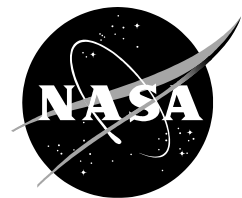NASA/TM—2017–219571

Further Validation of a CFD Code for Calculating the Performance of Two-Stage Light Gas Guns

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Abstract

Earlier validations of a higher-order Godunov code for modeling the performance of two-stage light gas guns are reviewed. These validation comparisons were made between code predictions and experimental data from the NASA Ames Research Center's 1.5" guns and covered muzzle velocities of 6.5 to 7.2 km/s. In the present report, code validation comparisons are presented for five experimental configurations with data from the Ames 0.22" (1.28" pump tube diameter), 0.28", 0.50", 1.00" and 1.50" guns. The total muzzle velocity range of the validation data presented herein is 3 to 11.3 km/s. The agreement between the experimental data and CFD results is judged to be very good. Muzzle velocities were predicted within 0.35 km/s for 74% of the cases studied with maximum differences being 0.5 – 0.7 km/s for a small number of cases.

I. Introduction

Reference 1 introduces a quasi-one-dimensional Godunov code for modeling the performance of two-stage light gas guns. The code solves the one-dimensional equations of mass, momentum, energy and species conservation. Source terms for friction (including friction for dense media) and heat and mass transfer are modelled at the gun tube wall. A simple non-equilibrium turbulence model is used for gas flows. The code is third-order accurate in space and second-order accurate in time. A very accurate Riemann solver is used. The code also models gunpowder burn in the first stage breech. Realistic equations of state are used for all media. In parallel with solving the main equations, the one-dimensional unsteady heat conduction equation is solved at ~200 locations along the gun tube wall. When the steel melting point is reached at the gun tube wall surface, a heat transfer/mass balance is performed and the appropriate amount of steel is assumed to melt off the wall. This melted steel is assumed to take the form of fine liquid droplets and to be immediately incorporated into the hydrogen working gas of the gun.

Figure 1 shows a schematic sketch of a two-stage gun. Upon ignition of the powder charge the (typically) plastic piston accelerates down the pump tube, compressing and heating the hydrogen gas. The hydrogen can reach very high pressures (of the order of 100,000 psi) and temperatures (of the order of 3000 K). When the pressure of the hydrogen reaches a certain level, the diaphragm behind the projectile ruptures and the hydrogen gas starts to accelerate the projectile down the launch tube. In Ref. 1, a number of validation comparisons are made between code predictions and experimental data from the NASA Ames 1.5"/6.25" two stage light gas gun. In the description of the two-stage guns, the first dimension is the launch tube diameter and the second number is the pump tube diameter. In the present report, five series of code validation comparisons involving experimental data for the Ames 0.22"/1.28", 0.28"/1.55", 0.50"/2.54", 1.0"/4.0" and 1.5"/6.25" guns are presented.

There are some difficulties in using experimental gun data to validate a CFD (computational fluid dynamics) code. With the same nominal gun operating condition, piston and muzzle velocities can show considerable shot to shot variation. This may be due, in part, to differences in the ignition and burning of the powder and/or differences in the fit and friction of the piston and the model. The CFD code has no way to allow for these differences and will always give the same velocities for the same gun operating condition. Another phenomenon that can affect the muzzle velocities is the drive gas blowing by the projectile and thus reducing the pressure on the projectile rear. There are several reasons why blow-by would tend to be more severe for smaller guns. The machining tolerances and finishes will be inevitably poorer, relative to the gun size, for smaller guns, since these tolerances and finishes tend to have fixed absolute values. In addition, the conduction of the frictional heat into the projectile will be relatively deeper for smaller guns, which could lead to relatively more projectile material being lost travelling down the barrel, which could also lead to increased blow-by for smaller guns. Blow-by will tend to be more severe for multi-

piece sabots enclosing models than for simple cylindrical slugs, since for the sabots, there are more passages for blow-by and also because, for the slugs, there is more likelihood that an effective Bridgman seal at the rear of the launch package will be created. Blow-by can vary from shot to shot and also cannot be modelled by the present version of the CFD code.

Figure 2 shows muzzle velocities versus range pressure for two series of shots (with 21 and 14 shots) with the Ames 1.5"/6.25" two stage light gas gun. Within each data series, the gun conditions are identical except that the launch masses vary by ±2.4% maximum. The rms values of the muzzle velocity differences from the trend lines are 0.08 to 0.10 km/s and the rms values normalized by the mean values are 0.019 to 0.024. For the six data set series (1 old and 5 new), considered for code validation, the corresponding rms values of the velocity differences range from 0.14 to 0.26 km/s for 5 sets and are 0.42 km/s for the sixth set. The corresponding normalized rms values range from 0.020 to 0.034 for four data sets with the remaining two sets having values of 0.044 and 0.061. As mentioned earlier, five sets of data will be considered for code validation. Sets will be rejected if there is strong evidence of blow-by, leading to low muzzle velocities and/or if there is excessive scatter in the data.

II. Guns Used to Provide Data for Code Validation

Table 1 lists the guns used to provide data for code validation. Key gun parameters and gun operating conditions are given in the table. Note that the guns are listed by launch tube diameter

Table 1. Guns Used to Provide Data for Code Validation

Series number	Gun	D_L (in)	L_L/D_L	D_P/D_L	L_P/D_P	Cone angle (degrees)	Powder mass (g)	Powder type
1	Ames 0.22"/1.28"	0.22	273	5.82	115	14.6	60 - 125	IMR 4227
2†	Ames 0.28"/1.55"	0.28	357	5.53	273, 205	8.6	15 - 55	IMR 4227
3	Ames 0.50"/2.54"	0.50	300	5.07	246	12.5	150 - 250	IMR 4198
4*	Ames 0.50"/2.54"	0.50	300	5.07	246, 152, 104	8.1, 12.5	170 - 215	IMR 4895
5	Ames 1.00"/4.00"	1.00	288	4.00	244	8.2	675 - 1200	IMR 4831††
6	Ames 1.50"/6.25"	1.50	256	4.15	208	8.6	2810 - 3000	HC-33-FS
7	Ames 1.50"/6.25"	1.50	256	4.15	131	8.6	1100 - 2800	HC-33-FS

Notes:

D and L refer to diameters and lengths of pump tubes and launch tubes

Subscript L refers to launch tube; subscript P refers to pump tube

IMR (Improved Military Rifle) powder is a type of powder developed by duPont from World War I through World War II.

HC - 33 - FS is a Hercules powder

*Series considered for code validation but rejected due to low muzzle velocities likely due to drive gas blowing by the launch package

†Series considered for code validation but rejected due to low muzzle velocities likely due to drive gas blowing by the launch package and due to inconsistancies

††Powder used in experiments was IMR 4996, see discussion in text.

Table 1 (continued). Guns Used to Provide Data for Code Validation

Series number	Gun	Piston mass (g)	Hydrogen pressure (psi)	Break valve rupture pressure (ksi)	Projectile mass (g)	Muzzle velocity (km/s)
1	Ames 0.22"/1.28"	100	40	20 (30)	0.0453 - 0.0756	9.84 - 11.3
†2	Ames 0.28"/1.55"	150 - 250	5.5 - 100	5 - 20	0.16 - 0.64	4.25 - 9.25
3	Ames 0.50"/2.54"	888 - 1115	10 - 30	10, 20	0.882 - 3.170	4.97 - 9.46
4*	Ames 0.50"/2.54"	707 - 821	19.2 - 58.8	4.2, 4.49	1.160 - 1.439	5.62 - 8.08
5	Ames 1.00"/4.00"	5579, 7394	20 - 60	5, 10	7.31 - 24.36	3.70 - 7.98
6	Ames 1.50"/6.25"	17,064 - 21,420	45, 68.3	10.0 - 17.6	29.02 - 33.58	6.72 - 7.22
7	Ames 1.50"/6.25"	21,774	65.8, 68.3	3.2, 12.3	31.20 - 95.09	3.00 - 7.29

and not by the chronological order in which the relevant data was taken. Two different series of relevant shots were made with both the Ames 0.50"/2.54" and 1.50"/6.25" guns.

III. Prior Code Validation vs Data from the NASA Ames 1.50"/6.25" Gun

The CFD code used herein must, of necessity, be "tuned" to produce good results. This follows since (1) the piston friction cannot be calculated from first principles and (2) that the powder burn rates given in the literature do not correspond to those observed in two-stage light gas guns. Since the piston friction cannot be calculated from first principles, a simple model is constructed and then the coefficient is adjusted to match experimental data. The powder burn rates given in the literature are found to underpredict the experimentally observed powder burn rates and, hence, the rates given in the literature are adjusted to match an experimental data point chosen to be near the "center of gravity" of the muzzle velocities. In general, both tunings must be iterated together to match powder chamber pressure histories and piston velocities. (Tuning is further discussed in pp. 21 – 23 of Ref. 1.) Tuning has been performed for all CFD results discussed herein. In Ref. 1, a number of validation comparisons are made between code predictions and experimental data from the NASA Ames 1.50"/6.25" two stage light gas gun. Reference 1 (pp. 24 – 27) shows comparisons of powder chamber and pump tube pressure histories, final position of the front of the piston and piston and muzzle velocities. Overall, the validation of the code against actual gun data presented in Ref. 1 was judged to be very good. The differences between the experimental and CFD muzzle velocities were 0.3 km/s or less.

The version of the CFD code used for the early code validations discussed above did not model bore erosion, the incorporation of the eroded wall material into the hydrogen working gas and the consequent weighing down of the gun working gas. Figures 10 – 13 of Ref. 2 show that, for the Ames 0.5"/2.54" gun, bore erosion begins to occur at muzzle velocities of 6 – 7 km/s and becomes very substantial at muzzle velocities of 8 – 9 km/s, causing muzzle velocity losses of 2 to 4 km/s at such conditions. The larger 1.50"/6.25" gun should be less susceptible to bore erosion for reasons of surface-to-volume ratio and the relatively smaller depth of heat soak into the barrel during firing. Nevertheless, it was decided to repeat the CFD piston and muzzle velocity calculations discussed above with a more recent version of the code which includes bore erosion effects and compare the results with the experimental measurements. The comparisons for piston and muzzle velocities are shown in Figs. 3 and 4, respectively. Each plot shows the CFD results for both the old and new versions of the code. From Fig. 3, the disagreement between the experimental and the new code CFD piston velocities is ~2% or less for 5 data points, with one data point showing a difference of 3.8%. From Fig. 4, the disagreement between the experimental

and the new code CFD muzzle velocities is 3.3% or less for 3 data points, with 2 data points showing differences of 5.5% and 7.2%. The validation of the CFD code against actual gun data for muzzle velocities was judged to be acceptable, although not as tight as for the piston velocities. From Figs. 3 and 4, it can be seen that the new code CFD results are superior to the old code CFD results for the piston velocities, but actually somewhat inferior for the muzzle velocities. However, the muzzle velocity range covered by these validations was rather limited, ranging between 6.7 and 7.2 km/s.

IV. New Code Validations vs Data from the NASA Ames 1.50"/6.25" Gun

New code validation data was obtained by modeling 10 shots made with the Ames 1.50"/6.25" gun in the time frame April 2010 to September 2014. Nine of these validations were at relatively low muzzle velocities (3 to 5 km/s), while one shot had a muzzle velocity of ~7 km/s. Figure 5 shows the comparison of experimental and CFD piston velocities for the series 7 conditions of Table 1. The piston friction has been tuned to match the experimental and CFD piston velocities for the chosen "average" data point. (The powder burn rate tuning coefficient was kept at a value determined by an earlier tuning.) The experimental and CFD piston velocities are in excellent agreement, the maximum differences being ±10 m/s for the range from 350 to 645 m/s. (It should be pointed out that this agreement is not "automatic", since, after the burn rate is tuned for the selected mean data point, the CFD code must correctly model a wide range of powder burn conditions, with substantial variations in the maximum powder pressure.) Figure 6 shows the comparison of experimental and CFD muzzle velocities for the series 6 conditions of Table 1. The agreement of the experimental and CFD velocities was judged to be very good, although not as tight as for the piston velocities. The differences are 0.1 km/s or less for 6 shots, with 4 shots having differences up to ±0.34 km/s. For the series 7 data set, the rms value of the muzzle velocity differences from the trend line is 0.19 km/s and the rms value normalized by the mean value is 0.044. These are about twice the corresponding values for the two series of nearly identical shots discussed in Sec. I. It is believed that the relatively increased scatter is due to the fact that there are many variables for series 7 data set (e.g., powder load, hydrogen pressure, piston mass, etc.) For the point marked with an asterisk, the projectile was very heavy, ~95 g, and the usual code assumption that the projectile is a simple plastic slug lead to excessive projectile friction and a muzzle velocity that was far out of line. When the projectile length was halved, keeping the same projectile mass, which was closer to reality, the muzzle velocity lined up with those of the remaining shots, as can be seen in Fig. 6.

V. New Code Validations vs Data from the NASA Ames 1.00"/4.00" Gun

New code validation data was obtained by modeling 17 shots made with the Ames 1.00"/4.00" gun in the time frame February to April, 1966. Muzzle velocities ranged from 3.5 to 8.5 km/s. We note that the powder used for the actual firings was IMR 4996, but that the powder used for the CFD modelling was IMR 4831. The author was unable to find powder grain dimensions for the IMR 4996 powder and chose the IMR 4831 powder as a substitute. The IMR 4831 powder was chosen because its web dimension was intermediate between those for the powders used with the Ames 1.50"/6.25" and 0.50"/2.54" guns. Figure 7 shows the comparison of experimental and CFD piston velocities for the series 5 conditions of Table 1. The piston friction has been tuned to match the experimental and CFD piston velocities for a chosen "average" data point. (The powder burn rate tuning coefficient was kept at a value determined an earlier tuning.) For 15 out of 17

shots, the experimental and CFD piston velocities are in good agreement, the maximum differences being ±20 m/s. For the two remaining shots, the differences are larger, 35 and 50 m/s. For the shot with the largest difference, two other shots at nominally identical conditions produced piston velocities that were in good agreement with the CFD results (3 green data points). Figure 8 shows the comparison of experimental and CFD muzzle velocities for the series 5 conditions of Table 1. For 13 out of 17 shots, the experimental and CFD muzzle velocities are in good agreement, the maximum differences being ±0.25 km/s. For three shots, the differences are ±0.40 km/s and for one shot 0.65 km/s. The shot-to-shot variation in gun performance for nominally nearly identical gun operating conditions is evidenced in Fig. 8 by the green data points. For nominally nearly identical gun operating conditions, the muzzle velocity varies by 0.25 km/s for the green data points.

VI. Code Validations vs Data from the NASA Ames 0.50"/2.54" Gun

Reference 2 discusses CFD modeling of bore erosion in two-stage light gas guns. For the work of Ref. 2, the code used in the work of Ref. 1 was modified to include the effects of bore erosion. The work of Ref. 2 shows that, in general, bore erosion is not important below muzzle velocities of 6 - 7 km/s. Data from about 40 shots from the NASA Ames 0.5"/2.54" gun is presented in Ref. 2. The gun and operating conditions are those of series 3 and 4 in Table 1 and comparisons were shown for powder chamber pressure histories and piston and muzzle velocities (pp. 27, 28, 31 and 32 in Ref. 2). On pages 31 and 32 of the reference, CFD values are shown with and without bore erosion. (Circle and plus sign data points, respectively.) From the reference, it can be seen that the CFD results without bore erosion can be in error in muzzle velocity by as much as 2 to 4 km/s. In the present paper, we use only the results of Ref. 2 with bore erosion. Overall, the validation of the code (with bore erosion) against actual gun data for the NASA Ames 0.50"/2.54" gun was judged to be very good. Figure 9 shows the comparison of experimental and CFD muzzle velocities for the series 3 and 4 conditions of Table 1. The two shots for which the powder burn rates and piston friction were tuned are marked with asterisks in the figure. It was noted in Ref. 2 and can be seen in Fig. 9 that the differences between the experimental and CFD muzzle velocities are larger for the series 4 shots than for the series 3 shots, with a definite tendency for the experimental muzzle velocities for the series 4 shots to be low (by about 0.4 km/s on the average). For the data of series 4, the projectiles (typically spheres) were launched with four-piece sabots. As mentioned previously, four-piece sabots are relatively more subject to drive gas blow-by and a consequent loss of muzzle velocity. The shots of series 3 were made with solid polycarbonate slugs, which are less subject to blow-by. Some more details of this point are given in Ref. 2, p. 16 and in Sec I above. From the preceding discussion, it was decided to reject the series 4 data for the present code validation effort, but to keep the series 3 data. Figure 10 is a version of Fig. 9 showing only the series 3 data, rather than the data from both series. The agreement between experimental and CFD muzzle velocities is within 0.35 km/s for 10 out of 16 data points, with 4 data points having differences of 0.35 – 0.50 km/s and 2 data points having differences of 0.57 and 0.67 km/s. The muzzle velocity range covered by the validations of the series 3 conditions was 5.0 – 9.46 km/s. However, it is necessary to note that only 2 out of 16 shots had muzzle velocities below 6.7 km/s. Thus, the coverage of the 6.7 to 9.5 km/s muzzle velocity range is fairly dense (14 shots). Figure 11 shows the comparison of the experimental and CFD piston velocities for the series 3 data.

VII. New Code Validations vs Data from the NASA Ames 0.28"/1.55" Gun

An attempt was made to generate additional code validation using extensive data (27 shots) from the 0.28"/1.55" gun. (The data was obtained from log books covering shots made in the 1960s.) Figure 12 shows the comparison of experimental and CFD piston velocities for the series 2 conditions of Table 1. The powder burn rate has been tuned to match the experimental and CFD piston velocities at the chosen "average" data point. (The piston friction tuning coefficient was kept at a value determined an earlier tuning.) The experimental and CFD velocities are in good agreement, the maximum differences being ±17 m/s except for one point (which may be mis-notated in the log book) having a difference of 55 m/s. The piston velocities range from 500 to 900 m/s.

Figure 13 shows the comparison of experimental and CFD muzzle velocities for the series 2 conditions of Table 1. The scatter of the data is considerably larger than in Fig. 6 for series 7 and in Fig. 10 for series 3. Total scatter is frequently as much as 1.0 km/s. For two pairs of points (blue data points) at nominally identical conditions, the experimental muzzle velocities disagree by 0.7 and 1.0 km/s. For velocities above 6.5 km/s, the average trend line of the experimental data is ~0.4 km/s below the CFD values. This is very similar to the behavior of the series 4 data for the 0.50"/2.54" gun (see Sec. VI). The low muzzle velocities of the series 4 data are believed to be due to drive gas blowing by the projectile and it is believed that the same phenomenon applies to explain the low muzzle velocities for the 0.28"/1.55" gun above 6.5 km/s. The 0.28"/1.55" gun has a history of not shooting as well as other, larger guns at Ames. This may be due to the occurrence of a certain amount of drive gas blow-by for even the best projectiles. Because of the inconsistencies, wide scatter and low muzzle velocities for the series 2 data, it was decided to reject this data for the current code validation effort.

VIII. New Code Validations vs Data from the NASA Ames 0.22"/1.28" Gun

New code validation data was obtained by modeling two high velocity (9.84 and 11.3 km/s) shots made with the Ames 0.22"/1.28" gun. These shots (series 1 in Table 1) are reported in Ref. 3 and further details of the gun and launch conditions are given in Ref. 4. Since neither powder chamber pressure data nor piston velocities were available for these two shots, the piston friction and the powder burn rates could not be tuned to experimental data as was done for the remaining test series of Table 1. Rather, the powder burn rate tuning multiplier was taken to be that for the series 3, with IMR 4198 powder. Note that the three IMR powders have the same burn rate expression provided by the manufacturer although the dimensions of the grains are different for each powder. The piston friction tuning coefficient was taken to be 0.94 times the value for the series 2 (for a 0.28"/1.55" gun) in Table 1. The exact powder charges used for the two high velocity shots are not known but the total range quoted in Ref. 4 for launches of 0.0414 – 0.0457 g projectiles to velocities of 6.4 to 11.3 km/s was 60 – 125 g. CFD calculations were made for powder loads of 60 to 92 g and the muzzle velocities were found to increase up to powder loads of 82 g, and then found to abruptly decrease, followed by a slow rise on a further increase of powder load. The abrupt decrease of muzzle velocity on increasing powder load is due to a change of the pressure peak on which the break valve (diaphragm) ruptures. A representative train of pressure pulses at the projectile base is shown in Fig. 14. This is for a particular gun operating condition for a 0.787"/0.22" gun with helium working gas. For comparison with the experimental data, we have chosen the maximum CFD muzzle velocities calculated at powder loads of 82 g.

Figure 15 shows the comparison of experimental and CFD muzzle velocities for the series 1 conditions of Table 1. The two solid data points show the comparisons for the nominal break valve

rupture pressure of 20 ksi. The maximum difference between the CFD and experimental muzzle velocities is 0.6 km/s. If we take the break valve rupture pressure to be 30 ksi instead of the nominal 20 ksi, we obtain the hollow data points and the maximum difference between the CFD and experimental muzzle velocities drops to 0.4 km/s. We note that, for the lower velocity shot, the experimental muzzle velocities are lower compared to the CFD values than for the higher velocity shot. This may well be due to the fact that, in this case, the launch tube was rifled, and we currently have no way to model the additional drag due to rifling in our code.

IX. Discussion of Results

Here, we compare experimental and CFD piston and muzzle velocities for the NASA Ames 0.22"/1.28", 0.28"/1.55", 0.50"/2.54", 1.00"/4.00" and 1.50"/6.25" guns. Figure 16 shows the comparison of experimental and CFD piston velocities for five series of data. For each data block, the powder burn rate and/or the piston friction was tuned to match the experimental and piston velocities at the chosen "average" value of piston velocity. Thereafter, no further tuning was done. In particular, no tuning was done for projectile friction – rather the projectile friction was held constant at a value that had worked well in the past. It turns out that the muzzle velocity is very insensitive to variations in the projectile friction (within reason). (See discussion in Ref. 1, p. 23.) The agreement between the experimental and CFD piston velocities was judged to be very good. Ninety percent of the data points showed differences of less than ±20 m/s, 3 points had differences of 25 – 30 m/s and 2 data points had differences of 45 and 50 m/s. The data retained for the final code validation graph in this report are the muzzle velocity data of series 1, 3, 5, 6 and 7 in Table 1. Figure 17 shows the comparison of experimental and CFD muzzle velocities for these five series of data. Overall, the agreement between the experimental and CFD muzzle velocities over the wide velocity range of 3 to 11 km/s was judged to be very good. The differences between the experimental and CFD muzzle velocities were 0.35 km/s or less for 74% of the data points, 0.35 - 0.5 km/s for 18% of the data points and 0.5 - 0.7 km/s for 4 out of 50 data points. It must be pointed out that, for muzzle velocities above 6 – 7 km/s, the gun code must take into account erosion of the steel gun tube wall material and the incorporation of it into the hydrogen working gas of the gun. This weighs down the working medium of the gun and leads to substantial reductions in muzzle velocity below those calculated without gun tube erosion (see Ref. 2, Figs. 10 – 13). From Fig. 10 in the reference, muzzle velocities can be overpredicted by up to 3 – 4 km/s when bore erosion is not taken into account.

X. Summary and Conclusions

Code validation comparisons in an earlier report on a third-order Godunov code for modeling the performance of two-stage light gas guns were reviewed. These validations involved data from the Ames 1.5"/6.25" gun. Five additional series of code validation comparisons were then presented. These involved data from the Ames 0.22"/1.28", 0.28"/1.55", 0.50"/2.54", 1.00"/4.00" and 1.50"/6.25" guns. Overall, the agreement between the experimental data and CFD results over the wide muzzle velocity range of 3 to 11 km/s was judged to be very good. Muzzle velocities were predicted within 0.35 km/s for 74% of the cases studied with maximum differences being 0.5 km/s and for 4 out of 50 cases, 0.5 – 0.7 km/s. It was shown in Ref. 2 that erosion of the steel gun tube wall material and the incorporation of it into the hydrogen working medium of the gun, thus weighing it down, must be taken into account to make good predictions at muzzle velocities above 6 – 7 km/s with the present gun code.

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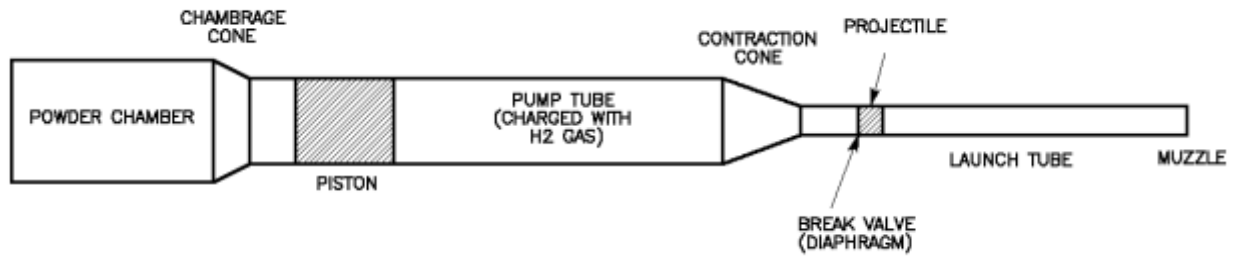
Figure 1. Schematic sketch of a two-stage light gas gun.
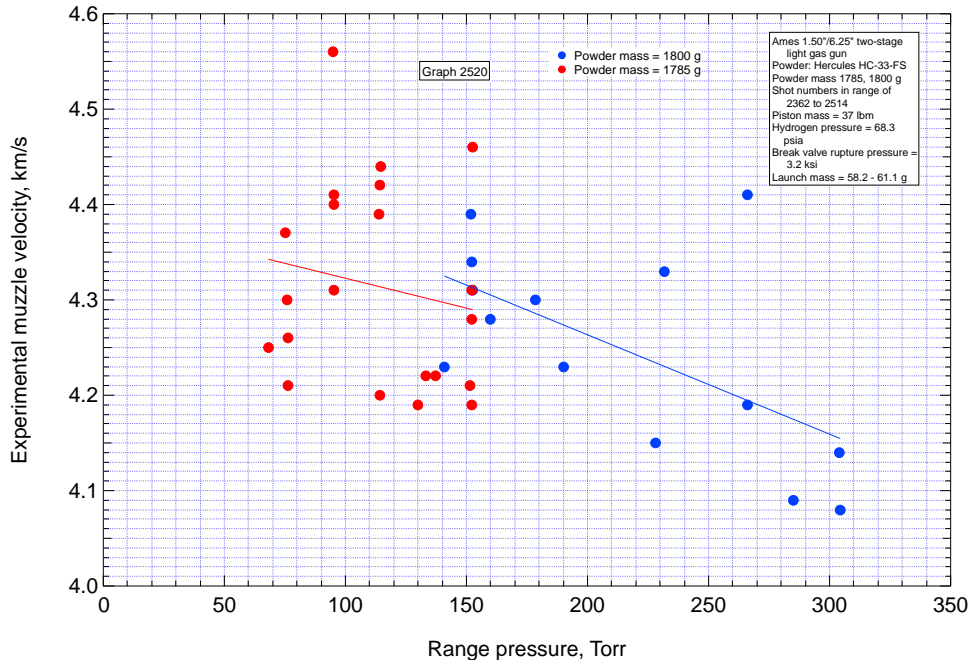
Figure 2. Plots of muzzle velocity versus range pressure for two sets of data for the Ames 1.5"/6.25" gun. Within each data set, the gun operating conditions are identical except for launch mass variations of ±2.4% maximum.
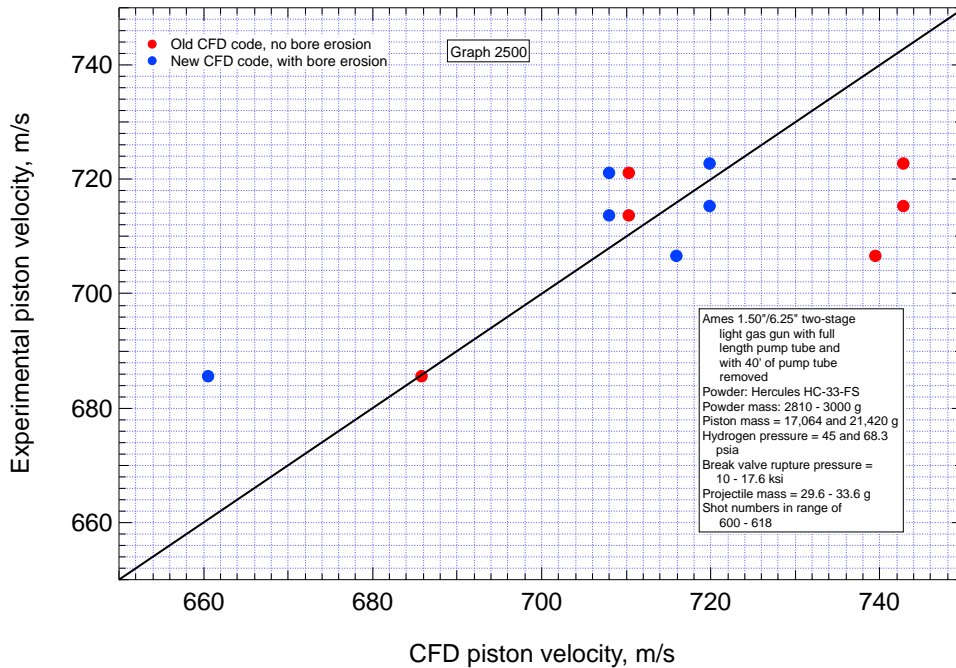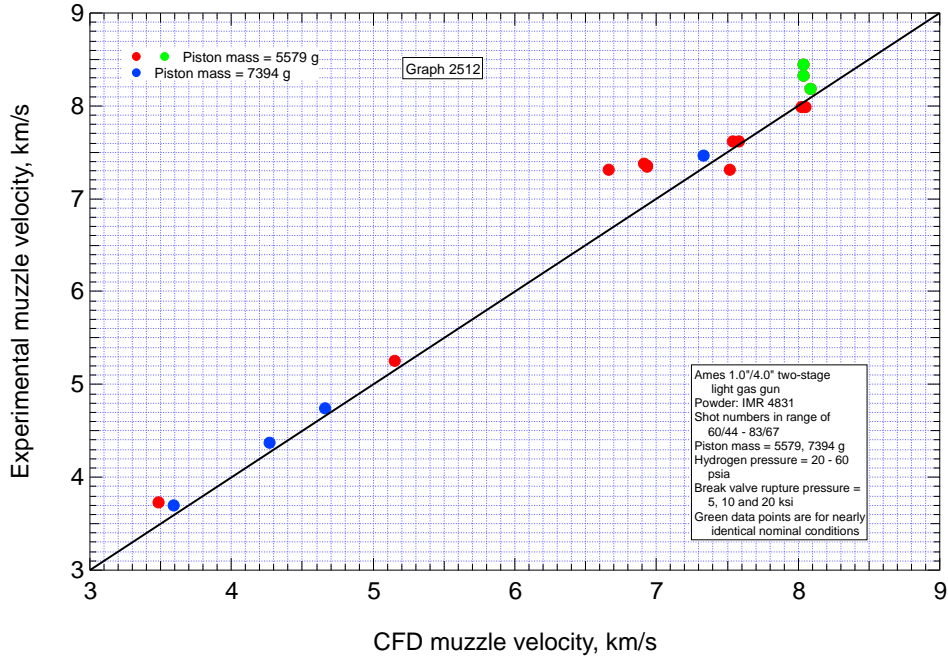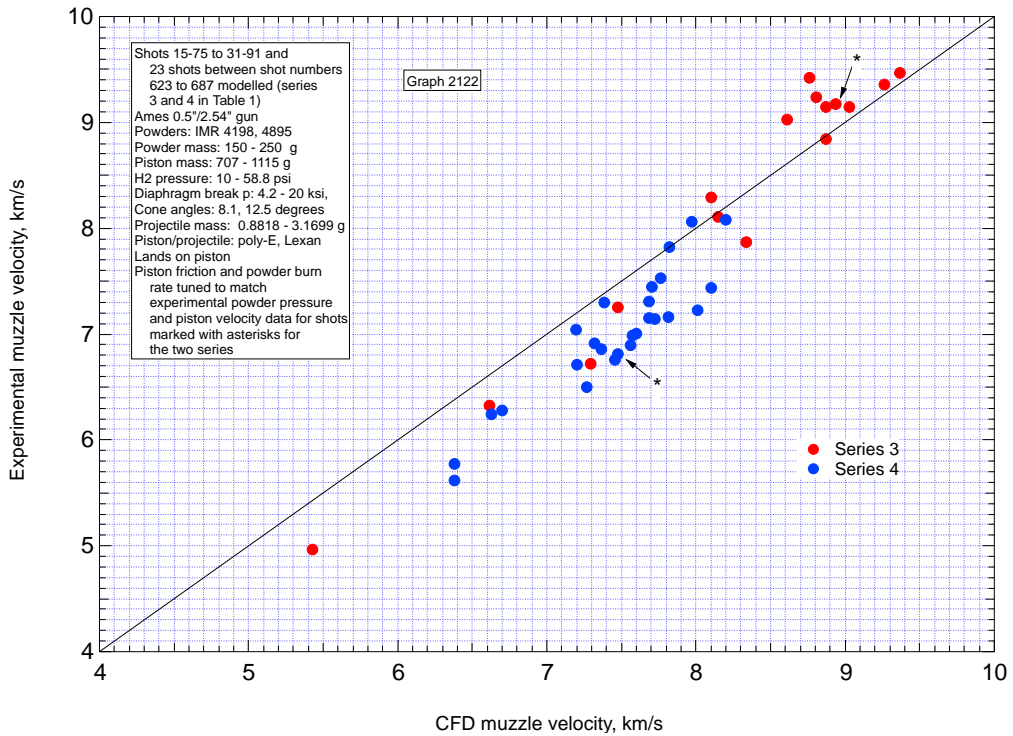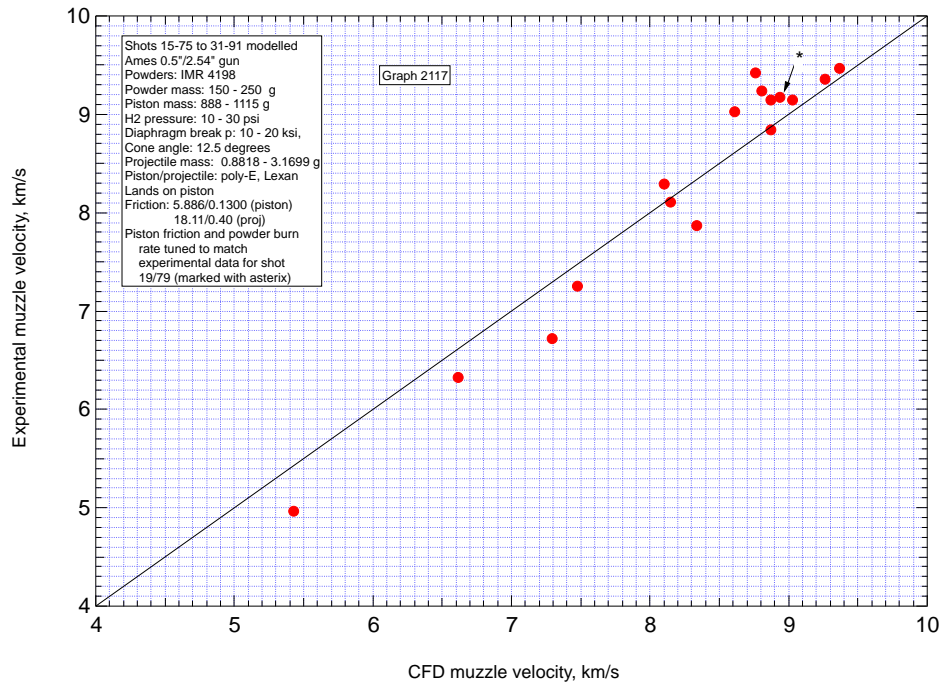

Figure 3. Comparison of experimental and CFD piston velocities for the series 6 gun and operating conditions given in Table 1.
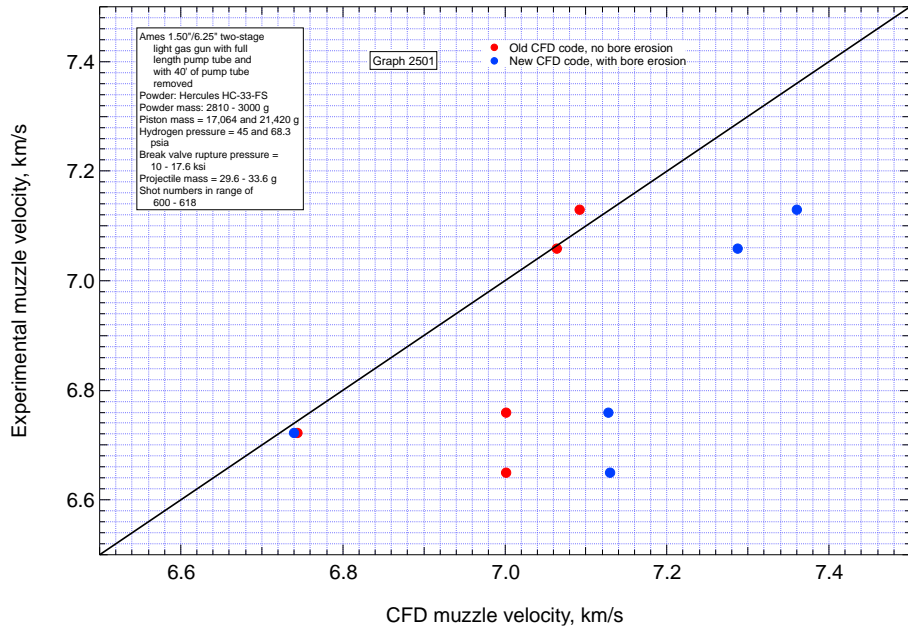
Figure 4. Comparison of experimental and CFD muzzle velocities for the series 6 gun and operating conditions given in Table 1.
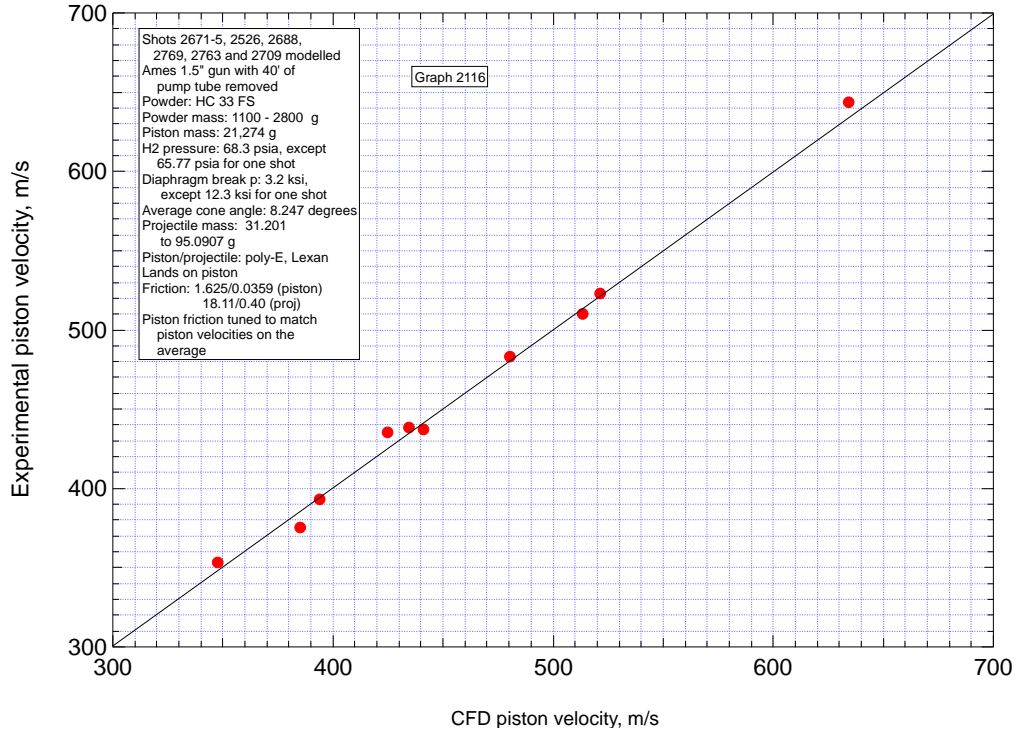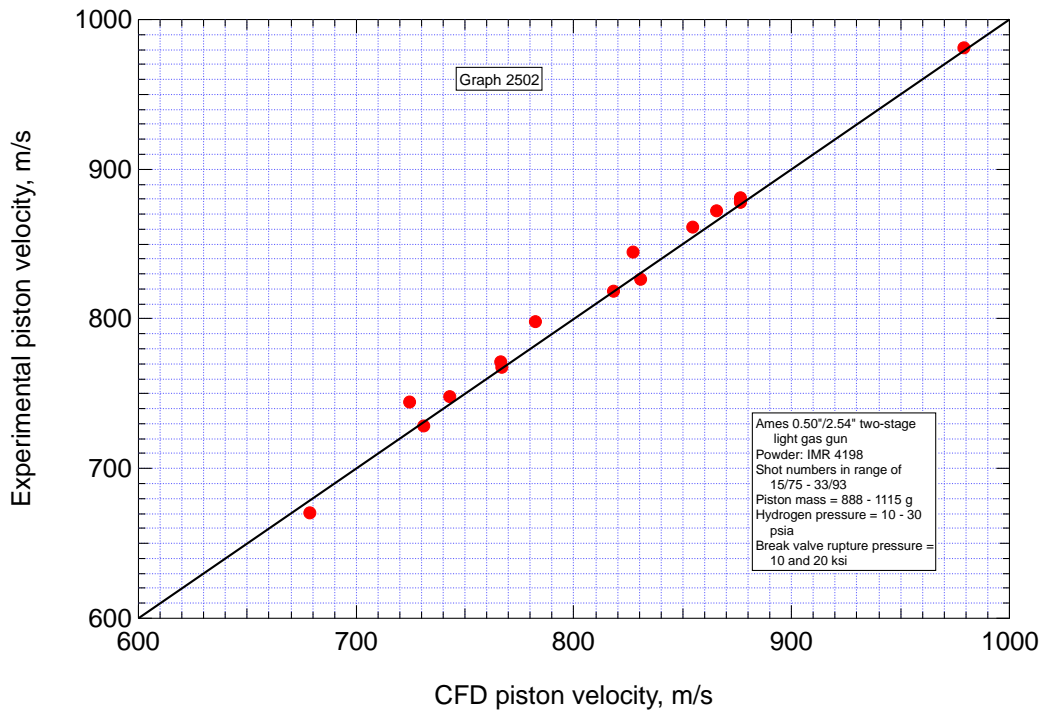

Figure 5. Comparison of experimental and CFD piston velocities for the series 7 gun and operating conditions given in Table 1.
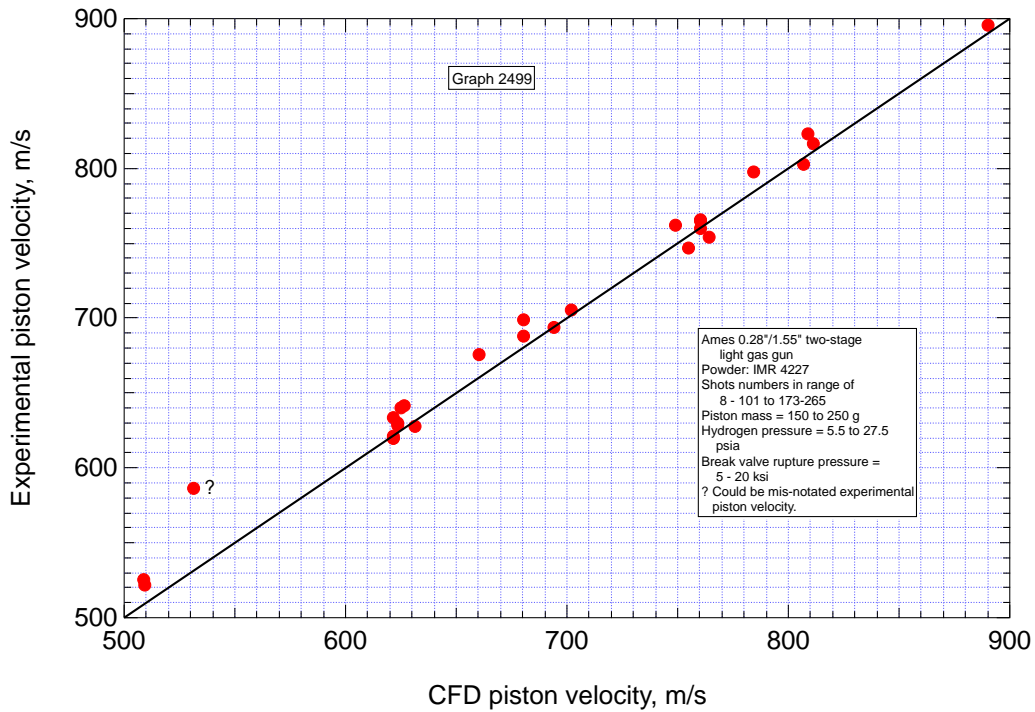
14
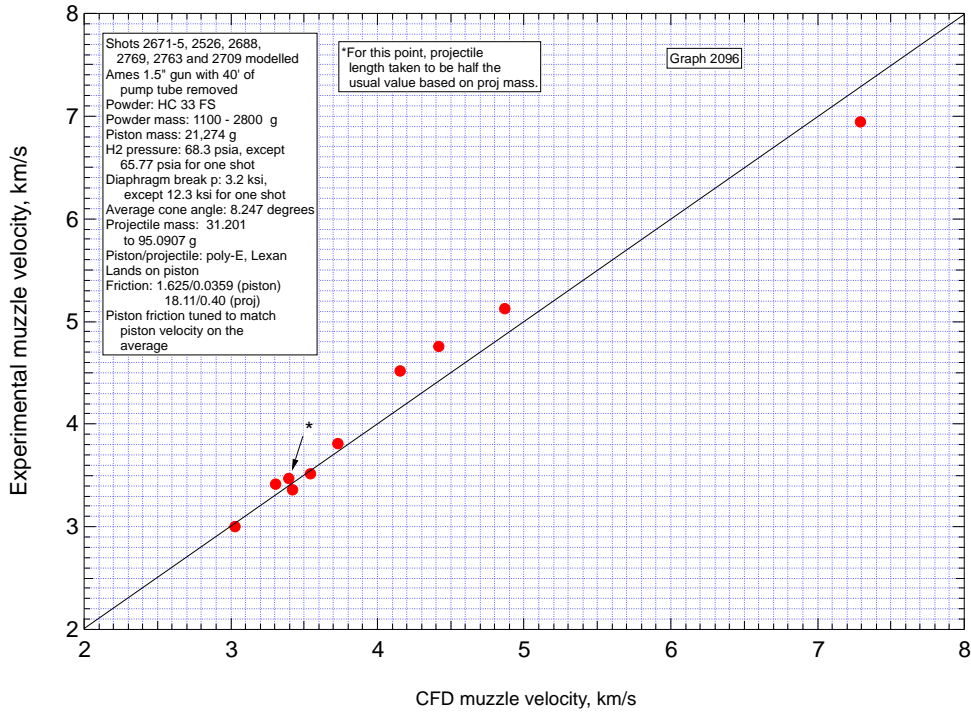
Figure 6. Comparison of experimental and CFD muzzle velocities for the series 7 gun and operating conditions given in Table 1.
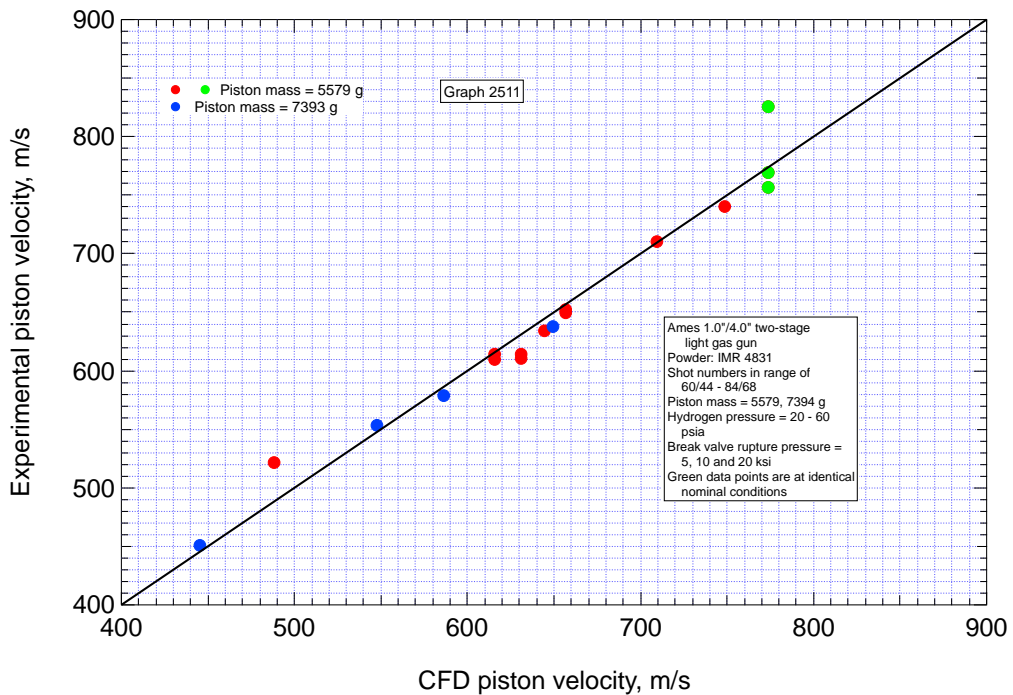
Figure 7. Comparison of experimental and CFD piston velocities for the series 5 gun and operating conditions given in Table 1.
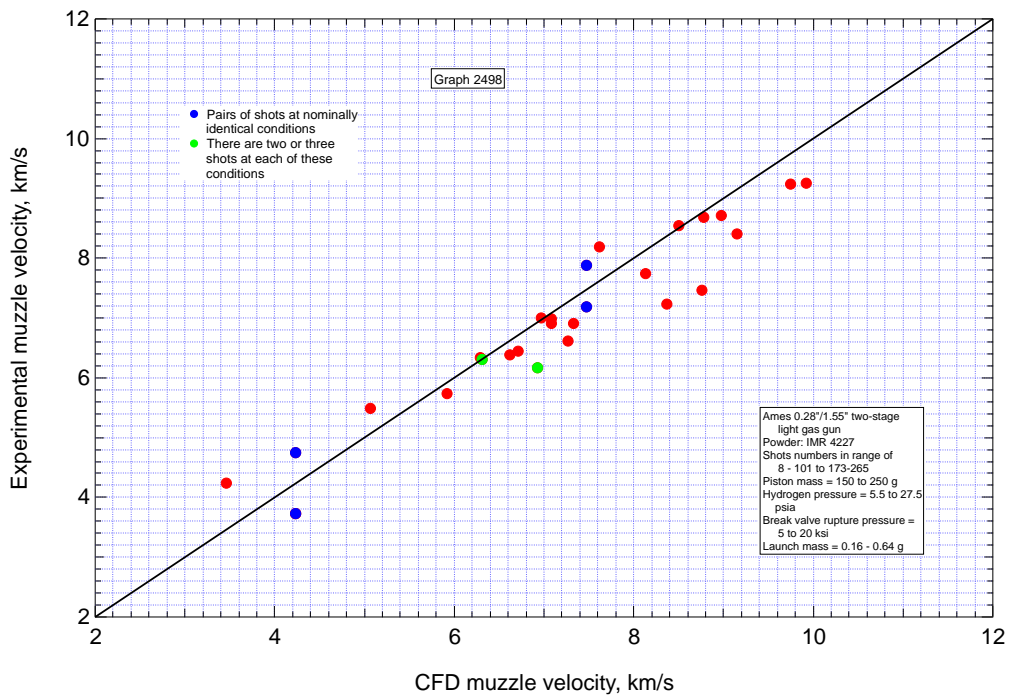
Figure 8. Comparison of experimental and CFD muzzle velocities for the series 5 gun and operating conditions given in Table 1.

Figure 9. Comparison of experimental and CFD muzzle velocities for the series 3 and 4 guns and operating conditions given in Table 1.

Figure 10. Comparison of experimental and CFD muzzle velocities for the series 3 gun and operating conditions given in Table 1.
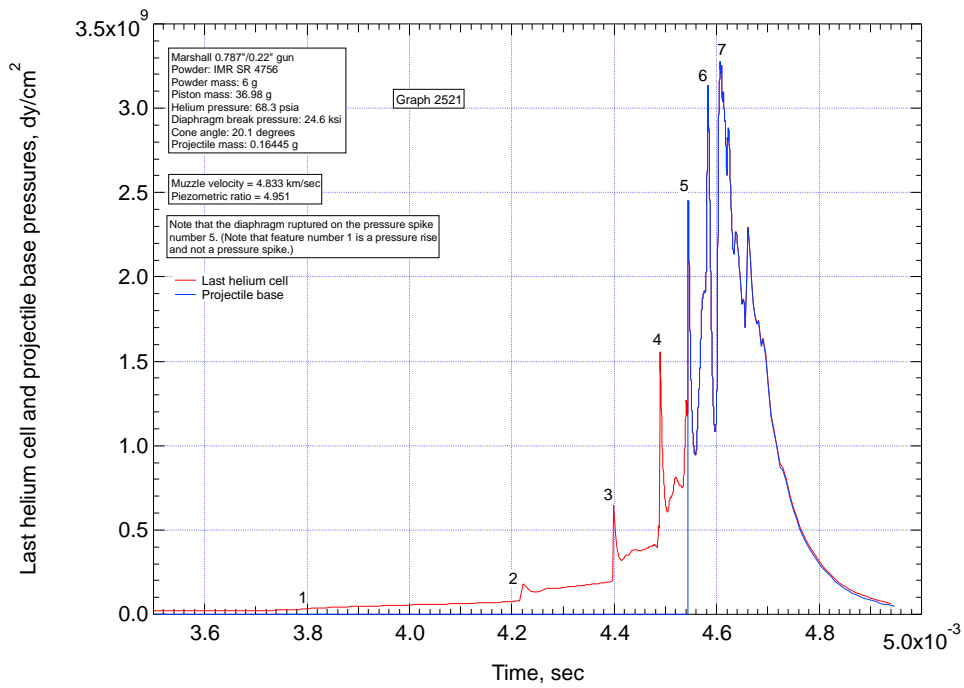

Figure 11. Comparison of experimental and CFD piston velocities for the series 3 gun and operating conditions given in Table 1.

Figure 12. Comparison of experimental and CFD piston velocities for the series 2 gun and operating conditions given in Table 1.

Figure 13. Comparison of experimental and CFD muzzle velocities for the series 2 gun and operating conditions given in Table 1.

Figure 14. Representative train of pressure pulses at the projectile base. This is for a particular gun operating condition for a 0.787"/0.22" gun with helium working gas.
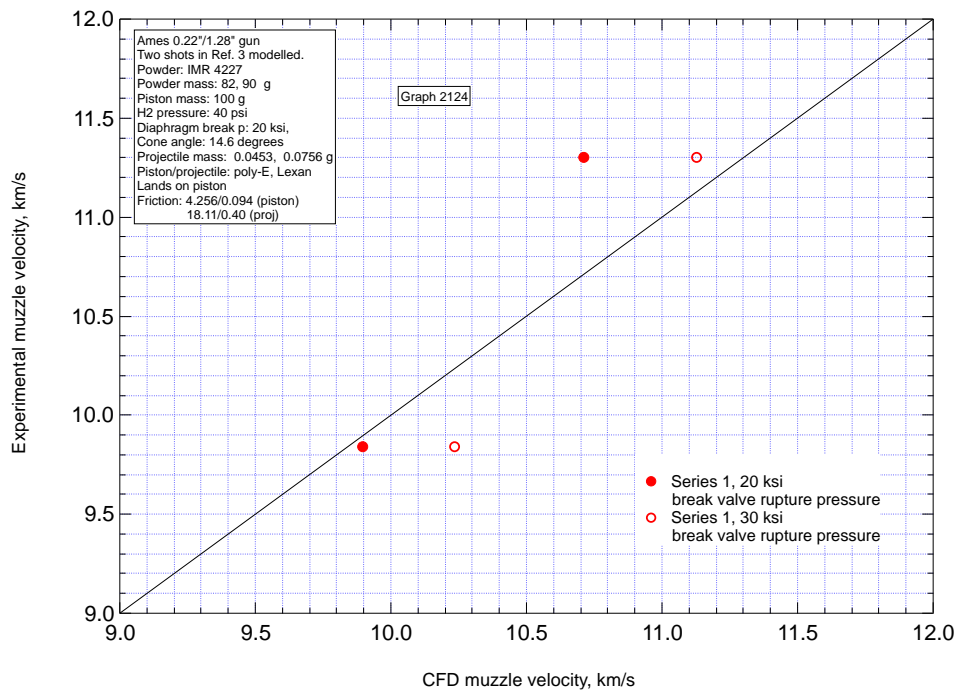

Figure 15. Comparison of experimental and CFD muzzle velocities for the series 1 gun and operating conditions given in Table 1.
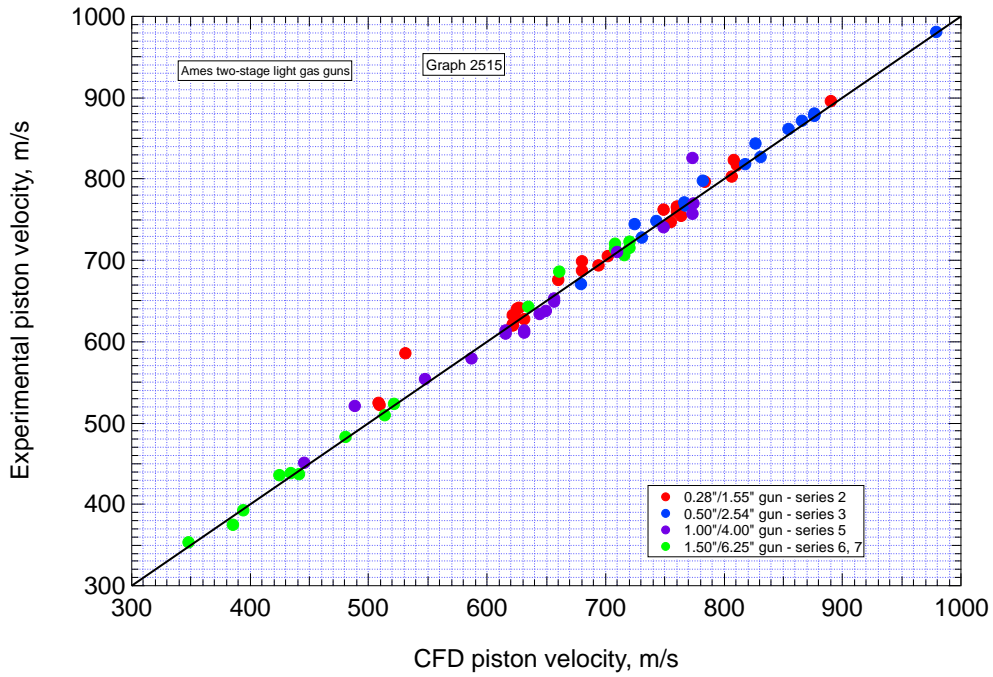
Figure 16. Comparison of experimental and CFD piston velocities for the series 2, 3, 5, 6 and 7 guns and operating conditions given in Table 1.
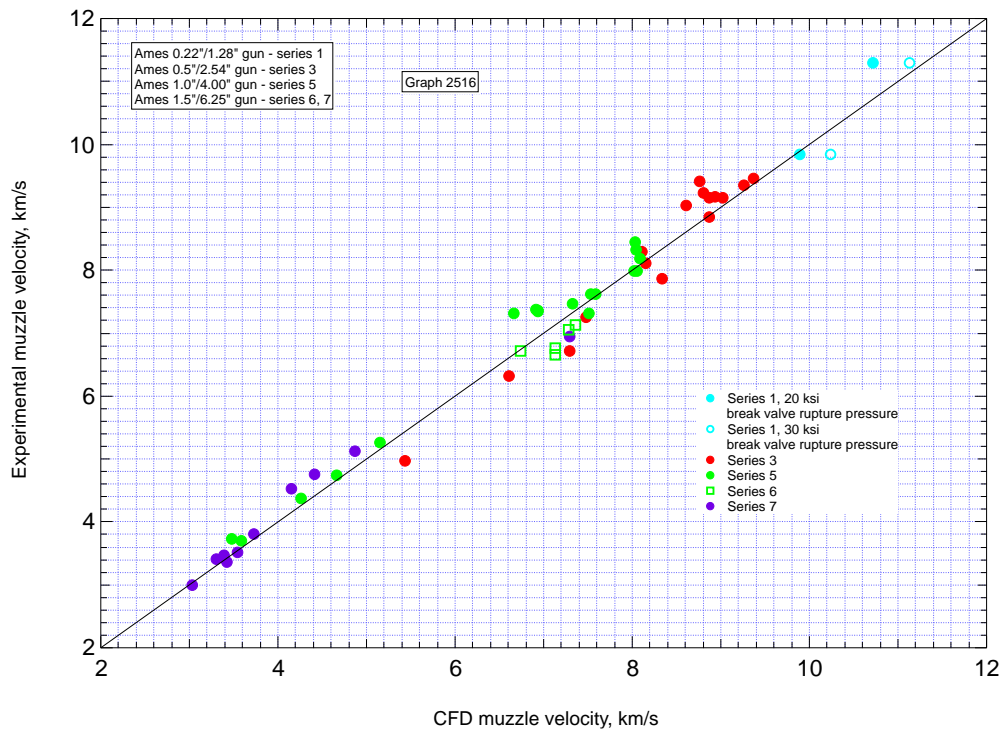

Figure 17. Comparison of experimental and CFD muzzle velocities for 5 series of guns and operating conditions given in Table 1.