Immersion time effects on composite propellant burn rate

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Abstract. Acoustic Emission Strandburner is one of popular methods to measure the solid propellant burn rate. Immersion is a critical factor, as HTPB-based propellants contain ammonium perchlorate, a water-soluble oxidizer. This study aims to evaluate the effect of short-time immersion in water on propellant burn rate. Propellant samples were tested under three conditions: without immersion (normal condition), after 60 seconds of immersion, and after 120 seconds of immersion. The results showed that the burn rate at a chamber pressure of 2–6 MPa ranged from 5.38 – 8.36 mm/s, 5.60–7.93 mm/s, and 5.38 – 8.35 mm/s for normal condition, 60 seconds immersion, and 120 seconds immersion, respectively. Statistical analysis using a one-way ANOVA revealed no significant differences in burn rate among the three conditions. These findings indicate that short-term immersion in water does not significantly affect the combustion performance of the propellant..

1. Introduction

The performance of rocket motors is significantly influenced by the characteristics of the propellants used as fuel. Composite solid propellants are the most widely adopted due to their broad operational temperature range, controlled burn rate, high storage stability, adequate mechanical properties, and relatively low production costs [1]. These propellants typically consist of ammonium perchlorate (AP) as the oxidizer, hydroxyl-terminated polybutadiene (HTPB) as the polymeric binder, aluminum as the metallic fuel, and various additives with a composition of 65–68%, 10–15%, 5–15% and 0-5% by weight, respectively [1, 2].

Burn rate is the most essential internal ballistic parameter in designing and operating of a rocket motor [1]. It is defined as the linear regression rate of the propellant surface in the direction perpendicular to combustion, or the distance traversed by the flame front per unit time under specific pressure and temperature conditions [3]. Burn rate not only governs the rate of gas production but also directly influences the mass flow rate of combustion gases exiting the motor, thereby affecting thrust generation [4] Several factors influence the burn rate, including propellant composition, chamber pressure, and initial grain temperature.

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Ammonium perchlorate as an oxidizer is particularly significant as it is the dominant component in most composite solid propellants [5, 6].

Burn rate measurements can be performed using various techniques, such as Crawford strand burners, small-scale ballistic motors, and full-scale rocket motors [1]. Other methods include closed bomb testing, accoustic emission, ultrasonic techniques, microwave sensing, X-ray imaging, plasma capacitance, pressure probes, interrupted combustion, and high-speed imaging. Among these, the Acoustic Emission Strand burner (AES) is gaining popularity due to its simplicity, speed, cost-effectiveness, and high accuracy—reportedly up to 98% [3, 7].

AES operates on the principle of detecting acoustic signals generated during the underwater combustion of a propellant at specific pressures. The continous acoustic signals generated by the specimen during combustion are converted into electric signals, amplified by a preamplifier, and sent to the data acquisition system for calculation [7, 8].

However, this immersion condition introduces a new variable: water solubility of AP, which is approximately 24.5 g per 100 g of water at 25 °C [9]. Since AP is water-soluble, immersion may lead to partial leaching of the oxidizer, potentially affecting burn rate measurements. Several investigations have been made to determine the effects of water and humidity on AP or solid propellants. Fournier and Brady determined the AP diffusion coefficients when immersed in different water salinity levels and temperatures for 12 weeks [10]. After 10 days of aging at different relative humidity levels, the burn rate of solid propellants decreased due to the growth of AP crystal size and surface morphology changes, resulting in less accessible surface area. The alterations coincide with the moisture content of the aging environment [11].

The novelty of this study is that short duration water immersion effect on burn rate measurement of composite propellant by an AES has been studied systematically. Even the water solubility of AP is known, but the effect of short time immersion such as underwater AES testing has not been discussed. Therefore, this study was conducted to evaluate the effect of propellant immersion time on the measured burn rate, with specific attention to the influence of short-term water exposure on combustion performance.

2. Methodology

The propellant used in this study was a composite solid propellant composed of an HTPB–TDI binder system, ammonium perchlorate (AP) as the oxidizer, and aluminum (Al) as the metallic fuel, with a total solid content of 82.5% by weight. Test samples were prepared in the form of square rods measuring 5 × 5 mm in cross-section and approximately 100 mm in length, using a dedicated combustion test sampling device.

Acoustic Emission Strandburner (AES) was used to measure propellant burn rate. This device employs an acoustic emission method, with water as the combustion medium. (Figure 1). Each sample was mounted onto a holder using nickelin wire and an inhibitor coating (Figure 2), then immersed in a test chamber filled with approximately 500 mL of water. The sample length and desired test pressure were entered into the AES software before the test began.

Testing was conducted at three pressure levels: 2, 4, and 6 MPa, with a minimum of five replicates per pressure level, depending on the consistency of the data obtained. The immersion conditions applied were 0 seconds (no immersion), 60 seconds, and 120 seconds, where immersion time was recorded from the moment the sample holder entered the chamber, as indicated by a software signal light.

Fig. 1. Burn rate testing apparatus : Acoustic Emission Strand Burner (AES)

Fig. 2. Sample holder of Accoustic Emission Strandburner

The immersion times of 60 and 120 seconds were chosen to represent realistic short-term conditions during burn rate testing, including specimen insertion, system stabilization, and ignition preparation in water medium. These times were specifically designed to reflect practical handling circumstances rather than protracted moisture aging. Short immersion periods were used to determine if the limited water incorporation in AES procedures could cause burn rate changes through initial AP dissolution or surface reactivity effects, while preventing long-term oxidizer dilation from diffusion.

The output of the testing procedure included combustion time and burn rate (in mm/s). A comparative analysis of burn rate values was then performed across the different pressures and immersion durations. To assess the statistical significance of the results, one-way analysis of variance (ANOVA) was used to determine the influence of each variable on the propellant's burn rate. The primary objective of the statistical analysis was hypothesis testing rather than predictive modelling, specifically determining if short-term water exposure on solid propellant causes noticeable bias in burn rate measurements.

3. Results And Discussion

Burn rate measurements were obtained using the Acoustic Emission Strand burner (AES), yielding data in the form of acoustic emission graphs, combustion time, and burn rate values at various chamber pressures. The relationship between burn rate (r) and combustion pressure (P) was analyzed using the Saint Robert’s law, expressed as follows (1):

$$r=aP^n \tag{1}$$

where:

- r = burn rate (mm/s)
- a = pre-exponential constant
- P = combustion chamber pressure (MPa)
- n = pressure exponent

The average burn rate values at pressures ranging from 2 to 6 MPa for the three treatment conditions—normal, 60-second immersion, and 120-second immersion—are shown in Table 1. Based on the Saint Robert equation, the constants (a) and pressure exponents (n) were determined and are presented in Table 2.

Table 1. Average burn rate values for all three test conditions

Normal Condition		Immersion Time			
		60 seconds		120 seconds	
P (MPa)	r (mm/s)	P (MPa)	r (mm/s)	P (MPa)	r (mm/s)
6.308	8,522	6.602	7.991	6.106	8.407
4.562	7.498	4.866	7.682	4.593	7.506
2.855	6.199	2.872	6.202	3.048	6.369

Table 2. Values of the constant a and exponent n for each test condition

Testing Conditions	a	n	R^2
Normal	4.0697	0.4017	0.999
Immerse for 60 seconds	4.5018	0.3157	0.942
Immerse for 120 seconds	4.0806	0.3996	1

The results indicate that the n value, which reflects the sensitivity of the burn rate to pressure, decreased after 60 seconds of immersion. This suggests that combustion became less influenced by pressure, possibly due to localized disturbances on the grain surface resulting from water penetration. In contrast, after 120 seconds of immersion, both a and n returned to values close to those under normal conditions, with a coefficient of determination (R^2) equal to 1—indicating a stable and consistent combustion pattern.

This phenomenon is consistent with the effects of short-term moisture exposure, which, according to the literature, can lead to surface softening and uneven oxidizer distribution on the propellant surface—without significantly degrading overall combustion performance [8]. Meanwhile, longer-term moisture exposure can cause more progressive effects such as oxidizer particle bridging, microcrack formation, and oxidizer agglomeration, which may significantly affect regression and burn behavior [12].

The propellant used in this study contains 75% by weight of ammonium perchlorate (AP) as the primary oxidizer, which plays a dominant role in determining burn rate. A reduction in AP content is theoretically known to lower density, burn rate, and specific impulse [13],[14]. Although AP is water-soluble, its release from the HTPB matrix involves a complex mechanism, including water diffusion into the polymer network, local dissolution of AP, and migration out of the matrix. Among these, diffusion is considered the rate-controlling step [10].

The predicted burn rate values over a pressure range of 2–8 MPa, calculated using the Saint Robert equation, are shown in Table 3 and visualized in Figure 3.

Table 3. Comparison of propellant burn rates at pressures of 2–8 MPa for three immersion conditions

P (MPa)	r (mm/s)		
	normal	60 seconds	120 seconds
2	5.376	5.603	5.383
2.5	5.881	6.012	5.885
3	6.327	6.368	6.330
3.5	6.732	6.686	6.732
4	7.102	6.974	7.101
4.5	7.447	7.238	7.443
5	7.769	7.483	7.763
5.5	8.072	7.711	8.064
6	8.359	7.926	8.350
6.5	8.632	8.129	8.621
7	8.893	8.321	8.880
7.5	9.143	8.504	9.128
8	9.383	8.679	9.367

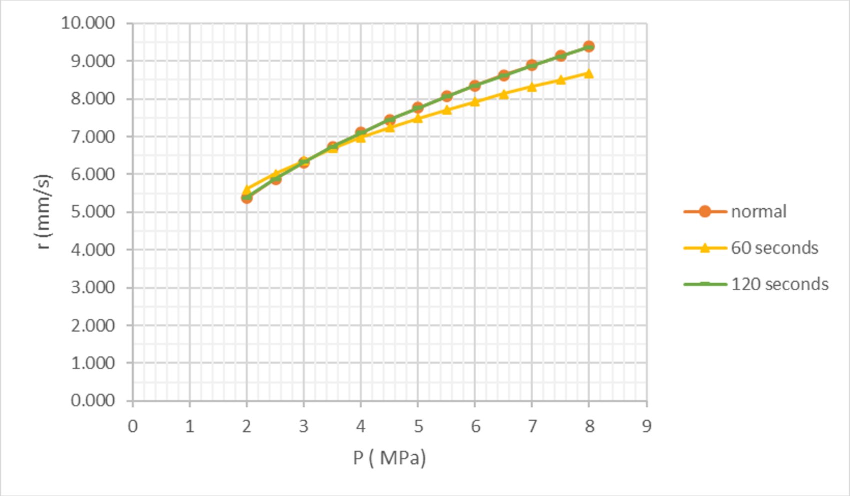

Fig. 3. 1Graph of the relationship between propellant burn rate and pressure for three immersion conditions : normal (0 second), 60 seconds, and 120 seconds

As illustrated in Figure 3, the three burn rate curves—representing normal conditions, 60-second immersion, and 120-second immersion—largely overlap, indicating that the burn rates under the three treatments are relatively similar.

To statistically assess whether the observed differences were significant, a one-way ANOVA test was performed under the null hypothesis (H_0) that there is no significant difference among the three groups. The descriptive statistics and ANOVA results are presented in Tables 4 and 5.

Table 4. Descriptive statistics of the average propellant burn ratein three treatment

Groups	Count	Sum	Average	Variance
normal	13	99.11418	7.624168	1.63834
60 seconds	13	95.63355	7.356427	0.960885
120 seconds	13	99.04716	7.619013	1.619848

Table 5. Results of analysis of variance (ANOVA) of propellant burn rate

Source of Variation	SS	df	MS	F	P-value	F crit (α=0.05)
Between Groups	0.60954	2	0.30477	0.216709	0.806207	3.259446
Within Groups	50.62887	36	1.406358			
Total	51.23841	38				

One way ANOVA is an appropriate and adequate framework for evaluating group means differences given the single factor experimental design and restricted exposure levels. Since no other environmental or composition variables were examined, more complex statistical techniques like regression modeling or multifactor analysis w under realistic ere not required. The results demonstrate that immersion time up to 120 seconds do not cause statistically significant differences in burn rate ($p>0.05$), which supports the trustworthiness of AES mesurements under realistic short-term immersion setting.

The results of ANOVA show that the calculated F-value (F) is less than the critical F-value (Fcrit), supporting the acceptance of H_0. Therefore, it can be concluded that no statistically significant difference exists in the burn rate of the propellant between the normal condition and after immersion for 60 or 120 seconds. This finding aligns with previous studies, which reported that the diffusion coefficient for perchlorate leaching from HTPB-based composite propellants immersed in water ranges between 1.07×10^{-12} and 1.53×10^{-12} m^2/s [10]. Given the short immersion durations of 60 to 120 seconds, the estimated amount of AP released is only around 0.05%, which is insufficient to cause any meaningful alteration in combustion characteristics.

Previous studies examined the amount of AP leached when immersed in a water for long term. After more than 17 hours of immersion, mass of AP reduced about 5%. the longer the immersion time, the higher the reduction in AP mass. Consequently, the surface area of the AP also decreases [10]. Reducing the AP content by 5% by weight in propellant composition, may decrease burn rate by up to 20% [15]. However, in practise, specimen immersion during AES burn rate testing only takes a few minutes, therefore no significant effect on the burn rate as demonstrated in this study.

4. Conclusion

The experimental results indicate that the burn rate of the composite propellant at pressures of 2–6 MPa ranges from 5.38 – 8.36 mm/s under normal conditions, 5.60–7.93 mm/s after

60 seconds of immersion, and 5.38 – 8.35 mm/s after 120 seconds of immersion. Based on one-way ANOVA analysis, no statistically significant differences were found among the three conditions. It can therefore be concluded that immersion in water for up to 120 seconds does not significantly affect the burn rate of the HTPB/AP-based composite propellant.

All authors are main contributors. Dwi Setyaningsih and Aprilia Fitri Yastuti designed and performed the experiments, analyzed the datas, and wrote the manuscript.

References

1. G.P. Sutton, O. Biblarz, Rocket propulsion elements, (John Wiley and Sons, Canada, 2016)
2. J. Ashish, G. Swaroop, and K. Balasubramanian, Effect of ammonium perchlorate particle size on flow, ballistic, and mechanical properties of composite propellant, Nanomaterials in Rocket Propulsion Systems, Elsevier, 299-362, (2018). https://doi.org/10.1016/B978-0-12-813908-0.00008-3
3. G. Gupta, L. Jawale, Mehilal, B. Bhattacharya, Various methods for the determination of the burning rates of solid propellants : an overview, Cent. Eur. J. Energ. Mater. **12(3)**, 593-620 (2015).
4. S. Chaturvedi and P.N. Dave, Solid propellants: AP/HTPB composite propellants, Arabic. J. Chem. **12(8)**, 2061–2068, (2019). https://doi.org/10.1016/j.arabjc.2014.12.033
5. R. Sangtyani, H.S. Saha, A. Kumar, A. Kumar, M. Gupta, and P.V. Chavan, An alternative approach to improve burning rate characteristics and processing parameters of composite propellant, J. Combust. Flame. **209**, 357–362, (2019). https://doi.org/10.1016/j.combustflame.2019.04.054
6. H. Yaman, V. Çelik, and E. Degirmenci, Experimental investigation of the factors affecting the burning rate of solid rocket propellants, J. Fuel. **115**, 794–803, (2014). https://doi.org/10.1016/j.fuel.2013.05.033
7. A. F. Nour Eldin, W. M. Adel, and A. Elsabbagh, Evaluation of solid propellant burning rate by using strand burner and static firing tests, J. Phys. Conf. Ser. **2811** 012027, (2024). https://doi.org/10.1088/1742-6596/2811/1/012027
8. E. Elsaka, S. Elbasuney, H. Mostafa, T. Elhedery, and A. Eldakhakhny, Burning rate measurement of composite propellant using acoustic wave emission in comparison with other techniques, J. Eng. Sci. Mil. Technol. **4(2)**, 226–232, (2020). https://doi.org/10.21608/ejmtc.2021.64610.1167
9. D.R. Lide, CRC handbook of chemistry and physics, (CRC Press, Boca Raton, FL, 2005).
10. E.W. Fournier and B.B. Brady, Perchlorate leaching from solid rocket motor propellant in water, J. Propuls. Power. **21(5)**, 937–941, (2005). https://doi.org/10.2514/1.14246
11. B.A. McDonald, J.R. Rice, and M.W. Kirkham, Humidity induced burning rate degradation of an iron oxide catalyzed ammonium perchlorate/HTPB composite propellant, J. Combust. Flame. **161(1),** 363–369, (2014). https://doi.org/10.1016/j.combustflame.2013.08.014
12. J.C. Thomas, T.E. Sammet, C.A.M. Dillier, A.R. Demko, F.A. Rodriguez, and E.L. Petersen, Aging effects on the burning rates of composite solid propellants with nano-additives, Jt. Propuls. Conf., 1–15, (2018). https://doi.org/10.2514/6.2018-4960
13. A. Manash and P. Kumar, Comparison of burn rate and thermal decomposition of AP as oxidizer and PVC and HTPB as fuel binder based composite solid propellants, J. Def. Technol. **15(2)**, 227–232, (2019). https://doi.org/10.1016/j.dt.2018.08.010
14. S. Park, S. Choi, K. Kim, W. Kim, and J. Park, Effects of ammonium perchlorate particle size, ratio, and total contents on the properties of a composite solid propellant, J.

Propellants Explos. Pyrotech. **45(9)**, 1376–1381, (2020). https://doi.org/10.1002/prep.202000055

15. J. C. Thomas, G. R. Morrow, C. A. M. Dillier, and E. L. Petersen, Comprehensive study of ammonium perchlorate particle size/concentration effects on propellant combustion, J. Propuls. Power **36(1)**, 95–100, (2020). https://doi.org/10.2514/1.B37485