Burning Characteristics of Firework Stars and Lifting Charge

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Abstract: *Burning experiments were carried out for stars and lifting charge in the air and in a closed vessel. Three types of stars were used, that is, ordinary spherical, half-restricted spherical and hemispherical surface-restricted stars were used as models for flying burning. Partly restricted stars gave longer burning times than the ordinary stars, but not enough to explain the flying burning behavior. This was attributed to the burning of the ignition promoter in the restricted stars.*

The ratio of the time to maximum pressure to the stationary burning time of stars was about 0.44 and that of the lifting charge was about 0.24, presumably because the burning rate of the stars is smaller than that of the lifting charge.

Keywords: *firework stars, lifting charge, burning time, stationary burning, flying burning*

Introduction

The present authors have studied the ballistics of firework stars.[1,2] In the course of the study, it was shown that the flying burning time is longer than the stationary burning time of a star. Kosanke and Kosanke observed by means of a photograph that the burning star expelled from a shell in the air had a black part.[3] This may be the reason for the longer burning times of flying stars.

In order to determine the nature of flying burning, the burning times of ordinary and half-restricted stars are measured using an open cup by a high-speed video camera, and using a closed vessel by a pressure transducer.

The burning time and pressure profile of the lifting charge are also measured using same methods as mentioned above and the results are discussed.

Experimental

Samples

The red peony and silver crown stars both for no. 5 shells (a Japanese no. 5 round shell corresponds to a western 6 inch shell) were supplied by Sunaga Hanabi Co. Ltd. in Ashikaga-city, and the lifting charge was made by Nippon Kayaku Co. Ltd. The restrictor was a mixture of an epoxy resin and a silicon polymer.

Three types of stars, as shown in Figure 1, were

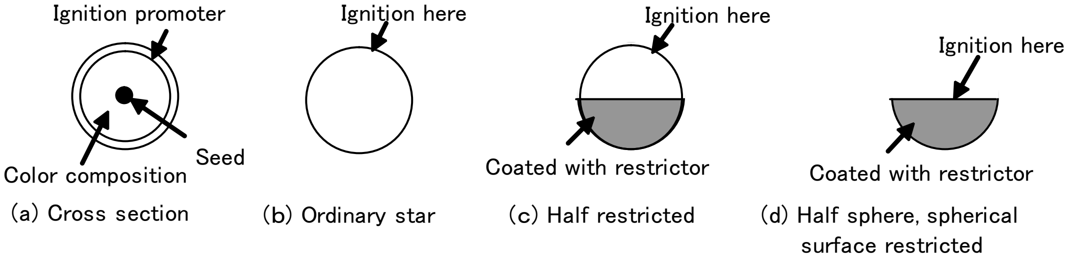

Figure 1. *Cross section and three types of stars used in the experiments.*

Table 1. *Results of the stationary burning times of stars in the open air.*

Sample	Shape	Run	Mass/g	Diameter/mm	Height/mm	Burning time/ms
Red peony star for no. 5 shell	Sphere	1		15.10		3416
		2	2.759	15.05		3252
		3	2.847	15.15		3515
		4	2.637	14.65		3265
		5	2.653	14.60		3294
		6	2.867	15.30		3190
		7	2.640	14.56		3305
		8	2.983	15.41		3366
		9	2.705	14.79		3229
	Mean		2.767	14.96		3315
	SD[a]		0.120	0.31		102
	RSD[b]		0.043	0.02		0.03
	Sphere (half-coated with restrictor)	10	2.850	15.10		4172
		11	2.716	14.95		4093
		12	2.862	15.00		4074
		13	2.714	14.90		4017
		14	2.827	14.85		4329
	Mean		2.794	14.96		4137
	SD[a]		0.073	0.10		121
	RSD[b]		0.026	0.01		0.03
	Half sphere (spherical surface coated with restrictor)	15	2.090	15.30	10.05	4417
		16	2.065	15.15	10.35	4205
		17	1.966	14.80	9.80	3983
		18	1.986	15.65	10.25	4084
		19	2.071	15.20	10.35	4233
	Mean		2.036	15.22	10.16	4184
	SD[a]		0.056	0.31	0.24	164
	RSD[b]		0.027	0.02	0.02	0.04

[a] Standard deviation. [b] Relative standard deviation (SD/mean).

used for stationary burning both in the open air and in a closed vessel. The stars were covered by an ignition promoter as shown in Figure 1 (a).

Stationary burning in the open air

Stationary burning in the open air was carried out in a draft chamber. A star was put on a heat resistant board in a stainless steel vat and ignited by a torch. The burning time was determined by a high-speed video camera (Phantom VRI-V4.2, 1000 frames s^{-1}).

The lifting charge was poured into a steel cup of 20 mm inner diameter and 20 mm depth placed on the heat resistant board. It was ignited by a Nichrome wire and the burning time was measured as mentioned above.

Table 1 (contd). *Results of the stationary burning times of stars in the open air.*

Sample	Shape	Run	Mass/g	Diameter/mm	Height/mm	Burning time/ms
Silver crown star for no. 5 shell	Sphere	20	3.462	15.05		4050
		21	3.320	14.75		3925
		22	3.315	14.70		3907
		23	3.239	14.75		4493
		24	3.594	15.10		4336
		25	3.250	14.61		3588
		26	3.315	14.85		4464
		27	3.331	14.95		3666
		28	3.075	14.53		4478
	Mean		3.322	14.81		4101
	SD[a]		0.144	0.19		355
	RSD[b]		0.043	0.01		0.09
	Sphere (half-coated with restrictor)	29	3.595	15.35		4238
		30	3.370	14.95		4237
		31	3.185	14.85		4126
		32	3.368	14.90		4157
		33	3.502	14.95		4195
	Mean		3.404	15.00		4191
	SD[a]		0.155	0.20		49
	RSD[b]		0.046	0.01		0.01
	Half sphere (spherical surface coated with restrictor)	34	2.025	14.90	8.95	4257
		35	2.030	14.95	8.67	4729
		36	2.266	15.25	9.40	4479
		37	2.355	15.10	9.70	4479
		38	2.055	14.85	9.15	3887
	Mean		2.146	15.01	9.17	4366
	SD[a]		0.154	0.16	0.40	316
	RSD[b]		0.072	0.01	0.04	0.07

[a] Standard deviation. [b] Relative standard deviation (SD/mean).

Stationary burning in a closed vessel

The stationary burning test in a closed vessel was carried out in a strand burning tester with 0.0011 m^3 inner volume. The pressure profile was measured and recorded by a pressure transducer, a pre-amplifier and a analyzing data recorder.

A star or lifting charge in the cup was put on a support, and the Nichrome wire was placed in contact with the surface of the sample. The support with the sample was set in the tester, and an electric current was sent through the wire and the sample was ignited. In the case of the hemispherical star, a small amount of the lifting charge was used for promoting the ignition of the cut surface of the star. The color stars used here were covered by

Table 2. *Results of the stationary burning of stars for no. 5 shells in the closed vessel.*

Sample	Shape	Run	Mass/g	Diameter/ mm	Height[c]/ mm	P_{max1} (10^5 Pa)	P_{max2} (10^5 Pa)	t_{max1}/ms	t_{max2}/ms	Mean t_s/ms	t_{max1}/t_s	t_{max2}/t_s
Red peony star for no. 5 shell	Sphere	1	2.814	14.92		1.148	0.873	308	1320	3315	0.09	0.40
		2	2.798	15.21		1.049	0.930	422	1320		0.13	0.40
		3	2.697	15.09		0.997	0.848	352	1760		0.11	0.531
		4	2.810	15.20		1.056	1.007	370	1540		0.11	0.47
		5	2.870	15.06		1.114	0.799	440	1320		0.13	0.40
	Mean		2.798	15.09		1.073	0.891	378	1452		0.11	0.44
	SD[a]		0.063	0.12		0.059	0.080	53	197		0.02	0.06
	RSD[b]		0.022	0.01		0.055	0.090	0.14	0.14		0.14	0.14
	Sphere (half-coated with restrictor)	6	2.891	15.14		1.040	1.138	572	1540	4137	0.14	0.37
		7	2.913	15.00		0.789	1.229	572	1672		0.14	0.40
		8	2.640	14.67		0.644	1.127	528	1848		0.13	0.45
		9	3.016	15.43		0.804	1.311	440	1980		0.11	0.48
		10	2.570	14.17		0.511	1.301	440	1936		0.11	0.47
	Mean		2.806	14.88		0.758	1.221	510	1795		0.12	0.43
	SD[a]		0.191	0.48		0.198	0.087	67	185		0.02	0.05
	RSD[b]		0.068	0.03		0.261	0.071	0.13	0.10		0.13	0.10
	Half sphere (spherical surface coated with restrictor)	11	2.224	15.38	10.09	0.707	1.111	1144	1672		0.27	0.40
		12	2.580	16.17	11.35	0.636	1.060	1496	3080		0.36	0.74
		13	2.108	15.46	10.22		1.144		2288	4184	0.00	0.55
		14	2.075	15.19	10.15	0.634	1.000	1276	2992		0.31	0.72
		15	1.931	14.89	9.73	0.662	1.111	1364	2992		0.33	0.72
	Mean		2.184	15.42	10.31	0.660	1.085	1320	2605		0.32	0.62
	SD[a]		0.245	0.48	0.61	0.034	0.056	148	612		0.14	0.15
	RSD[b]		0.112	0.03	0.06	0.052	0.052	0.11	0.23		0.46	0.24

[a] Standard deviation. [b] Relative standard deviation (SD/mean). [c] Height of the half sphere.

an ignition promoter. The cut surface without the ignition promoter was difficult to ignite by means of the electrically heated wire only.

Results and Discussion

Stationary burning of stars in the open air

Results of the stationary burning in the open air and in the closed vessel are listed in Tables 1 and 2, respectively. Examples of the pressure profiles of the burning stars in the closed vessel are shown in Figure 2a/2b.

It is seen from Table 1 that the burning time of the silver crown star is longer than that of the red peony star with the same geometry. The burning times of the three types of a star increased in following order:

Spherical star without resin coating < spherical star with half surface coated by resin < hemispherical star with spherical surface coated by resin

Some burning characteristics of these stars are shown from Figure 2. For spherical stars without resin coating, an initial steeper pressure rise was observed. Then the pressure dropped once, then

Table 2 (contd). *Results of the stationary burning of stars for no. 5 shells in the closed vessel.*

Sample	Shape	Run	Mass/g	Diameter/mm	Height[c]/mm	P_{max1} (10^5 Pa)	P_{max2} (10^5 Pa)	t_{max1}/ms	t_{max2}/ms	Mean t_s/ms	t_{max1}/t_s	t_{max2}/t_s
Silver crown star for no. 5 shell	Sphere	1	3.392	14.84		1.067	1.406	440	1760		0.11	0.43
		2	3.447	15.03		1.020	1.360	528	1980		0.13	0.48
		3	3.250	14.77		0.954	1.288	484	1892		0.12	0.46
		4	3.283	14.48		1.055	1.439	440	1892	4101	0.11	0.46
		5	3.280	15.03		1.173	1.454	475	1848		0.12	0.45
	Mean		3.330	14.83		1.054	1.389	473	1874		0.12	0.46
	SD[a]		0.085	0.23		0.080	0.067	36	80		0.01	0.02
	RSD[b]		0.025	0.02		0.076	0.048	0.08	0.04		0.08	0.04
	Sphere (half-coated with restrictor)	6	3.340	14.71		0.485	1.494	352	2552		0.08	0.61
		7	3.368	15.50		0.608	1.583	372	2552		0.09	0.61
		8	3.450	15.00		0.713	1.429	440	2376	4191	0.11	0.57
		9	3.274	14.70		0.423	1.252	370	2728		0.09	0.65
		10	3.410	15.16		0.561	1.449	528	2596		0.13	0.62
	Mean		3.368	15.01		0.558	1.441	412	2561		0. 10	0.61
	SD[a]		0.067	0.34		0.112	0.121	73	126		0.02	0.03
	RSD[b]		0.020	0.02		0.201	0.084	0.18	0.05		0.18	0.05
	Half sphere (spherical surface coated with restrictor)	11	2.463	14.88	10.08	0.627	1.350	1144	3608		0.26	0.83
		12	2.066	14.74	9.14		1.514		3960		0.00	0.91
		13	2.392	15.16	9.78	0.570	1.302	1428	3256	4366	0.33	0.75
		14	2.260	14.84	9.43	0.544	1.236	1760	4268		0.40	0.98
		15	2.298	14.73	9.49	0.631	1.213	1188	3080		0.27	0.71
	Mean		2.296	14.87	9.58	0.593	1.323	1380	3634		0.316	0.83
	SD[a]		0.151	0.17	0.36	0.043	0.120	282	490		0.152	0.11
	RSD[b]		0.066	0.01	0.04	0.072	0.090	0.20	0.13		0.481	0.14

[a] Standard deviation. [b] Relative standard deviation (SD/mean). [c] Height of the half sphere.

high pressure continued and the pressure decreased to a constant value corresponding to the end of burn.

The initial steeper pressure rise may be due to the rapid burning of the ignition promoter coating the less ignitable color composition of the star. The next pressure rise is due to the burning of the main color composition of the star.

The maximum pressures P_{max1} of the first peak of the profiles of the silver crown and red peony stars were similar. The second peak pressures $P_{max2}$of both stars were different, that is, the second peak pressure of the silver crown star was higher than that of the red peony star suggesting that the combustion temperature and/or gas production of the former is higher than that of the latter.

The burning times of the stars were not estimated from the pressure profiles of the burning test in the closed vessel. The burning times of stars can be determined by a high-speed video camera record of the duration of the combustion flame in the stationary burning test in the open air. The mean ratios of the time to maximum pressure to

Table 3. *Mean ratios of various burning times to the stationary burning times of stars.*

Star	Condition	Mean ratio	Reference
Blue peony, silver peony and silver crown	Flying	$t_f/t_s = 1.6$	1
Silver crown for no. 4 shell	Flying	$t_f/t_s = 1.4$	2
Silver crown for no. 5 shell	Flying	$t_f/t_s = 1.5$	2
Red peony for no. 5 shell	Coated by resin[a]	$t_{sc1}/t_s = 1.25$	This work
Red peony for no. 5 shell	Coated by resin[b]	$t_{sc2}/t_s = 1.26$	This work
Silver crown for no. 5 shell	Coated by resin[a]	$t_{sc1}/t_s = 1.02$	This work
Silver crown for no. 5 shell	Coated by resin[b]	$t_{sc2}/t_s = 1.06$	This work

[a] Half the sphere is coated by the resin. [b] Hemisphere with spherical surface coated by the resin.

the flame duration time were similar (about 0.45) for both spherical silver crown and red peony stars without resin coating. The reason for the difference in burning times between the closed vessel and the open air may be attributable to a property of the pressure profile of burning spherical stars and the pressure effect on the burning rate of stars.

For the half-resin-coated spherical star, the maximum pressure of the first peak was smaller than that of the star without resin coating, presumably because the exposed amount of the ignition promoter of the former was half that of the latter. The time to maximum pressure of the second peak of the half-coated star was longer than that of the star without resin coating.

For the hemispherical star with the spherical surface coated, the shape of the profiles was different from other types of stars. There were two step pressure increases, of which the first was a little steeper and the second was a little gentler. The first steeper pressure rise seems to be due to the burning of the ignition promoter coated by the restrictor. The burning of the sandwiched promoter may be slower than that of the exposed promoter and faster than that of the color composition of the star.

The time to the maximum pressure of a star increased in the following order:

Spherical star without resin coating < spherical star with half surface resin coating < hemispherical star with spherical surface resin coated

Comparison of the times of flying and stationary burning

Table 3 lists the mean ratios of the times of the flying and stationary burning of stars.

Table 4. *Stationary burning time of the lifting charge in the cup.*

Run	LC/g	Burning time/ms	Run	LC/g	Burning time/ms
1	1.0	114.2	6	2.0	149.0
2	1.0	140.0	7	2.0	124.4
3	1.0	114.6	8	2.0	120.2
4	1.0	111.4	9	2.0	109.6
5	1.0	112.6	10	2.0	142.8
Mean		118.6	Mean		129.2
SD[a]		12.1	SD[a]		16.3
RSD[b]		0.102	RSD[b]		0.126

[a] Standard deviation. [b] Relative standard deviation (SD/mean).

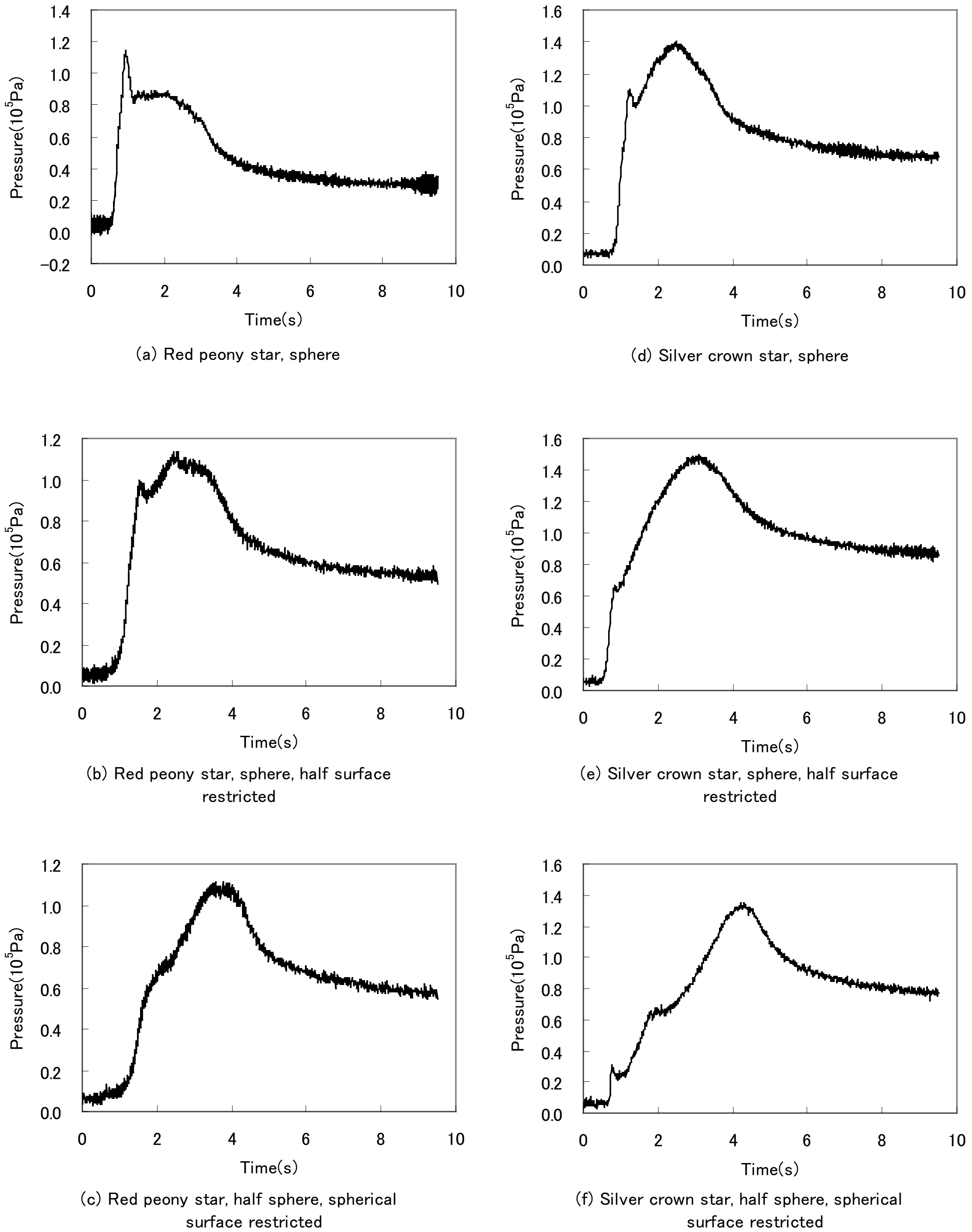

Figure 2. *Examples of the pressure profiles of burning stars in the closed vessel.*

The partial restriction of the surface of stars resulted in longer burning times, but not enough to explain the longer flying burning times. This may be due to the burning of ignition promoter remaining between the color composition and the restrictor.

Burning characteristics of the lifting charge

The stationary burning times of the lifting charge are listed in Table 4 and examples of the pressure

Table 5. *Summary of the burning experiments of the lifting charge in the open cup and in the closed vessel.*

Run	LC/g	P_{max} (10^5 Pa)	t_{max}/ms	Mean t_s/ms	t_{max}/ts
1	1.0	3.397	24.2		0.20
2	1.0	2.979	28.6		0.24
3	1.0	2.959	30.8	118.6	0.26
4	1.0	2.230	28.6		0.24
5	1.0	2.808	30.8		0.26
Mean		2.874	28.6		0.24
SD[a]		0.422	2.7		0.02
RSD[b]		0.147	0.1		0.09
6	2.0	5.251	30.8		0.24
7	2.0	5.453	30.8		0.24
8	2.0	5.548	30.8	129.2	0.24
9	2.0	5.381	28.6		0.22
10	2.0	5.600	30.8		0.24
Mean		5.447	30.4		0.23
SD[a]		0.138	1.0		0.01
RSD[b]		0.025	0.0		0.03

[a] Standard deviation. [b] Relative standard deviation (SD/mean).

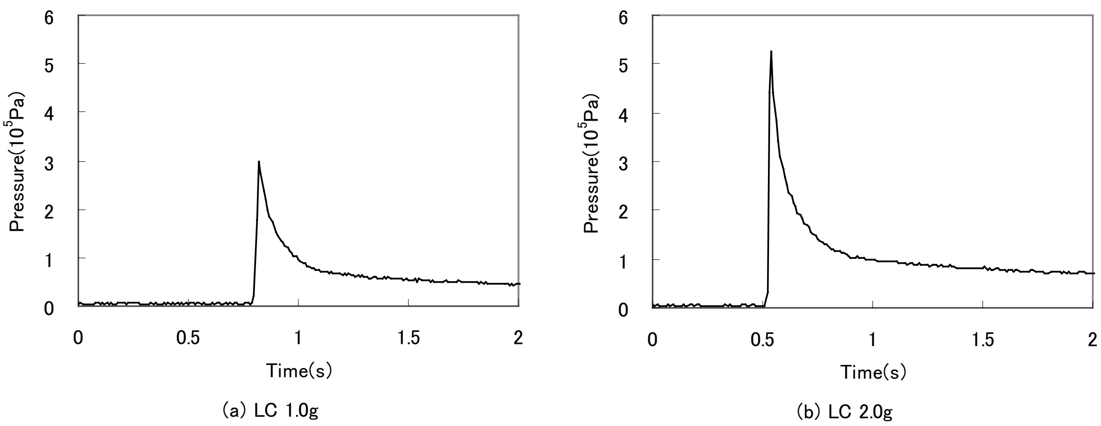

Figure 3. *Examples of the pressure profile of burning lifting charge in the closed vessel.*

profiles of the lifting charge in the closed vessel are shown in Figure 3.

The mean ratio of the time to maximum pressure to the stationary burning time (t_{max}/t_s) was 0.26 which is smaller than that of about 0.45 for burning of the ordinary stars, presumably because of the higher burning rate of the lifting charge than that of the stars.

A burning experiment using lifting charge was done in a closed vessel and in the open air by Shibata, Hasegawa *et al*.[4]). A sample of the lifting charge was poured into a plastic tube of 7 mm inner diameter and 30 mm depth. The times to maximum pressure in the closed vessel and the burning time in the open air were 100 ms and 270 ms, respectively. The ratio of the time to the maximum pressure to the burning time in the open air (t_{max}/t_s) was 0.37.

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