

# Influence of a humidor on the aerodynamics of baseballs

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We investigate whether storing baseballs in a controlled humidity environment significantly affects their aerodynamic properties. We measure the change in diameter and weight of baseballs as a function of relative humidity in which the balls are stored. The trajectories of pitched and batted baseballs are modeled to assess the difference between those stored at 30% relative humidity versus 50% relative humidity. We find that a drier baseball will curve slightly more than a humidified one for a given pitch velocity and rotation rate. We also find that aerodynamics alone would add 2 ft to the distance a wetter baseball ball is hit. This increased distance is compensated by a 6 ft reduction in the batted distance due to the change in the coefficient of restitution of the ball. We discuss consequences of these results for baseball played at Coors Field in Denver, where baseballs have been stored in a humidor at 50% relative humidity since 2002. © 2008 American Association of Physics Teachers.

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## I. INTRODUCTION

The game of baseball is strongly influenced by the aerodynamics of its central object, the ball. A typical home run ball hit at sea level will travel 400 ft rather than the  $\sim 750$  ft it would travel in vacuum.<sup>1</sup> And the same batted ball might be expected to go 420 ft in the thin air of Denver, 1 mile above sea level. This increase is less than might be expected from aerodynamic considerations alone due to the prevailing northeast winds in Denver.<sup>2</sup> Because the ball is expected to travel farther, the idea of introducing a major league team (The Colorado Rockies) to the Denver area was met with opposition in the early 1990s. Hitters counted on the “Coors Field advantage” to help boost their hitting numbers, such as home runs, runs batted in, and batting average. Pitchers dreaded throwing in Denver because the thin air was blamed for the lack of break of a curveball or slider.

In 2002 the Rockies organization attempted to mitigate these effects by storing the balls in a humidity-controlled environment. The conventional wisdom held that a light and dry ball travels farther than a heavy and moist ball. Coors Field engineer Tony Cowell reported that baseballs stored in the dry atmosphere of Denver were both lighter and smaller than the weight and circumference specified by the rules of Major League Baseball.<sup>3</sup> Since the 2002 season the Rockies have stored their baseballs in a humidor maintained at a temperature of 70 °F and 50% relative humidity, consistent with the specifications of baseball manufacturer Rawlings.

The use of the humidor remains a matter of controversy and fascination. It is widely believed that Coors Field has yielded fewer home runs and fewer runs in the humidor era. The statistics for various offensive and defensive benchmarks at Coors Field support a small but measurable correlation with the presence of the humidor as shown in Table I, which shows some statistics for games played at Coors Field in the seven seasons before the humidor was installed compared to the same statistics from the first five seasons afterward. For comparison, the same numbers for the entire National League are presented in the same two time frames.

In all the categories there has not been a significant change for the National League as a whole. This fact presumably represents an average over a host of other changes that might have taken place over this time. In contrast, there is a trend at

Coors Field toward lower earned run averages and fewer runs (indicating more successful pitching) by more than two standard deviations. In a game as complex as baseball, it is difficult to attribute a cause-and-effect relation between these results and the humidor. For example, Rockies pitchers may have been more talented since 2002; they may also have benefited from a larger called strike zone implemented in 2001;<sup>7</sup> the consequences of these changes are difficult to quantify by means other than the performance statistics we use to check the humidor’s effect.

Nevertheless, one may wonder what effects the humidor might possibly have on the game. In the late 1980s, the then president of the National League, A. Bartlett Giamatti, asked Robert Adair, a Yale physicist, to test the effect of a humidor on baseballs. Adair found that under the most extreme conditions the humidified balls gained weight and were less elastic.<sup>1</sup> Kagan<sup>8</sup> has carefully measured the dependence of the ball’s coefficient of restitution on the relative humidity and converted this dependence into batted ball distance, finding that storing balls in an increased relative humidity environment reduces the distance a well-hit ball travels by 3 ft for every 10% change in relative humidity.<sup>8</sup> This effect would account for a 6 ft reduction in fly-ball distances at Coors Field after the humidor was installed. Another possible effect of the humidor is to make the surface of the balls more supple, enabling the pitchers to maintain a better grip and therefore pitch as they would with balls stored in higher relative humidity elsewhere. This effect has been reported by pitchers but remains unexplored quantitatively.

Kagan’s work focused on the influence of relative humidity on the bat-ball collision.<sup>8,9</sup> In this article we expand this work to investigate how storing a ball in a humidor affects the aerodynamics of the ball in flight. To do so, we perform measurements of the change in diameter and weight of baseballs as a function of the relative humidity. We find that this variation is less than the variation already allowed by the rules of Major League Baseball.<sup>7</sup> Nevertheless, the lightest, smallest allowed balls, if dried out, will exceed the limits in the rulebook. To assess the effect of these changes on the ball’s flight, we numerically solve the equations of motion for pitched and batted balls, including lift and drag forces, and the dependence of these forces on the speed and spin rate of the ball. We find that, on average, curveballs break slightly

Table I. Examples of various statistics at Coors Field before and after the inception of the humidifier in 2002. These are compared to the NL averages in the same two periods. There is a noticeable drop in ERAs, HR per team per game, and runs scored. The uncertainties are calculated using the year-to-year variance of the mean. These data were obtained from Refs. 4 and 5 except average fly-ball distances. These were obtained from Ref. 6, which reports only the years 2000 and 2001 and 2002–2007.

	Before	After	Difference
Rockies ERA at Coors	6.14(21)	5.34(26)	0.80(33)
NL ERA at Coors	6.50(19)	5.46(24)	1.04(31)
NL average ERA	4.37(7)	4.28(6)	0.09(9)
HR/team-game at Coors	1.59(9)	1.26(8)	0.33(12)
NL average HR/team-game	1.06(4)	1.05(2)	0.01(5)
Runs/team-game at Coors	6.94(20)	5.87(18)	1.07(27)
NL average runs/team-game	4.7(8)	4.58(6)	0.18(10)
Average fly ball distance	323(4)	318(1.5)	5(4)

more for dried baseballs than for humidified baseballs, and that batted balls travel slightly less far when they are dry than when they are humidified for a given initial trajectory. The combined effect of relative humidity on the elasticity and aerodynamics of the ball suggests that posthumidior batted balls travel approximately 4 ft less than dry baseballs.

The rest of the paper is outlined as follows. Section II provides the results of an experiment on the effect of the relative humidity on the size and weight of the ball. Section III discusses models of aerodynamic forces acting on a baseball in flight. Section IV evaluates the effects of relative humidity on the aerodynamics for curveballs and well-hit baseballs. In Sec. V we summarize our results and discuss possibilities for future work.

## II. EXPERIMENT

To assess the effect of relative humidity on the baseballs we measured the weight and diameter of a collection of balls stored at various relative humidities. We stored five Major League baseballs in each of three airtight containers in which the relative humidities were held at the constant values 32%, 56%, and 74%. These relative humidities were maintained by including saturated salt-and-water solutions inside the containers.<sup>10</sup> The relative humidity in each box was monitored and was constant to within  $\pm 1\%$ , which was also our approximate measurement uncertainty. The temperature was not carefully controlled but remained near 70 °F throughout the experiment.

The masses of the balls were measured to  $\pm 0.1$  g using a digital balance. Ball diameters were measured by placing them on a flat marble slab and measuring the top of the ball using an accurate height gauge. Balls were marked so that the same diameter could be reliably measured more than once. Measurement uncertainties of the diameters were estimated to be  $\pm 0.013$  in.

The diameter of each ball was measured across five different orientations. Three of these were on approximately mutually orthogonal directions on the leather surface. The other two diameters were across the seams, hence slightly larger than the leather diameters. Variations of the measured diameters from one ball to the next, and even from one axis to another on the same ball, were larger than the measurement uncertainty. Because of these variations, direct comparisons

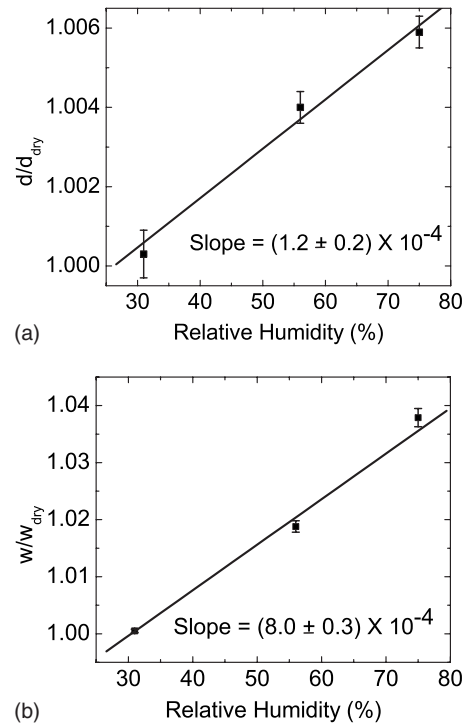


Fig. 1. (a) Relative diameter and (b) relative weight as a function of relative humidity (RH).

between the diameters of dry and wet baseballs do not show the effect of relative humidity. We therefore report the data as the fractional change in the diameter  $d/d_{\text{dry}}$  from that of a dry ball held at 32% relative humidity. Based on this measurement, we are unable to distinguish a difference in the expansion of the ball's diameter measured on the leather as opposed to on the seams. We therefore averaged all five measurements of  $d/d_{\text{dry}}$  for each ball and all 25 measurements for the five balls in each container.

The experiment began with all balls held in a dry environment for a time exceeding 2 months. Two sets of balls were then moved into the 56% relative humidity and 74% relative humidity containers. The quantities  $d/d_{\text{dry}}$  and the weight ratio  $w/w_{\text{dry}}$  were recorded at weekly intervals, showing that they saturated on a time scale of  $\sim 2$  weeks. For comparison, the balls at Coors Field are assumed to be stored for longer times. The humidifier stores 400 dozen baseballs, and the stock is rotated bringing the oldest balls out first.<sup>4</sup>

The steady-state dependence of ball size and weight with humidity is reported in Fig. 1. A linear fit to the data shows that a particular diameter of a given ball can be expected to increase by 0.012% for each percent of relative humidity, or by about 0.24% upon changing the humidity from 30% (typical of summer weather in Denver) to 50% (the specification of the humidifier). Likewise, the weight of the balls increases by 0.08% for each percent relative humidity, or 1.6% between 30% and 50% relative humidity. Hence humidifying the balls increases the density of the balls by 0.9%.

Figure 2 shows a plot of the circumference versus weight. The region indicated by the solid lines shows the allowed limits on circumference and weight specified by the rules of Major League Baseball. The dashed line shows what these specifications become if the ball is dried to 30% relative humidity from 50% relative humidity. Strikingly, drying out

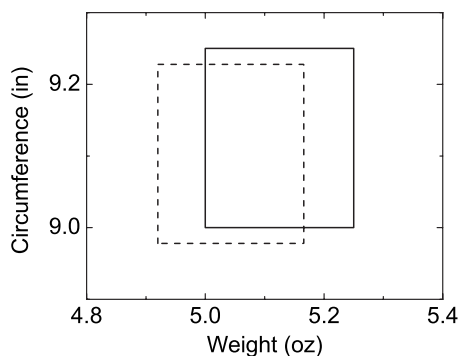


Fig. 2. The solid line represents allowed variations of major league baseballs; the dashed line represents these same dimensions shifted to account for a 20% reduction in the relative humidity.

a baseball produces a smaller change than, say, substituting the smallest, lightest ball for the largest, heaviest one allowed by the rules.

Armed with these data, the calculations presented in the following assess the difference between a “dry” ball and a “humid” ball; that is, the dry ball is by definition 0.24% smaller in diameter and 1.6% lighter than the humid one.

### III. AERODYNAMIC FORCES

The aerodynamics of balls in flight have been studied since the time of Newton, who was the first to appreciate the Magnus force responsible for the curve of a tennis ball.<sup>11</sup> This force, along with the drag force, determines the trajectory of the ball in flight. A free-body diagram of a baseball in flight is shown in Fig. 3. A baseball moving to the right with a counterclockwise spin (a backspin) experiences a lift force with an upward vertical component.

Although these forces are understood qualitatively for baseballs, their details remain somewhat obscure. In this section we summarize existing measurements of drag and lift forces for baseballs and construct models that we will use in our trajectory calculations.

#### A. Drag

The drag force originates from the air displaced by the ball as it travels. It is therefore proportional to the cross-sectional surface area  $A$  of the ball and to the density  $\rho$  of the air it displaces. From dimensional considerations the drag force  $\mathbf{D}$  must then depend on the square of the velocity. We write

$$\mathbf{D} = -\frac{1}{2}\rho C_D A v^2 \hat{\mathbf{v}}, \quad (1)$$

where the dimensionless drag coefficient  $C_D$  characterizes the strength of the drag force. The direction of the drag force opposes the motion of the ball.

This form of the drag force assumes an aerodynamic regime where the fluid’s viscosity is low, or equivalently, where the Reynolds number  $Re$  is large. The Reynolds number is defined by

$$Re = \frac{vd}{\nu}, \quad (2)$$

where  $v$  is the ball velocity,  $d$  is the diameter of the ball, and  $\nu$  is the kinematic viscosity of the fluid. Baseball is played in a regime where  $Re \sim 10^4$ – $10^5$ , and viscosity plays a fairly small role.

However, the drag coefficient for a spherical object changes dramatically in a certain range of  $Re$ . Near this “drag crisis”  $C_D$  can drop by a factor of 2–5 due to a change from laminar to turbulent flow.<sup>12</sup> The wake region formed behind the ball begins to shrink due to boundary layer separation. Eddies build up in the wake region causing pressure to increase on the side of the ball opposite the direction of travel. The reduction in  $C_D$  is so great that it diminishes the total drag force, despite the quadratic dependence on velocity, for  $Re \sim 10^5$ .

Frohlich<sup>13</sup> noted that the game of baseball is played in the regime where the drag crisis plays a crucial role. In addition, using the results of Achenbach<sup>14</sup> on sand-roughened spheres, Frohlich pointed out that the roughness of a baseball affects the value of  $Re$  at which the crisis occurs. Namely, a rougher ball reaches the onset of the drag crisis for a smaller value of  $Re$ , hence a lower velocity. Achenbach defined the roughness of a baseball using the average height of the seam above the hide relative to the diameter of the baseball hide. As the ball rotates, this disparity can appear on average as a “sand-roughened” sphere. Frohlich also pointed out that if a hitter can “punch” through the crisis, that is, get the ball to exceed the speed where the crisis occurs, the reduced drag would add distance to the ball’s flight.

Sawicki *et al.*<sup>15</sup> extracted information on  $C_D$  versus  $Re$  from data taken at the 1996 Atlanta Olympic games and found a possible occurrence of the drag crisis.<sup>16</sup> In contrast, the experimental results of Ref. 17 suggest that the drag crisis is less dramatic for baseballs than suggested in Ref. 15. Because of this discrepancy, we perform trajectory simulations using several models of the drag force. Figure 4 presents the four drag coefficient profiles considered, including a smooth ball that is not expected to represent a real baseball. The curve attributed to Frohlich<sup>13</sup> represents a surface roughness of about  $5 \times 10^{-3}$ .

In Fig. 4  $Re$  has been converted into  $v_s$ , which is the velocity of a standard baseball (5.125 oz, 9.125 in. in circumference) in the atmosphere of Denver. Denver is located 1 mile above sea level and therefore has a lower air density and a higher kinematic viscosity. A drag crisis that would occur at 70–100 mph at sea level would instead occur at speeds near 100–130 mph in Denver. Thus, the drag crisis is likely a bigger factor for baseball played at sea level than in Denver. We have shifted the published data<sup>17</sup> to account for the air density at Denver. We stress that these curves are approximate fits to published data sets and shifted according

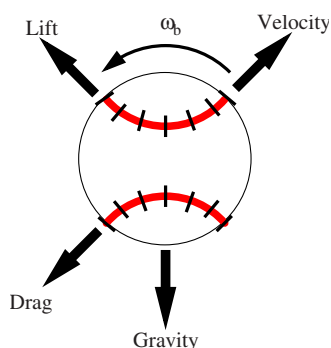


Fig. 3. Aerodynamic and gravitational forces acting on a baseball.

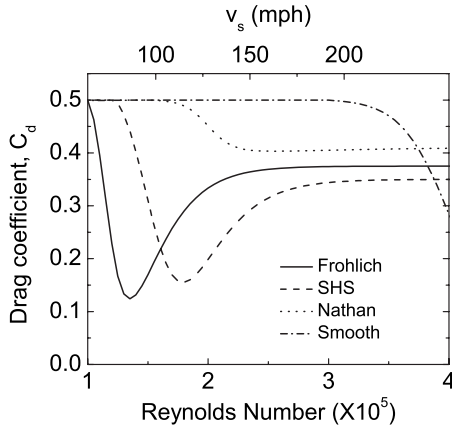


Fig. 4. Drag coefficient  $C_D$  as a function of the Reynolds number  $Re$ . On the top axis  $Re$  is converted into a velocity for a standard ball (5.125 oz, 9.125 in. in circumference) at representative Denver air pressure and kinematic viscosity. Each curve represents an approximate fit to the data from a given publication.

to the value of  $\nu$  and  $d$  in the value of  $Re$ . Nevertheless, the general features and differences between the curves are represented. The curves were modeled using an offset plus the sum of decreasing and increasing hyperbolic tangent functions.

## B. Lift

The lift force plays a comparatively minor role in determining the distance of a batted baseball, but it is very important for pitched baseballs. Lift is responsible for the break of the curveball and the slide of the slider. Like drag, the lift force is also proportional to the cross-sectional area and the density of air. The direction of the force is perpendicular to the direction of motion because the rotation of the ball serves to shift the wake region from directly behind the ball, resulting in a force directed oppositely to the wake region. The lift force  $\mathbf{L}$  is given by

$$\mathbf{L} = -\frac{1}{2}\rho C_L A v^2 \hat{\mathbf{v}} \times \hat{\boldsymbol{\omega}}_b. \quad (3)$$

The lift coefficient  $C_L$  does not depend strongly on the value of  $Re$  because it arises from rotation shifting the wake region, not the size of the wake region nor the eddies forming within it. Adair<sup>1</sup> uses a differential model of  $C_D$  to determine an approximate  $C_L$ . Careful measurements in Refs. 15 and 17 find that  $C_L$  depends linearly on the spin parameter  $S$ , which is given by

$$S = \frac{r\omega_b}{v}, \quad (4)$$

where  $r$  and  $v$  are the radius and velocity, respectively, of the ball and  $\omega_b$  is the rotation rate of the ball in radians per second. Baseball is played in a regime where  $S$  lies in the range  $0 < S < 1/2$ , where the lift coefficient's dependence on  $S$  is approximately<sup>15</sup>

$$C_L = \begin{cases} 1.5S, & (S < 0.1) \\ 0.09 + 0.6S, & (S > 0.1) \end{cases}. \quad (5)$$

In addition, the orientation of the seams has a noticeable

effect, according to the unpublished work of Sikorsky and Lightfoot referenced in Always *et al.*<sup>16</sup> We ignore this effect in the present work.

## IV. TRAJECTORY CALCULATIONS

The equation of motion for the baseball in flight is given by

$$\dot{\mathbf{v}} = -\mathbf{g} + \frac{1}{m}(\mathbf{D} + \mathbf{L}), \quad (6)$$

where  $\mathbf{v}$  is the ball's velocity,  $m$  is its mass,  $\mathbf{g}$  is the acceleration due to gravity, and the aerodynamic forces  $\mathbf{D}$  and  $\mathbf{L}$  are given in Eqs. (1) and (3). For simplicity, we restrict the ball's motion to a vertical plane and require the rotation axis to be orthogonal to this plane. The trajectory then lies entirely in this plane. All calculations assume a "standard" Denver atmosphere, with air density  $0.91809 \text{ kg/m}^3$  (as compared to  $1.0793 \text{ kg/m}^3$  at sea level) for a temperature of  $70^\circ \text{F}$ . We assume a kinematic viscosity for Denver at this temperature of  $2.095 \times 10^{-5} \text{ m}^2/\text{s}$  (compared to  $1.8263 \times 10^{-5} \text{ m}^2/\text{s}$  at sea level).<sup>18</sup>

We use Eq. (6) to assess the difference between dry and humid baseballs for two observable quantities. One quantity is the break of a pitched ball, that is, the additional drop in elevation of a ball with forward motion due to a downward lift force. The other is the distance a batted ball travels before hitting the ground. In both cases we explore the difference as a function of the ball's initial velocity.

### A. Aerodynamics of pitched baseballs

A typical major league pitcher releases the ball from a height of 6.25 ft and a distance from the plate of 53.5 ft at Coors Field.<sup>19</sup> It has been claimed that curveballs at Coors Field break more (due to better grip) if the balls are stored in a humidity-controlled environment, bringing them closer to curveballs in other major league venues.<sup>20</sup> We evaluate this claim by comparing the relative arrival heights of curveballs launched horizontally with a given velocity between 72 mph (often called a "slurve") and 88 mph (often called a "power" curve).

We consider two balls thrown with identical initial conditions. The first is a standard baseball with circumference 9.125 in. and mass 5.125 oz, which is the mean ball specified by the rules of baseball. The second is this same ball, but stored in a dry environment, reducing its circumference and weight by 0.24% and 1.6%. We compute the difference in the heights of these balls upon reaching the plate, defined as  $\Delta y = y_s - y_d$ , where  $y_s$  is the height upon arrival of the standard ball and  $y_d$  is the height of the dried ball.

The result is shown in Fig. 5. For all initial velocities,  $\Delta y$  is positive, indicating that the dry ball breaks more than the standard baseball. It is a small effect, changing the break of the ball by at most 0.25 in. This general result holds regardless of the specific form used for  $C_D$ . As the speed of the pitch is increased, the difference in final height is diminished, and the two balls break more similarly. This similarity is due primarily to the amount of time the ball is in flight: a faster curveball will reach the plate sooner, thereby experiencing the acceleration due to lift for a shorter duration.

To see why the dry ball breaks more, it is important to understand the consequences of Eq. (6). We define the dif-

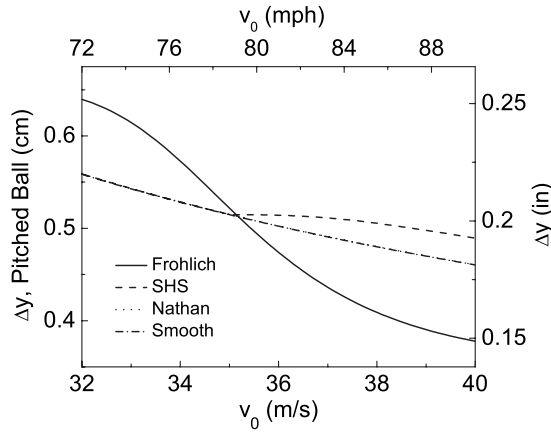


Fig. 5. Relative break of a curveball thrown at Coors Field versus velocity. Positive values of  $\Delta y$  mean that the drier baseball breaks more than the standard Rawlings baseball for a given initial velocity and spin rate. For ease of comparing to baseball units, the top axis is labeled in miles per hour and the right axis is labeled in inches.

ference in accelerations due to lift,  $\Delta a_L = a_{s,L} - a_{d,L}$ . From Eq. (3) the value of the acceleration due to lift is given by

$$a_L = -\frac{1}{2} \frac{\rho A}{m} C_L v^2. \quad (7)$$

If the value of  $\Delta a_L$  is positive, the dry baseball experiences more acceleration due to lift. Because the initial pitch conditions are the same, the only parameters that change when the ball is dried out are  $A$ ,  $w = mg$ , and  $C_L$ . The fractional change in  $a_L$  as the ball is thrown is

$$\frac{\Delta a_L}{a_{s,L}} = \frac{\Delta C_L}{C_{s,L}} + \frac{\Delta A}{A_s} - \frac{\Delta w}{w_s}. \quad (8)$$

Since the direction is downward, if the value of  $\Delta a_L/a_{s,L} < 0$ , there is more break. Because  $C_L \sim d/2$  [see Eqs. (4) and (5)] and  $A \sim d^2$ , we can simplify Eq. (8) to

$$\frac{\Delta a_L}{a_{s,L}} = 3 \frac{\Delta d}{d_s} - \frac{\Delta w}{w_s}. \quad (9)$$

Based on the experimentally determined changes in diameter ( $\Delta d/d_s = 0.24\%$ ) and the weight ( $\Delta w/w_s = 1.6\%$ ), we find that  $\Delta a_L/a_{s,L} \approx -0.88\%$ . Therefore, the drier baseball experiences more lift acceleration and breaks more. Although it is true that the standard ball experiences a greater lift force, this force is overcome by the ball's greater inertia due to its increased weight.

Nevertheless, reports from pitchers and batters alike assert that the humidified balls break more. Our result shows that this effect cannot be due purely to the aerodynamics. Pitchers also report that the humidified balls are easier to grip.<sup>20</sup> It is possible that they can put a greater spin on the ball. This possibility would require Eq. (9) to be modified to include a term  $+\Delta\omega/\omega_s$ . Because the lift force is also proportional to spin, it would take only an additional spin of  $\Delta\omega/\omega_s = 0.9\%$  to overcome the aerodynamic effect arising from increased density of the humidified ball. Any additional spin the pitcher can provide beyond this value will further overcome the aerodynamic tendency of the standard ball to break less. It might be this effect on grip that is responsible for the ability of pitchers to perform at Coors Field more like they do elsewhere since the introduction of the humidifier.

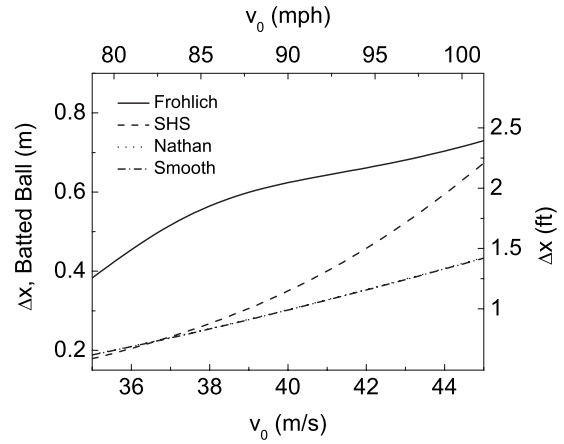


Fig. 6. Relative variation in the range of a well-struck baseball hit at Coors Field as a function of the velocity off the bat. Positive values of  $\Delta x$  mean that the drier baseball falls short of the standard baseball. For ease of comparing to baseball units, the top axis is labeled in miles per hour and the right axis is labeled in feet.

We also note the dependence on the type of drag curve describing the crisis. Each curve is fairly consistent for midrange curveball speeds, but it is clear that the sand-roughened sphere of Frohlich<sup>13</sup> shows a wider variation with speed. Also, for higher speeds, the drag curve of Ref. 15 would predict a larger break variation than a smooth ball or one using the results of Nathan.<sup>17</sup> This uncertainty points to the need to measure more accurately the drag curve, including its dependence on the spin of the ball. Games played at sea level are more susceptible to the subtleties of the drag crisis due to the smaller value of  $\nu$ . A better understanding of the drag curve is imperative to understand quantitatively the slight variations of the game due to relative humidity changes or to the allowed variation in baseball dimensions.

## B. Aerodynamics of batted baseballs

A batted baseball's velocity off the bat depends on the initial speed of the pitch, the speed of the bat, the rotation of the pitch, the moment of inertia of the ball, and the impact parameter.<sup>21</sup> For simplicity we consider an optimally struck curveball, which leaves the bat with a speed of about 40 m/s at an angle of  $24.3^\circ$  from the horizontal.<sup>15</sup> In our calculations we assume a range of initial speeds 35–45 m/s off the bat at this angle. Figure 6 shows the difference  $\Delta x = x_s - x_d$ , where  $x_s$  is the distance the standard ball travels and  $x_d$  is the distance the dry ball travels.

In all cases the standard ball actually travels slightly farther but only by about 2 ft. Similar to the effect on lift, the acceleration due to drag is proportional to the ball's area but inversely proportional to its mass. Because the fractional change in mass is greater than that in area, the mass effect wins. We apply the same ideas as in Sec. IV A to find how the acceleration due to drag is affected by a change in relative humidity. We define  $\Delta a_D = a_{s,D} - a_{d,D}$ . The acceleration due to drag is

$$a_D = -\frac{1}{2} \frac{\rho A}{m} C_D v^2. \quad (10)$$

To find the fractional change for a fixed initial speed we write

$$\frac{\Delta a_D}{a_{s,D}} = \frac{\Delta C_D}{C_{s,D}} + \frac{\Delta A}{A_s} - \frac{\Delta w}{w_s}. \quad (11)$$

Note that if  $\Delta a_D/a_{s,D} < 0$ , the drier baseball will experience a larger acceleration due to drag. If we use the data from our experiments and assume for the moment that  $\Delta C_D = 0$ , we find that the value of  $\Delta a_D/a_{s,D} \approx -1.12\%$  for balls initially leaving the bat. Therefore, based solely on the change in the ball, we would expect humidified balls to travel slightly farther than dry balls for the same initial conditions.

This analysis is complicated by the fact that the velocity, and thus  $C_D$ , both change during the ball's flight. The value of  $\Delta C_D/C_{s,D} \neq 0$  over the entire range of launch velocities for the drag profiles of Refs. 13 and 15. In Ref. 15  $\Delta C_D/C_{s,D}$  monotonically decreases from zero to small negative values; for Ref. 13 we find that it increases from small negative values to small positive values. These changes can drastically change the amount of acceleration due to drag experienced by the ball during its flight. To understand the complete effect of the variation of the drag coefficient a full trajectory calculation is needed; the result is presented in Fig. 6. We see that the monotonically decreasing value of  $\Delta C_D/C_{s,D}$  in the drag profile of Ref. 15 causes the slope in the range variation to increase with greater launch velocity, thus deviating from the values of Ref. 17 and a smooth sphere. In the curve of Ref. 13 we see the slope in range variation diminish; this effect is due to the change in sign of  $\Delta C_D/C_{s,D}$ , which occurs around 40 m/s.

We know that relative humidity has other effects on the batted ball beyond aerodynamics. For example, Kagan<sup>8</sup> found that a 20% increase in the relative humidity reduces the ball's coefficient of restitution, resulting in about a 6 ft reduction in the distance of a batted ball. This change represents the net effect of two competing tendencies. The standard ball comes off the bat slower than the dry one and so would not go as far. The slower ball also experiences less deceleration due to drag and might be expected to go farther. Only the full trajectory calculation can tell which effect dominates.<sup>8</sup> It turns out that it is the velocity off the bat that dominates and therefore the standard ball should travel less far. We can naively expect the total change in range to be the sum of the collisional and aerodynamic effects, which yields about a 4 ft overall reduction in batted range. We will see that this estimate is reasonable.

### C. Net effect of the relative humidity on batted baseballs

Cross and Nathan<sup>22</sup> have worked out the dependence of the bat-ball collision on the parameters  $e$ ,  $d$ , and  $m$ —the coefficient of restitution, the diameter of the ball, and the mass of the ball, respectively. By using the measurements of Kagan<sup>8</sup> and our own, we can extract the changes in the launch parameters such as angle, speed, and spin rate of the ball. To do so we have to clearly define the assumptions made before the collision. We assume the ball arrives from the pitcher in the exact same location with the same velocity and spin for a dry and standard ball and that the hitter takes the same swing. Therefore, the only parameters that change in the collision due to relative humidity changes are  $e$ ,  $d$ , and  $m$ .

We present in Fig. 7 the total effect of the relative humidity on the range of a batted ball including the effects of the collision. The range variation is not quite the 4 ft expected from adding the collisional and aerodynamic effects indepen-

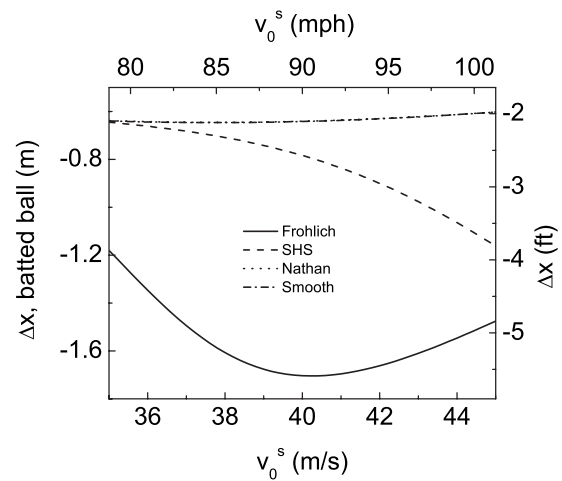


Fig. 7. Relative variation in the range of a well-struck baseball hit at Coors Field as a function of the velocity of the dry ball off the bat including the effects of an increased coefficient of restitution. Negative values of  $\Delta x$  mean that the drier baseball flies further than the standard baseball. For ease of comparing to baseball units, the top axis is labeled in miles per hour and the right axis is labeled in feet.

dently, presumably due to the nonlinear interaction of the variables involved. The results for the drag profiles of a smooth ball and the one in Ref. 17 show little change in range due to variations in  $\Delta C_D/C_{s,D}$ , although they start to deviate slightly as the launch velocity is increased. The small diminution in the range variation is due to the  $v^2$  dependence of the deceleration due to drag. Balls leaving with a larger velocity off the bat experience more deceleration. The increase in range variation of the drag profile of Ref. 15 is due to the large change in  $C_D$  during its trajectory although only smaller Re values are sampled. The drag profile of Ref. 13 samples both the drop and rise of  $C_D$ , and there is a maximum in the range variation, which occurs near 40 m/s.

A more detailed study of the drag profile for spinning baseballs is needed to fully understand the effects of relative humidity variation. At Coors Field these relative humidity variations are a small effect on the range of a batted baseball,  $\sim 3$  ft, an average of the values for a standard ball launched at 40 m/s. This value is consistent with what is observed (see Table I). A more detailed study that includes the prevailing northeast winds,<sup>2</sup> a breakdown of fly balls to left, left-center, center, right-center, and right field, and a three-dimensional model is needed to determine the range variations. The fly-ball data listed are averaged over all field directions and balls hit to left field will be more affected due to the wind patterns in Coors Field than those hit to right field.

## V. CONCLUSIONS

We have shown that storing baseballs in humidity-controlled environments can slightly increase their size, weight, and density. This change has small consequences for the aerodynamics of a ball in flight. Based solely on aerodynamic considerations, humidified balls will break slightly more, by about 0.2 in., while batted balls may travel farther, on the order of a couple of feet. Both effects appear counter-intuitive but follow from the aerodynamics of spheres in air. Both effects are also common in experience; a baseball and whiffle ball are the same size, but the denser baseball curves

far less and can be batted much farther. The effect on the batted ball is largely negated by the decreased coefficient of restitution of the humidified ball, causing an overall reduction of a few feet in the distance a ball travels. In addition to collisions and aerodynamics, other effects may contribute to the humidifier's influence on the game of baseball. An intriguing possibility is that the humidified balls are easier to grip, allowing pitchers to put a greater spin on a humid ball than on a dry one.

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