motor are essential for achievement of this method. The experimental results obtained by Strand and Gerber[4] indicated that termination of propellant by liquid injection comes from the thermal quenching of propellant burning surface and continuing cooling on the surface until the hot gas in chamber is exhausted, and the water jet normal to propellant surface is the most efficient injection technique. Trowbridge et al.[5] concluded that the binder type and curing agent play prominent roles in the liquid quantity required for extinction of composite solid propellants, and that the dependence becomes stronger as the chamber pressure goes up. An analytical study done by Harry et al.[6] showed that the cooling rate of impinging jet on a hot surface depends upon the normal momentum of liquid jet, and that the cooling rate by jet spreading is an order of magnitude lower than that under jet footprint on the burning surface, so that the extinction on the area under the footprint is much faster than that by jet spreading. Therefore, the extinguishment of solid rocket motor by liquid injection is a complex process. The liquid quantity to meet the requirement for extinction is related to the propellant type, the chamber pressure, the injection pressure drop, and liquid properties. To the best of our knowledge, no more experimental results have been reported for aluminized composite propellants (especially for aluminized HTPB propellants which are widely used in the engineering), and the effect of liquid properties on the liquid quantity required for reliable extinction has not been studied. In this study, the extinction characteristics of four types of propellants by liquid injection are investigated at various chamber pressures and injection pressure drops. The emphasis of this study is on the effect of liquid properties and the liquid quench process of aluminized composite propellants.

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Liquid Quench Mechanism of Solid Propellants

In terms of the extinction theory of solid propellant,[7] the steady-state combustion of propellant becomes transient burning when an external disturbance, such as rapid depressurization, deradiation, or liquid injection, is imposed into combustion process. If the strength and the variation rate of external disturbance are up to critical values, the extinction of propellant is obtainable. During liquid injection process, the cooling of liquid jet on burning surface is a kind of external disturbance on propellant combustion. When the liquid jet with high velocity is impinged on burning surface, the heat transfer process including film boiling, transition boiling, nucleate boiling, and liquid convection takes place under jet footprint and liquid spreading area (Fig. 1). Meanwhile, a small amount of liquid droplets is rebounded into gas phase and vaporizes in the gas phase to bring out the cooling effect. The liquid quantity back-splashed is dependent upon the sticking property of liquid.

The convection heat transfer can be negligible, because at that condition the difference between the temperature on the burning surface and the temperature of liquid jet is low. The experimental study[8] of boiling heat transfer by high-velocity

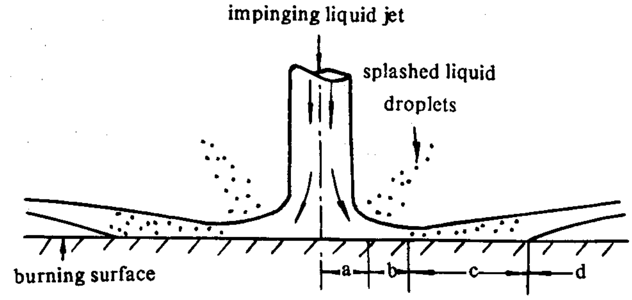

Fig. 1 Heat transfer induced by liquid jet impinged on burning surface of solid propellant. The regions in which heat transfer is dominated are a) liquid convection, b) nucleate boiling, c) transition boiling, and d) film boiling.

jet impinged on a hot surface indicates that the nucleate boiling almost does not exist in the boiling curve of liquid. Therefore, the transition boiling and the film boiling of liquid jet on burning surface play an important role in the extinction of solid rocket motor. The heat flux of transition boiling of liquid on a hot surface is controlled by liquid properties (evaporation heat, surface tension, density, etc.) and jet velocity.[9] In the film boiling, the heat flux is mainly dependent upon jet velocity at definite surface temperature.[10]

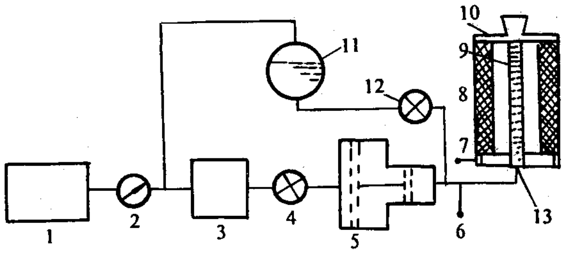

Fig. 2 Schematic diagram of apparatus used in the study: 1—high-pressure N_2 source, 2—pressure regulator, 3—low pressure N_2 store tank, 4—solenoid valve I, 5—piston accumulator, 6 and 7—pressure transducer, 8—propellant grain, 9—injector, 10—rocket motor, 11—liquid store tank, 12—solenoid valve II, and 13—aluminium disk.

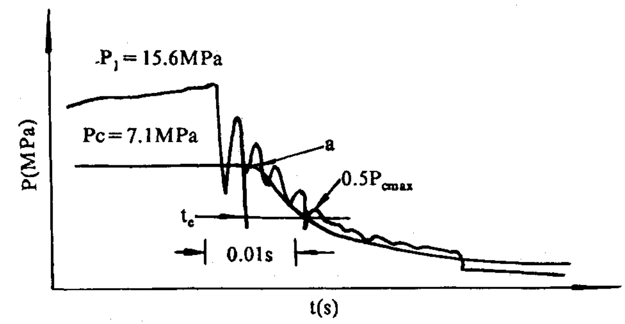

Fig. 3 Pressure-time history during liquid quench of solid rocket motor.

Table 1 Propellants used in experiment

Propellant	Binder	Al, %	Q_f, KJ/g	n
S03	Double base	0	3.699	0.517
S04	PU	0	5.244	−0.382
S06	PU	15.0	5.935	0.281
S08	HTPB	18.5	6.984	0.402

The jet velocity is proportional to the injection pressure drop (ΔP). Elevated pressure drop leads heat flux of film boiling and transition boiling to increase, which makes the external disturbance to propellant combustion stronger and faster, so that the liquid quantity required decreases and the extinction speed increases. Meanwhile, the liquid properties exert an influence on the liquid quantity required.

The energy absorbed by liquid jet on the burning surface of propellant comes from the heat stored in solid phase, heat released by condensed phase reaction during transient burning, and heat feedback from gas phase through conduction, convection, and radiation. Therefore, the energy characteristics of solid propellant (flame and burning surface temperatures) exert an important effect on the liquid quantity required for extinction. As the depressurization process in the combustion chamber companies liquid quench process, the heat released by condensed phase reaction during transient burning is related to depressurization rate and burning rate pressure exponent (n).[11]

From the analysis above, it can be deduced that the liquid quantity required and the extinction speed of solid rocket motor are dominantly controlled by the type of solid propellant, chamber pressure, injection pressure drop, and liquid properties. To study the effects of these factors is the main purpose of this study.

Experimental Techniques

The schematic diagram of apparatus used in this study is shown in Fig. 2. The working principle is as follows. The nitrogen at high pressure is regulated to a definite lower pressure and is kept in a N_2 store tank. When solenoid valve I is operated, the lower pressure nitrogen drives the piston in accumulator to pressurize the liquid to be injected. If the liquid pressure is up to the ruptured pressure of aluminium disk plus the chamber pressure, the disk is burst and the liquid jets from 1024 1-mm-diam holes of the injector, assembled at the center of test motor, are impinged vertically at high velocity on burning surface of propellant. With solenoid valve II operated, the liquid stored in liquid tank drives piston to reset and fill the accumulator with a definite amount of liquid to be injected for next test. The injection pressure and chamber pressure were measured by two dynamic pressure transducers. The test motor was mounted vertically so that the liquid remaining within the chamber after extinction is able to flow down to the down end of chamber for collection and measurement.

The pressure of nitrogen in the right side of the accumulator is about 3.5–4.0 MPa, the pressurization ratio of piston accumulator is 6, and the maximum instant mass flow rate of

Table 2 Typical data of experiments in this study

Propellant	Liquid	P_c[a]	P_l[a]	ΔP[a]	$\Delta P/P_c$	Wr,[b] g	Wv,[c] g	S,[d] cm²	Ws, g/cm²	$\left\lvert \frac{dp_c}{p_c\,dt} \right\rvert$, 1/s
S03	Water	3.36	15.00	11.64	3.464	91.6	68.4	172.3	0.3970	113.64
		9.35	15.09	5.74	0.614	42.9	117.1	256.7	0.4561	35.13
	Water + 0.5% CE	9.73	16.50	6.77	0.696	37.8	122.2	412.2	0.2964	39.25
		2.46	8.0	5.54	2.252	98.4	61.6	232.5	0.2649	86.00
S04	Water	5.23	10.59	5.36	1.025	57.5	102.5	258.9	0.3959	48.72
		3.18	7.59	4.41	1.387	89.8	70.2	165.3	0.4247	56.89
	Water + 0.5% CE	6.08	11.8	5.72	0.941	72.4	87.6	294.8	0.2972	54.91
		3.94	6.03	2.09	0.531	95.4	64.6	186.8	0.3458	43.05
S06	Water	3.83	13.59	9.76	2.548	24.5	135.5	206.3	0.6570	60.98
		2.4	6.43	4.03	1.679	74.6	85.4	163.4	0.5226	48.08
		3.83	9.06	5.23	1.366	No quench	—	—	—	—
		4.83	11.61	6.78	1.404	No quench	—	—	—	—
S08	Water	5.10	14.67	9.57	1.876	33.2	126.8	175.8	0.7213	62.50
		2.13	19.33	17.20	8.075	60.0	100.0	169.4	0.5903	156.25
		3.47	9.58	6.11	1.761	No quench	—	—	—	—
		6.44	17.00	10.56	1.640	No quench	—	—	—	—

[a]Pressure in MPa. [b]Liquid quantity remaining within the chamber after testing. [c]Liquid quantity vaporized during liquid quench. [d]Area of burning surface.

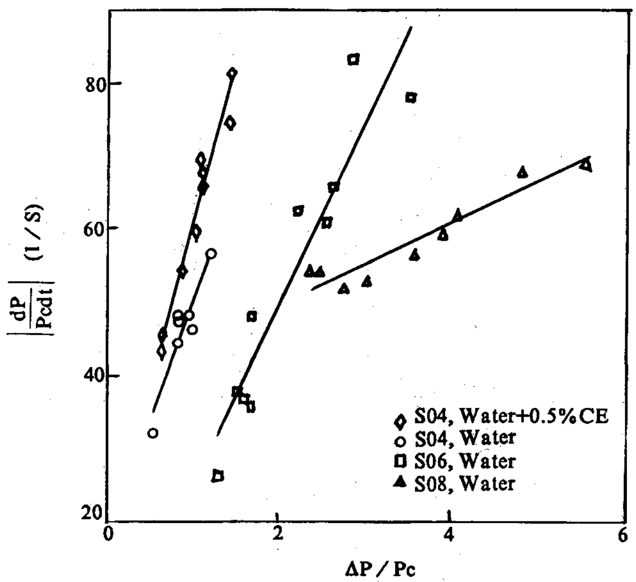

Fig. 4 Depressurization rate.

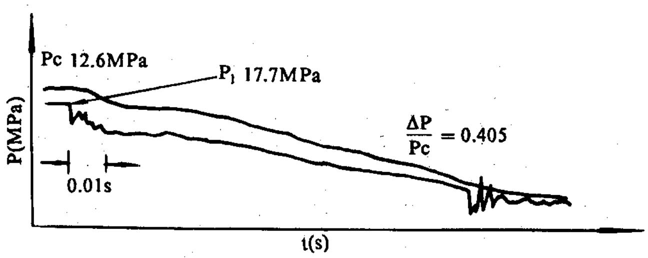

Fig. 5 Pressure-time history showing liquid quench process with low depressurization rate (propellant S03, water + 0.5% CE).

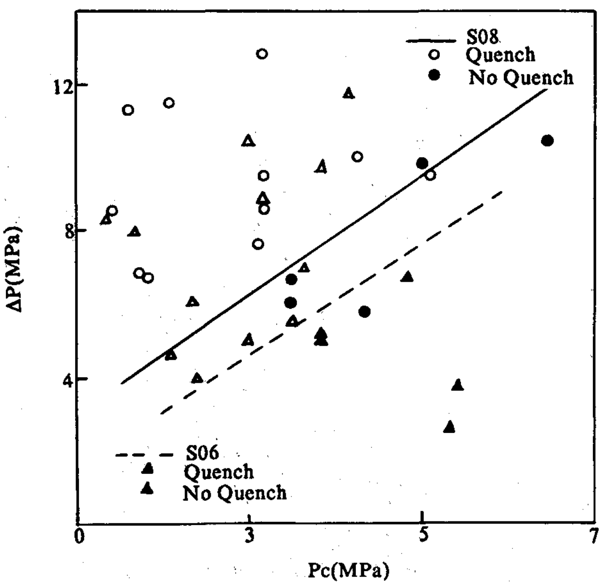

Fig. 6 Critical injection pressure drop.

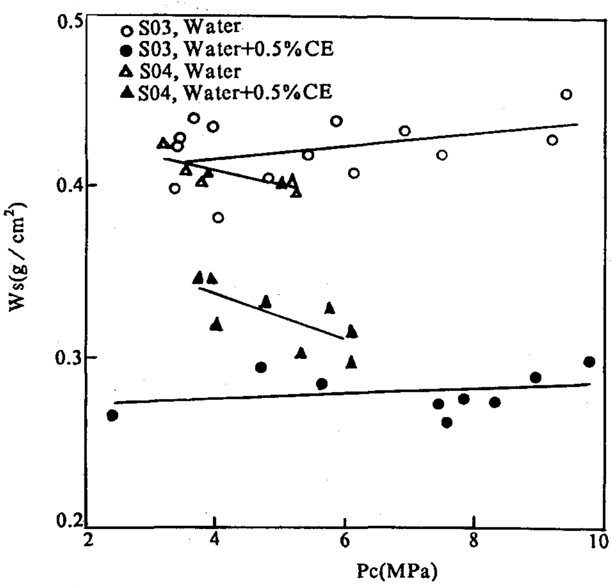

Fig. 7 Effect of chamber pressure on liquid quantity required for extinction of propellants S03 and S04.

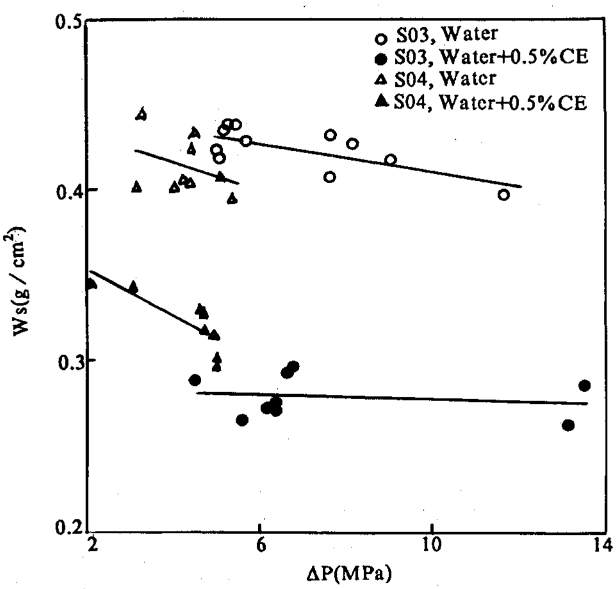

Fig. 8 Effect of injection pressure drop on liquid quantity required for extinction of propellants S03 and S04.

the system is about 3 kg/s. Because the injection is accomplished within 20–30 ms, and the liquid pressure is high enough, it is much more difficult to measure accurately the instant flow rate of liquid. Therefore, the injection pressure drop is regarded as the characteristic parameter of the liquid injection system. The injection pressure varies with the thickness of aluminium disk. The liquid quantity injected in this study is 160 g. The length-internal/external diameters of a perforated grain is 75–50/112 (mm). The outside surface, and the fore and aft ends of grain are inhibited with a kind of liner filled with asbestos to prevent the area from burning. The grains quenched by liquid injection were reused after being dried. In terms of the initial burning surface of grain and burning rate of propellant, the diameter of nozzle throat is changed from 5.5 to 15.5 mm to obtain different chamber pressure.

Four types of solid propellants were used in the study (Table 1). PU and HTPB denote polyurethane binder and hydroxy-terminated polybutadiene binder, respectively. S03 is a kind of double-base propellant. S04, S06, and S08 are ammonium perchlorate- (AP) based composite solid propellants. S04 is a special kind of propellant with negative pressure exponent ($n = -0.382$). The addition of calcium carbonate, (2.5 wt %) in the propellant is responsible for the burning rate behavior. The percentage of aluminium (Al) powder, the burning rate pressure exponent (n), and the heat of explosion at constant volume (Q_f), measured with a closed-bomb technique of propellant, are all listed in Table 1. To study the effect of liquid properties on liquid quench of solid rocket motor, two kinds of liquids 1) water and 2) water with additive CE of 0.5 wt %, were used in the experiment. The additive CE is a kind of organic compound. The test of properties of water with 0.5% CE indicates that the evaporation heat (2.961 KJ/g) and viscosity are 31.5%, and about 10% higher than those of pure water.

Experimental Results

Extinction Process of Solid Rocket Motor by Liquid Injection

Figure 3 shows a typical pressure-time curve during extinction of solid rocket motor by liquid injection. With the aluminium disk burst, the liquid pressure (P_l) decreases sharply and oscillates. At the same time, the liquid jet is impinged at high speed on the burning surface of propellant. The chamber pressure (Pc) decreases slightly later than P_l, and after slightly slowly decreasing, it decreases rapidly. The general behaviors of liquid quench of solid rocket motor in this study are in agreement with those described in Ref. 4. The depressurization rate during liquid quench is calculated based upon the time interval during which Pc decreases from Pc_{max} (at point a in Fig. 3) to $0.5Pc_{max}$. The injection pressure drop is defined as the difference between liquid pressure and chamber pressure before decreasing ($\Delta P = P_l - Pc_{max}$). The liquid quantity required for extinction of overall burning surface of grain is determined in terms of the difference of liquid quantity injected to that remaining in the motor chamber after being quenched. The liquid expected to be blown out of the chamber was not found on the test bench after testing.

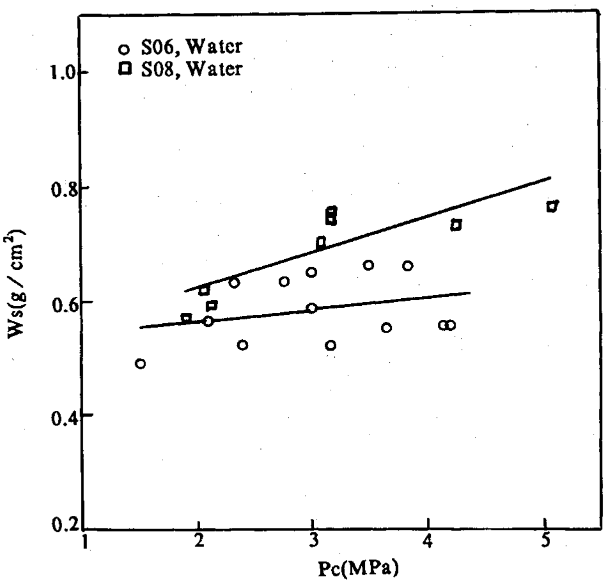

Fig. 9 Effect of chamber pressure on liquid quantity required for extinction propellants S06 and S08.

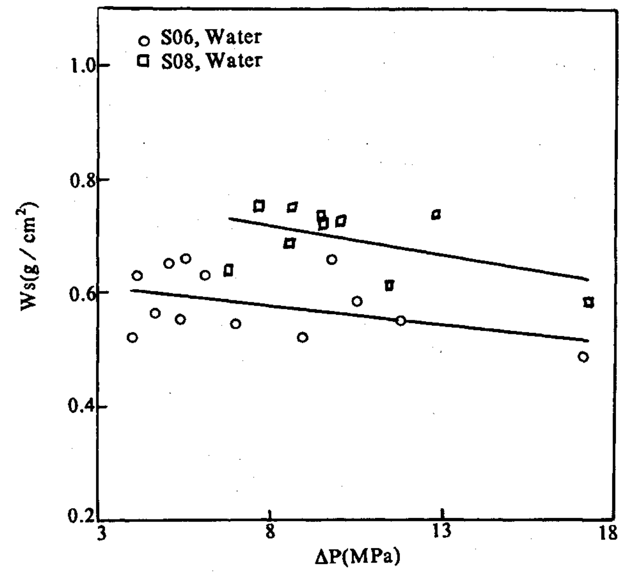

Fig. 10 Effect of injection pressure drop on liquid quantity required for extinction of propellants S06 and S08.

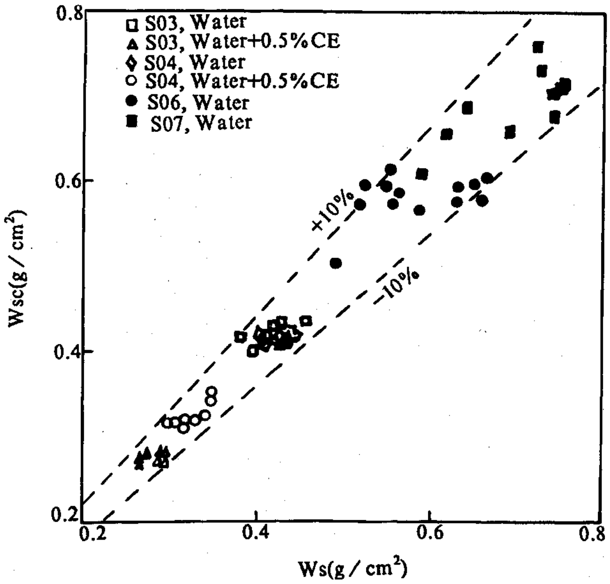

Fig. 11 Data of liquid quantity required for extinction measured and from correlation $Wsc = aQ_f + bPc + c\Delta P$.

The typical experimental data are listed in Table 2. *Ws* denotes that the liquid quantity required for extinction of 1-cm² burning surface (g/cm²). The data of liquid quantity required for extinction in this study are an order of magnitude higher than those obtained in Ref. 4, but are almost in the same order as those in Ref. 5. That may be because the chamber pressure in Ref. 4 is much lower than that in Ref. 5, and in this study.

Depressurization Rate and Critical Injection Pressure Drop

The variation of depressurization rate ($|(dPc/dt)/Pc|$) with the ratio of injection pressure drop to chamber pressure ($\Delta P/Pc$), is shown in Fig. 4. The depressurization rate decreases as $\Delta P/Pc$ decreases, and the propellant energy increases. The depressurization rate obtained with injection of water + 0.5% CE is slightly higher than that of pure water. If the chamber pressure is higher, and $\Delta P/Pc$ is lower, the liquid quench process becomes much slower (Fig. 5). Therefore, the elevated liquid pressure drop is favorable to speeding up extinction of solid rocket motor.

With Pc and P_l changed, the critical injection pressure drops (ΔPcr) for extinction are found for two types of aluminized composite solid propellants shown in Fig. 6 (the liquid quantity injected is kept as a constant). The extinction boundary is obtained in the figure. It is evident that ΔPcr increases with increasing propellant energy.

Liquid Quantity Required for Extinction

Figures 7–10 display the relationship between the liquid quantity required for extinction (*Ws*), and chamber pressure, and injection pressure drop for the four types of propellants within the ranges of Pc and ΔP in this experimental study. It is found that *Ws* increases with *Pc* and decreases with increasing ΔP for propellants S03, S06, and S08. But for propellant S04, *Ws* decreases not only with increasing ΔP, but also with increasing *Pc*.

Figures 7 and 8 also show that *Ws* is reduced significantly by the addition of CE of 0.5 wt % in water. For propellant

Table 3 Coefficients for $Wsc = aQ_f + bPc + c\Delta P$

Propellant	Liquid	a	b	c
S03	Water	0.11212	3.6743×10^{-3}	-2.0402×10^{-3}
S03	Water + 0.5% CE	0.07381	1.5280×10^{-3}	-5.7832×10^{-4}
S04	Water	0.08960	-1.0020×10^{-2}	-1.7840×10^{-2}
S04	Water + 0.5% CE	0.07560	-5.2230×10^{-3}	-1.0310×10^{-2}
S06	Water	0.09853	1.4312×10^{-2}	-6.0082×10^{-3}
S08	Water	0.09964	2.8806×10^{-2}	-8.4839×10^{-3}

S03, the liquid quantity reduced is about 35%, and for propellant S04, about 25%, which are identical with the increment of evaporation heat of water + 0.5% CE.

From Figs. 7–10, it can be deduced reasonably that the effects of Pc and ΔP on Ws are almost independent of one another. The results of linear regression for experimental data with the correlation $Wsc = aQ_f + bPc + c\Delta P$ are shown in Fig. 11, and the corresponding coefficients a, b, and c are listed in Table 3. The error is less than 10%. Therefore, the correlation can be used to estimate the liquid quantity required for liquid quench of solid rocket motor in the engineering design. The first term in the correlation presents the effect of propellant energy on the liquid quantity required. Table 3 shows that for pure water, the coefficient a is approximately equal to 0.1, i.e., $Ws \propto 0.1Q_f$, and for water + 0.5% CE, $a \approx 0.76$ and $Ws \propto 0.76Q_f$. The reduction of value a is about 24%, that is close to the increment of evaporation heat of water + 0.5% CE. Furthermore, the absolute values of b and c for water + 0.5% CE are lower than corresponding ones for pure water. Therefore, liquid properties play an important role on liquid quench of solid rocket motor. From data for pure water in Table 3, it is also found that the absolute value of b increases with propellant energy. It means that the dependence of liquid quantity required on chamber pressure increases with propellant energy. In other words, it is more difficult to extinguish the solid propellant with higher energy.

Discussion

From the analysis of liquid quench mechanism of solid rocket motor and the experimental results above, the following factors to affect liquid quench process of solid rocket motor can be considered.

Effect of Propellant Energy, Pressure Exponent, and Chamber Pressure

The propellant energy characteristics affect the flame temperature, the temperature on burning surface, and the heat feedback to burning surface. Increasing propellant energy inevitably elevates the heat absorbed by liquid jet during extinction to increase the liquid quantity required. The release rate of propellant energy is dependent upon the propellant burning rate. The variation of burning rate with chamber pressure is related to the burning rate pressure exponent of propellant (n). For different pressure exponents, the variation of burning rates and energy releasing rates of propellants with chamber pressure are different. When $n > 0$, the burning rate increases with increasing chamber pressure, and the heat released on burning surface is elevated with pressure, so that the liquid quantity required increases with chamber pressure. Conversely, when $n < 0$, the liquid quantity required decreases with increasing chamber pressure. Therefore, the effects of chamber pressure and pressure exponent of propellant merge into the effect of mass burning rate on the liquid quantity required. The liquid quantity required for liquid quench of solid rocket motor increases with mass burning rate and propellant energy.

Effect of Additive in Liquid

In this study, an additive CE of 0.5 wt % is added in water and elevates the evaporation heat of water. The higher evaporation heat of liquid results in less liquid quantity vaporized by absorbing a definite amount of heat energy, which makes the liquid quantity required decrease. The increase of evaporation heat of liquid increases the heat flux of boiling heat transfer of liquid jet impinged on burning surface, which makes the quenching of solid propellant faster. Therefore, the increase of depressurization rate is a reasonable result of the faster quench of propellant and the lesser quantity of liquid vapor evaporated.

Effect of Injection Pressure Drop

The injection pressure drop is a characteristic parameter of strength of external disturbance imposed into the combustion process of solid rocket motor. The increase of injection pressure drop leads the jet velocity and momentum to increase, elevates heat flux of boiling heat transfer on burning surface, and makes extinction speed of solid rocket motor increase. In this way, the liquid quantity required decreases with increasing the injection pressure drop.

If the injection pressure drop is lower than a critical value, the cooling effect of liquid jet on the burning surface and the decreasing of heat feedback from gas phase to burning surface are weakened. That makes the responsibility of temperature in the solid phase of propellant able to adjust itself to be suitable to the changing condition of combustion. Therefore, the extinction of solid rocket motor is not obtainable. The rocket motor would work at another equilibrium chamber pressure. In this case, the liquid injection plays a role of thrust modulation. Therefore, an indispensable condition required for liquid quench of solid rocket motor is that the injection pressure drop is higher than a critical value.

From the experimental study and the analysis above, it can be concluded reasonably that the liquid quench process of solid rocket motor is influenced by the energy characteristics, burning rate, and transient burning behaviors of solid propellant, the chamber pressure, the injection pressure drop, the heat transfer of liquid jet on burning surface, the evaporation of liquid droplets, and liquid properties. To reveal the innate characters of liquid quench of solid rocket motor, the coupling effects of transient burning of propellant, heat transfer of liquid jet impinged on burning surface, evaporation of liquid droplets, and internal ballistics of rocket motor should be considered in a comprehensive theoretical model. The research for a theoretical model is the next step of this study.

Conclusions

From the experimental study based upon the guidance of liquid quench mechanism of solid rocket motor, the following conclusions are obtained:

1) It is found that there is a critical value of liquid pressure drop during liquid quench of solid rocket motor. Only when the injection pressure drop is higher than the critical value is the extinction of solid rocket motor obtainable. The critical value of injection pressure drop increases with propellant energy.

2) The additive selected, appropriately added in liquid, is expected to significantly reduce the liquid quantity required for the extinction of solid rocket motor. In this study, the liquid quantity required reduced by addition of 0.5% CE by

weight in water for propellants S03 and S04, are about 35% and 25%, respectively.

3) The liquid quantity required for extinction of solid rocket motor is mainly dependent upon the propellant energy, i.e., it increases with increasing propellant energy. For pure water, $Ws \propto 0.1Q_f$, and for water + 0.5% CE $Ws \propto 0.76Q_f$. The variation of liquid quantity required with chamber pressure is related to pressure exponent of propellant (n). If $n > 0$, it increases with increasing chamber pressure; and if $n < 0$, it decreases with increasing chamber pressure. With the injection pressure drop increasing, the liquid quantity required decreases and the depressurization rate of solid rocket motor increases, respectively.

4) A comprehensive theoretical study on liquid quench of solid rocket motor should include the coupling effects of transient burning of propellant, heat transfer of liquid jet impinged on burning surface, evaporation of liquid droplets, and internal ballistics of rocket motor.

Acknowledgment

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