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Combustion Science and Technology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/gcst20

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To cite this article: Carlos Henrique Marchi, Antonio Carlos Foltran, Diego Fernando Moro, Nicholas Dicati Pereira da Silva, Luciano Kiyoshi Araki, Izabel Cecília Ferreira de Souza Vicentin, Éderson Luiz dos Santos Dias, Alexandre Vidal Bento & Marcos Carvalho Campos (in memoriam) (2021): Cold-Crafted KNSu Mechanically Pressed Burning Rate for Combustion Pressure Ranging from 0.9 to 7.7 bar, Combustion Science and Technology, DOI: 10.1080/00102202.2021.2011862

To link to this article: https://doi.org/10.1080/00102202.2021.2011862

Published online: 28 Dec 2021.

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COMBUSTION SCIENCE AND TECHNOLOGY
https://doi.org/10.1080/00102202.2021.2011862

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ABSTRACT

Potassium nitrate/sucrose propellant (KNSu) is a common solid propellant, which can be cold or hot crafted, employed in amateur and experimental model rockets. There is limited burning rate data available for the KNSu, particularly for the cold-crafted one. In this study, KNSu composed of 65% potassium nitrate and 35% sucrose was prepared through cold crafting and by pressing with a hydraulic press. For such a particular crafting method, we did not find any experimental data on the burning rate versus combustion pressure. Therefore, we experimentally determined the cold-crafted KNSu burning rate for pressure levels ranging from 0.9 to 7.7 bar. We employed a ballistic evaluation motor with varying nozzle diameters to obtain the desired combustion pressure. We demonstrate that the cold-crafted KNSu burning rate lies in the range of available data for the hot-crafted version. The burning rate is not sensitive to combustion pressure levels lower than 2 bar, and the combustion temperature is 98.7% of the theoretical value. We also explain the estimation the combustion pressure from the thrust-plotted curve or by using the engine burning video.

ARTICLE HISTORY
Received 21 September 2021
Revised 18 November 2021
Accepted 24 November 2021

KEYWORDS
KNSu; rocket engine; solid propellant; burning rate; nozzle

Introduction

This study aims to adjust the empirical relation for the potassium nitrate/sucrose propellant (KNSu) burning rate (r) through experimental combustion pressure (p_o). To achieve this, we prepared KNSu using a dry and cold process and molded it into a ballistic evaluation motor. KNSu, which is formed by a mixture of potassium nitrate (KNO_3) and sucrose ($C_{12}H_{22}O_{11}$), is a common solid propellant employed in amateur rocket models (Brinley 1960). As proposed by Nakka (2001a), the KNSu propellant was first crafted by Bill Colburn in 1943. The powder was compressed with water to facilitate its preparation. Regarding the use of KNSu, the first model rocket launch occurred in 1947.

The most common KNSu crafting method is the grinding, mixing, and melting of sucrose (table sugar) around nitrate grains. Thereafter, the molten mixture is cast inside the molds and left to dry. Generally, KNSu comprises 65% potassium nitrate and 35% sucrose, as described by Nakka (1984, 2021b).

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Another method uses 60% potassium nitrate and 40% sucrose. It involves casting a molten mixture in a rotating mold and the formation of a cylindrical grain (Vyverman 1978) through the application of centrifugal force. There are other crafting methods as stated by Leslie and Yawn (2002).

One of the least common methods to craft KNSu is using a hydraulic press, which was first employed by Bill Colburn in 1957 (Leslie and Yawn 2002). In this method, the components are ground, mixed, and placed inside the motor case. Thereafter, the mixture is compressed using a hydraulic press until it produces a hard compacted grain. Foltran, Moro, and Silva et al. (2015) reported this method and its burning rate at atmospheric pressure when utilizing 65% potassium nitrate and 35% sucrose.

The burning-front progression rate, referred to as the burning rate (r), is the rate at which the solid propellant burns at a specific pressure (NASA 1972). The main parameter contributing to the burning rate is the combustion pressure (p_o). Other parameters include the initial propellant grain temperature, combustion products flowing over the burning surface, and motor acceleration or spin (NASA 1972; Sutton and Biblarz 2010).

The burning process of solid propellants is a complex phenomenon. It is a common practice to model the burning process using empirical equations. The most common empirical equation is Vieille's law (Gupta, Jawale, Mehilal 2015), Saint Venant's law (Fry, DeLuca, Frederick et al. 2002), and Saint Robert's law (NASA 1972; NASA 1971; Sutton and Biblarz 2010), and it is expressed as follows:

$$r = a.p_o^n \tag{1}$$

where a and n denote empirical parameters adjusted to fit the experiments. Generally, the experiments are conducted inside ballistic evaluation motors, subscale motors, or Crawford burners. Table 1 lists various a and n coefficients for the hot-crafted KNSu, where SEF refers to Sociedade de Estudos de Foguetes (Portuguese for Rocket Studies Society). SEF was a Brazilian group cited by Vyverman (1978), but without bibliographic data. Its KNSu composition was 68% potassium nitrate, 27% sucrose, and 5% barium sulfate. We did not find any data for a and n coefficients regarding the KNSu cold-crafted with a hydraulic press.

KNSu has been employed in rocket engines and experimental tests since 1943, in model rockets since 1947, and in academic contests (Parkin 1959; Brinley 1960; Vyverman 1978; Nakka 1984; Marchi et al. 1990; Leslie and Yawn 2002; Foltran, Moro, Silva et al. 2015). KNSu also allows studies involving rocket propulsion, aerodynamics, and model rocket flight. Its advantages include low cost, ease of acquiring and preparation, and enhanced safety. Cold-crafted KNSu is safer than all the other methods; therefore, its burning rate is important for safe rocket engine design and accurate performance prediction.

This study aims to adjust Equation (1) for cold-crafted KNSu in ballistic evaluation motors To achieve this, the following objectives should be considered:

Table 1. Parameters a and n for the KNSu burning rate for p_o (bar) and r (mm/s).

Reference	Method	a (mm/s.bar^n)	n (.)
SEF (wd)	Casted	1.17	0.65
Vyverman (1978)	Centrifugated	2.00 to 2.20	0.40 to 0.42
Vyverman (1978)	Casted	1.10 to 3.30	0.60 to 0.70
Nakka (1984)	Casted	3.96	0.319

(1) Obtain r experimentally for p_o ranging from 0.9 bar to 7.7 bar.
(2) Fit the coefficients a e n over the experimental data r versus p_o.
(3) Experimentally obtain the combustion temperature (T_o) and its efficiency at 0.9 bar.
(4) Exhibit the rocket engine parameters for p_o ranging from 0.9 bar to 7.7 bar.
(5) Assess varying methods for obtaining the burning time to determine the burning rate.

In the following sections, we present the materials and methods employed in this study, details of the rocket engine, KNSu propellant, test bench, burning rate evaluation, and rocket engine parameters. Thereafter, we present the results, their discussion, and concluding remarks.

Materials and methods

Rocket engine

To perform experimental tests, we designed specific rocket engines, namely the MTP (Portuguese abbreviation for the propellant testing motor). Each engine primarily had three SAE 4340 alloy steel components: an engine case, an end cap, and a nozzle. The engine case had internal and external diameters of 60 and 80 mm, respectively, and a length of 208 mm. The cap and nozzle had M68 x 6 threads and a length of 36 mm. Furthermore, the engine case had a threaded lateral opening for connecting it to a manometer.

To obtain varying p_o, we designed 12 convergent conical nozzles with throat diameters (D_t) ranging from 2.5 to 20 mm and a 45° inclination angle. The nozzles only had a convergent part, but lacked a divergent part. Figure 1 shows two MTP engines, one with and the other without a nozzle. We can also observe the manometer opening and the manometer connected to the engine case.

KNSu propellant

The procedure for preparing the propellant involves the following steps:

(1) Measuring 0.65 M_s of the oxidizer, where M_s represents the propellant mass of each batch. Owing to its cost and easy accessibility, we employed the fertilizer Krista K type 12 00 43 1 Mg from Yara Tera that contains at least 90% KNO_3 and 5%–7% $MgSO_4$ (Yara 2016).
(2) Measuring 0.35 M_s of fuel. We employed a type of sucrose, amorphous, and refined sugar from União that contains at least 99% of $C_{12}H_{22}O_{11}$ (Brasil 2018).
(3) Grinding approximately 150 g of oxidizer for 30 s using a coffee grinder.
(4) Grinding approximately 150 g of fuel for 30 s using a coffee grinder.
(5) Mixing 600 g of fuel and oxidizer manually in a plastic bag (ziploc type) for 15 min.
(6) Pouring 214 g of propellant inside the engine case of MTP with the end cap.
(7) Pressing the propellant using a hydraulic press with a 59 mm punch and 10 ton force.

We did not use any additives to improve the propellant burn or ease its pressing.

Figure 1. Two MTP rocket engines.

We employed a Bovenau ST-15 hydraulic press with a 15 ton maximum capacity, a Marte AS500C digital scale with 0.01 g resolution to measure the propellant and its components, and a digital caliper rule with 0.01 mm resolution.

The resulting propellant grain was cylindrical, with a length (L_g) of 49 mm, diameter of 60 mm, and no thermal inhibition. Therefore, the propellant grain was in direct contact with the engine case.

To ignite the propellant, we applied three droplets of 3 M Scotch Flex glue over the propellant grain surface and distributed 1 g of gunpowder over the glue. Thereafter, a pyrotechnic fuse or electrical squib was used to ignite the gunpowder. Figure 2 shows the propellant grain loaded in the MTP with pyrotechnic fuse and without the nozzle. Ideally, ignition should occur over the 60 mm diameter propellant grain surface and propagate through its 49 mm length (L_g).

The particle size distribution of the propellant grain was as follows: 1.63% of the grains had a diameter ≥400 μm, 250 ≤ 8.45% < 400 μm, 180 ≤ 39.94% < 250 μm, 74 ≤ 41.10% < 180 μm, and 8.88% < 74 μm. These results were obtained using test sieves with mesh sizes of 400, 250, 180, and 74.

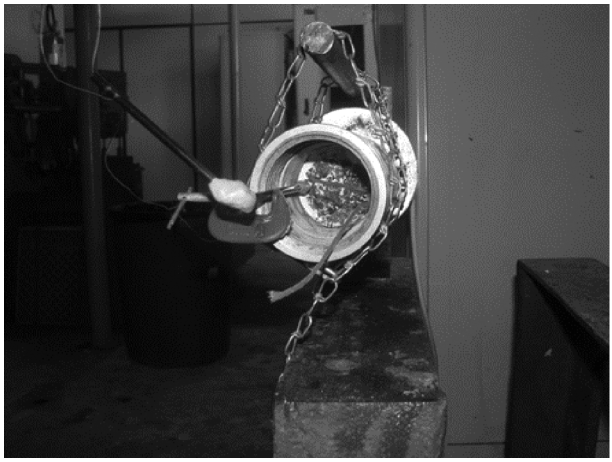

Figure 2. MTP rocket engine at the test bench showing the KNSu propellant grain and the gunpowder for ignition.

Test bench

The test bench is shown on the left side of Figure 3, along with one firing MTP. We can also see in Figure 3 the hot gases flowed out of the engine and load cell on the opposite side of the MTP. We employed a Hottinger Baldwin Messtechnik GmbH (HBM) 50 N S2-type load cell with 0.0025 N resolution. The acquisition system was Spider 8 with Catman 4.5 software, both from HBM. In each test, we positioned the MTP horizontally during firing as shown in Figure 3. The acquisition frequency was 200 Hz. We measured the combustion pressure using analogue manometers, as shown in Figure 1.

According to the expected combustion pressure, we employed one of the following manometers: Nava, 40.0 kPa ± 160 Pa; Willy, 98.1 kPa ± 490 Pa; Socios, 196 kPa ± 880 Pa; Socios, 588 kPa ± 1.96 kPa; Record, 3.92 bar ± 1.96 kPa; Socios, 3.92 bar ± 1.96 kPa; Naka, 9.81 bar ± 1.96 kPa; Naka, 27.5 bar ± 5.88 kPa; and Record, 34.3 bar ± 19.6 kPa; all measurements had uncertainties with 95% reliability.

We measured temperature using type-K thermocouples from Omega. The thermocouples had a 0.3 s response time, 4.2 K measurement uncertainty, and 95% reliability for temperatures up to 1456 K.

Figure 3. Burning MTP rocket engine and thrust curve at the monitor.

Burning rate evaluation

Several methods can be used to evaluate the burning rate and burning time (t) (Brown 1996; Fry, DeLuca, Frederick et al. 2002; Gupta, Jawale, Mehilal 2015; NASA 1972; Sutton and Biblarz 2010). In this study, we evaluated the burning rate using the following expression:

$$r = \frac{L_g}{t_b} \tag{2}$$

where t_b denotes the burning time, that is, the period of time during which the propellant grain is consumed owing to its burn.

We obtained the burning time using four parameters as follows:

(1) Manometer combustion pressure (p) using a manometer; the beginning is when pressure above ambient pressure levels is detected, and the end is when the pressure equals the ambient pressure level.
(2) Load cell engine thrust (e) using software Curva-Empuxo (2021); the beginning is when thrust above zero is detected, and the end is when it reaches zero level.
(3) Gas ejection visualization (v): we employed a Sony HDR-SR10 camera and software Tracker (2021); the beginning is when the gas starts to be ejected from the engine, and the end is when it stops.
(4) Sound intensity (s): we employed a Sony HDR-SR10 camera and software Audacity (2021); the beginning is when it detects louder sound intensity than the environment, and the end is when the sound intensity equals that of the environment.

By replacing the four parameters in Equation (2), we obtain four burning rates: r_p,r_e,r_v, and r_s, respectively.

By assessing the behavior of these varying burning times, we can obtain different methods of estimating the burning rate. If we have a burning rate curve, p_o can be estimated.

Rocket engine parameters

To assess the rocket engine performance, we computed the following physical parameters:

- Total impulse (I_t):

$$I_t = \int_0^{t_b^e} F\, dt \tag{3}$$

where F denotes the instantaneous rocket engine thrust.

- Average thrust (F_m):

$$F_m = \frac{I_t}{t_b^e} \tag{4}$$

- Average effective exhaust velocity (c):

$$c = \frac{I_t}{M_p} \tag{5}$$

where M_p represents the mass of propellant grain.

- Average specific impulse (I_s):

$$I_s = \frac{c}{g} \tag{6}$$

where g denotes the gravitational acceleration at sea level (9,80665 m/s^2).

- Average thrust coefficient (C_f):

$$C_f = \frac{F_m}{p_o A_t} \tag{7}$$

where A_t represents the nozzle throat area, and p_o denotes the average combustion pressure during burning time (t_b^p).

Results

We performed 57 tests with the MTP between July 27th, 2014 and July 16th, 2016 at the Polytechnic Center Campus of the Federal University of Paraná, Brazil. Among the performed tests, we selected 15 tests with neither anomalies, nor equipment or execution problems, for this study.

Table 2 lists the number, date, atmospheric pressure (p_a), temperature (T_a) readings, mass (M_p), length (L_g), diameter (D_g), and density (ρ) of each propellant grain for each test. In addition, we present the average value for each parameter and its standard deviation σ.

Table 3 summarizes the nozzle throat diameter (D_t), average combustion pressure (p_o), pressure (t_b^p), thrust (t_b^e), video (t_b^v), and sound intensity (t_b^s) burning times. In column D_t, the term "without" implies that we tested the rocket engine without a nozzle, that is, the burn occurred at atmospheric pressure (p_a).

Table 4 lists the burning rates for each burning time computed using Equation (2) and the propellant residuum relative to the propellant grain mass (Res) for each rocket engine.

Table 5 summarizes the MTP performance parameters from Equations (3)–(7). Figure 4 presents the thrust and combustion pressure versus burning time curves for test 44; the top and bottom curves represent thrust and pressure, respectively.

In tests 56 and 57, we measured the combustion temperature (T_o) without the nozzle. The thermocouple was positioned 10 mm from the surface of the propellant grain before ignition. The acquisition frequency was 200 Hz. The combustion temperature was 1422 K for test 56 and 1431 K for test 57. They were obtained from the averages at 4.73 and 4.90 s and had standard deviations of 20.8 and 21.8 K, respectively, which correspond to 1.5% of T_o values.

Table 2. Propellant grain and test data.

Test	Date	p_a (bar)	T_a (°C)	M_p (g)	L_g (mm)	D_g (mm)	ρ (kg/m^3)
1	27/07/14	0.9161	13.8	214.00	46.75	60.03	1617
9	28/09/14	0.9085	18.6	214.00	46.18	60.03	1637
31	04/06/15	0.9135	22.5	213.90	48.76	60.03	1550
51	19/02/16	0.9075	25.2	214.00	47.36	60.03	1597
56	16/07/16	0.9046	19.3	224.00	51.36	60.19	1533
57	16/07/16	0.9052	19.1	214.01	51.22	60.10	1473
32	04/06/15	0.9132	22.6	213.94	48.49	60.10	1556
33	04/06/15	0.9134	22.9	213.93	47.93	60.19	1568
34	04/06/15	0.9133	22.4	213.87	48.54	60.15	1551
35	04/06/15	0.9132	22.1	213.56	47.59	60.18	1578
36	04/06/15	0.9133	21.9	213.39	48.88	60.07	1540
37	04/06/15	0.9133	21.7	213.40	49.13	60.15	1529
43	11/07/15	0.9073	19.5	213.69	49.74	60.07	1516
44	11/07/15	0.9073	19.6	213.46	48.57	60.15	1547
45	11/07/15	0.9072	19.5	213.91	49.01	60.03	1542
Average		**0.9105**	**20.7**	**214.47**	**48.63**	**60.10**	**1556**
σ		0.0037	2.7	2.65	1.43	0.06	40

Table 3. Combustion pressure and burning times.

Test	D_t (mm)	p_o (bar)	t_b^p (s)	t_b^e (s)	t_b^v (s)	t_b^s (s)
1	Without	0.9161			20.120	19.477
9	Without	0.9085			18.885	19.176
31	Without	0.9135			26.059	26.088
51	Without	0.9075			20.988	20.766
56	Without	0.9046		18.195	18.852	20.775
57	Without	0.9052		18.275	20.887	21.251
32	20.03	0.9270	29.500		30.697	30.113
33	12.03	1.0033	28.267		28.095	28.407
34	10.01	1.18	20.200	20.560	21.855	21.723
35	8.03	2.19	16.400	15.415	16.383	16.532
36	7.01	2.85	14.300	12.915	14.181	14.351
37	6.02	3.63	13.900	13.560	14.381	14.551
43	6.02	4.10	12.367	11.675	13.013	11.657
44	5.00	7.23	10.533	9.360	11.579	9.769
45	4.51	7.68	9.000	9.010	9.376	9.008

Table 4. Burning rate and residuum versus combustion pressure.

Test	p_o (bar)	r_p (mm/s)	r_e (mm/s)	r_v (mm/s)	r_s (mm/s)	*Res* (%)
1	0.9161			2.324	2.400	
9	0.9085			2.445	2.408	10
31	0.9135			1.871	1.869	17
51	0.9075			2.257	2.281	13
56	0.9046		2.823	2.724	2.472	13
57	0.9052		2.803	2.452	2.410	15
32	0.9270	1.644		1.580	1.610	27
33	1.0033	1.696		1.706	1.687	26
34	1.18	2.403	2.361	2.221	2.234	26
35	2.19	2.902	3.087	2.905	2.879	32
36	2.85	3.418	3.785	3.447	3.406	35
37	3.63	3.535	3.623	3.416	3.376	39
43	4.10	4.022	4.260	3.822	4.267	39
44	7.23	4.611	5.189	4.195	4.972	38
45	7.68	5.446	5.440	5.227	5.441	39

Table 5. MTP performance parameters.

Test	p_o (bar)	I_t (N.s)	I_s (s)	F_m (N)	c (m/s)	C_f (.)
1	0.9161					
9	0.9085					
31	0.9135					
51	0.9075					
56	0.9046	2.4	1.1	0.1	10.8	
57	0.9052	3.5	1.7	0.2	16.3	
32	0.9270					
33	1.0033					
34	1.18	66.9	31.9	3.3	312.8	0.35
35	2.19	103.2	49.3	6.7	483.2	0.60
36	2.85	109.2	52.2	8.5	511.9	0.77
37	3.63	118.5	56.6	8.7	555.3	0.85
43	4.10	124.8	59.6	10.7	584.3	0.92
44	7.23	139.0	66.4	14.8	651.0	1.05
45	7.68	137.8	65.7	15.3	644.2	1.25

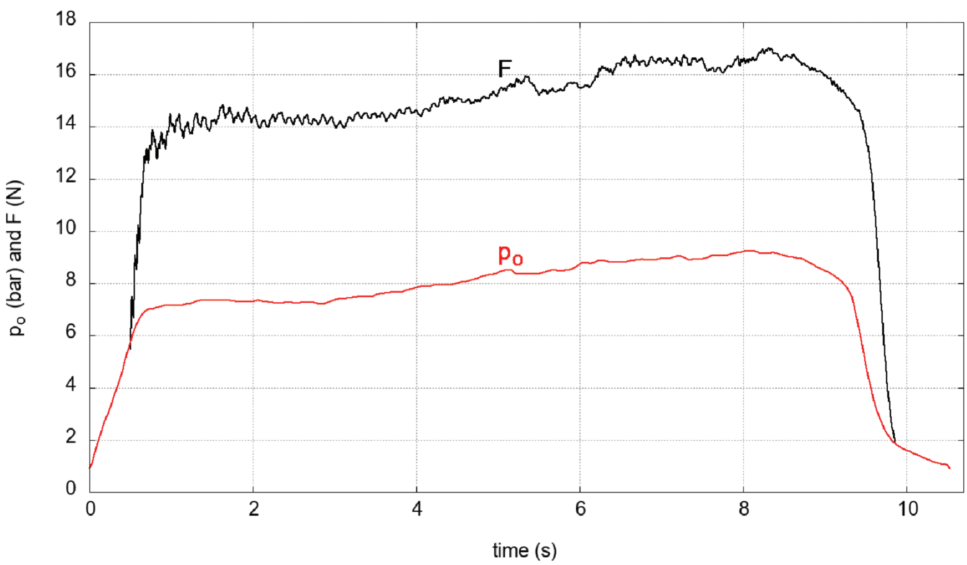

Figure 4. Thrust and pressure curves for test 44.

Discussion

The propellant grain average density (ρ) was 1556 ± 40 kg/m^3, which resulted from cold pressing with 10 tons, as summarized in Table 2. For the hot-crafted KNSu, Vyverman (1978) obtained a density range of 1650–1800 kg/m^3, whereas Nakka (1984) obtained a density of 1800 kg/m^3. For the cold-crafted KNSu, Marchi et al. (1990) obtained 1300 kg/m^3 with manual pressing, whereas Foltran, Moro, and Silva et al. (2015) obtained a density in the range of 1382–1683 kg/m^3 with cold pressing and from 2 to 10 ton force range. The theoretical KNSu density is 1888 kg/m^3. Thus, we observed that the hot-crafted KNSu propellant has a higher density even when using a hydraulic press in the cold-crafted method.

The KNSu theoretical combustion temperature determined using the PROPEP (2021) software was 1477 K for 0.9 bar and 65% potassium nitrate and 35% sucrose composition. For our propellant, we also must consider $MgSO_4$. Therefore, the theoretical combustion temperature ranges from 1433 to 1458 K. For tests 56 and 57, the combustion efficiency ranged from 97.5% to 99.9% (average value: 98.7 ± 1.2%).

In Table 4, we observe that the residuum range was: (i) 10%–17% for atmospheric pressure (0.91 bar) without a nozzle, and (ii) 26%–39% with a nozzle for p_o ranging from 0.93 to 7.68 bar, which exceeds the average atmospheric pressure (0.91 bar). The range of the theoretical residuum computed from PROPEP (2021) was from 32% to 39% for p_o ranging from 0.9 to 10 bar. In the case of burning at atmospheric pressure, the variance between the measured and theoretical residuum was because of the absence of a nozzle; consequently, half of the residuum was ejected during the burn. For tests 32–34, the variance was small despite the presence of nozzles because their diameters (20, 12 and 10 mm) were relatively larger when compared to the internal diameter of the engine case. For the 8 mm and smaller nozzle diameters, the theoretical and measured residuum are in good agreement.

In Figure 5, we plotted the nine points r_p versus p_o listed in Table 4 along with three adjusted curves, with an average that is expressed as follows:

$$r_p = 1.96\, p_o^{0.50} \tag{8}$$

The inferior and superior curves have the same exponent, n = 0.50, of the average one; the values of a for both the curves are 1.66 and 2.26 mm/s.bar^n, respectively. This is an approximated variation of ±15% of the values in Equation (8). The value of a = 1.96 mm/s.bar^n of Equation (8) is within the range of 1.10–3.96 mm/s.bar^n of the values listed in Table 1. Furthermore, the value of n = 0.50 is also in the range of 0.319–0.70 of the values listed in Table 1.

We adjusted the remaining results of Table 4, yielding the following average curves:

$$r_e = 2.20\, p_o^{0.45} \tag{9}$$

$$r_v = 1.86\, p_o^{0.48} \tag{10}$$

$$r_s = 1.87\, p_o^{0.52} \tag{11}$$

where their variations in the inferior and superior curves were approximately ±9.1%, ±14%, and ±12%, respectively. These values are valid for p_o ranging from 0.93 to 7.68 bar. The results show that the physical parameter employed to obtain the burning time has an impact on the curve r versus p_o and on the a and n coefficients.

Equation (9) can be used in KNSu engine tests to estimate p_o, even without using manometers. Accordingly, we must obtain the thrust burning time t_b^e, evaluate r_e, and compute the pressure from Equation (9). Equations (10) and (11) can also be used to estimate p_o. They are useful for model rocket launches: with the launch video, we can obtain t_b^v and t_b^s. Subsequently, r_v and r_s are evaluated, and p_o is obtained from Equations (10) and (11).

In Figure 6, we compare the burning rate curve obtained in this study with those obtained from Table 1. We only show the centrifuged KNSu average values for Vyverman (1978), that is, a = 2.10 mm/s.bar^n and n = 0.41, because there was

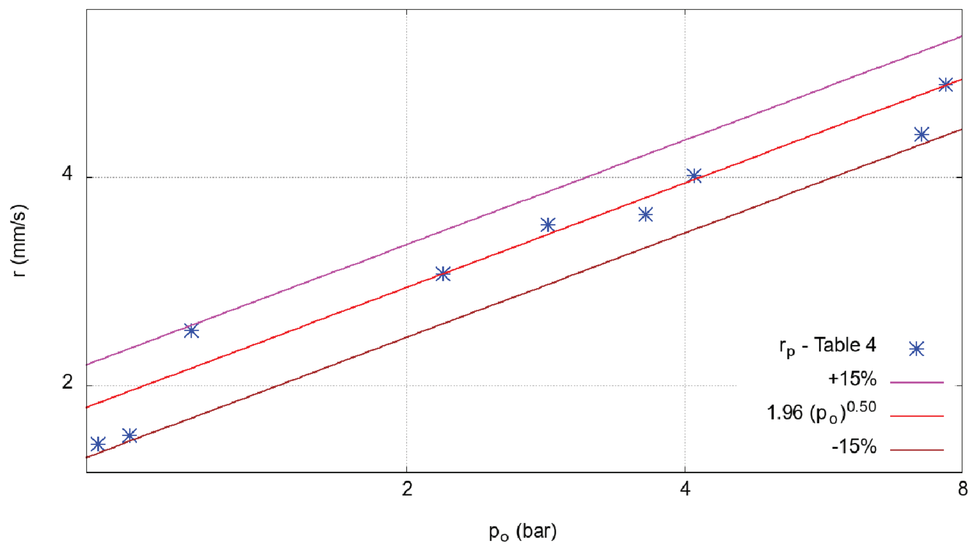

Figure 5. KNSu burning rate versus combustion pressure.

significant variation in the molten KNSu values. We observe that the burning rate curve obtained in this study is closer to that of Vyverman (1978) and is between that of SEF and Nakka (1984). In addition, the last two had lower and higher burning rates for a specific combustion pressure.

Regarding the data in Table 4 for nozzleless engines, at 0.91 bar atmospheric pressure, the average burning rate values were r_e = 2.81 mm/s, r_v = 2.35 mm/s, and r_s = 2.31 mm/s, with maximum variations of 0.4%, 20%, and 19%, respectively. Foltran, Moro, and Silva et al. (2015) reported r_v = 2.47 mm/s, which is the average burning rate for 20 tests. For these tests, the density ranges for burning at atmospheric pressure are listed in Table 2. The maximum variation was 11%, which involves five of the six r_v values obtained in this study. We employed similar components as in Foltran, Moro, and Silva et al. (2015) to craft the KNSu. Based on the data listed in Table 4, we can conclude that r_e,r_v, and r_s are not sensitive to p_o for pressures below 2 bar.

In this study, the burning time is indeed the action time, according to the definitions of Sutton and Biblarz (2010). Thus, the burning rates presented are slightly lower than the actual rates, estimated at less than 12% in the case of r_p and less than 7% in the case of r_e.

Conclusion

We experimentally determined the burning rate (r) for the cold, dry, and pressed KNSu at combustion pressures ranging from 0.9 to 7.7 bar. We obtained the function $r(p_o)$ that is given by Equation (8) with ±15% uncertainty. The burning rate obtained in this work is within the range of those reported in the literature using hot-prepared KNSu. We show that r_e,r_v, and r_s are not sensitive to p_o for pressures lower than 2 bar.

The hot-crafted KNSu density is higher than that of the cold-crafted KNSu, even with mechanical pressing. The experimental combustion temperature was determined to be 98.7 ± 1.2% from the theoretical value. Under adequate conditions, the theoretical and

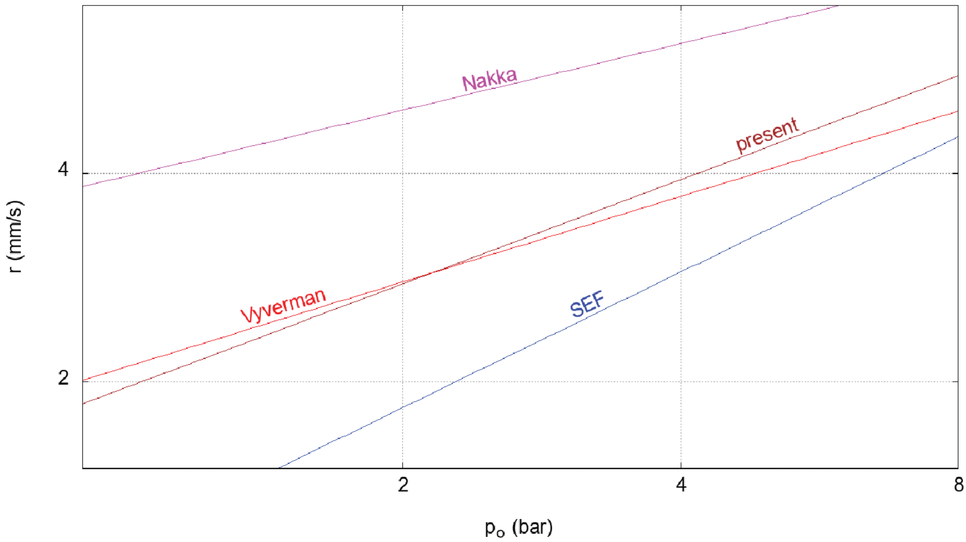

Figure 6. Comparison between KNSu burning rates.

experimental residuals from the burning of the KNSu propellant can exhibit good agreement. The highest specific impulse obtained was 66.4 s, and the thrust coefficient was 1.25.

We explained how to estimate p_o through Equations (9)-(11) using the thrust curve or a video of the engine burning without using manometers. Furthermore, we showed that this estimate is valid for KNSu tests.

For future and ongoing studies, we plan to: (i) improve the MTP to reduce the experimental uncertainty, improve the KNSu propellant analysis (ii) to determine the effects of varying compositions and (iii) prepare, and (iv) increase the pressure up to 100 bar.

Acknowledgments

We would like to acknowledge José Osmar Klein Jr and Lucas Schlossmacher for their support. We would also like to acknowledge the PRH, DEMEC, CAPES/PRÓ-ESTRATÉGIA, Ceramics Laboratory, LabMetro, and Canguiri farm for their support. We thank the reviewer of this work for his comments and suggestions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The authors acknowledge the Department of Mechanical Engineering of Federal University of Paraná (UFPR), the Uniespaço Program of the Brazilian Space Agency (AEB), and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil, for the physical and financial support given for this work. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazil, Finance Code 001. The first author receives a scholarship supported by CNPq.

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