

Influence of a humidior on the aerodynamics of baseballs

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Abstract

We investigate whether storing baseballs in a controlled humidity environment significantly affects their aerodynamic properties. To do this, we measure the change in diameter and mass of baseballs as a function of relative humidity (RH). We then model trajectories for pitched and batted baseballs to assess the difference between those stored at 30% RH versus 50% RH. The results show that a drier baseball may be expected to curve slightly more than a humidified one, and that the drier ball will also likely travel slightly less far when batted. We discuss consequences of these results for baseball played at Coors Field in Denver, where baseballs have been stored in a humidior at 50% RH since 2002.

I. INTRODUCTION

The game of baseball is strongly influenced by the aerodynamics of its central object, the ball. The very fact that the ball travels through the atmosphere is enough to make a typical home run ball hit at sea-level travel 400 feet rather than the ~ 750 feet it would travel in vacuum¹. Vice versa, that same 400 foot home run might be expected to go 420 feet at the altitude of Denver, one mile above sea-level. For this reason, the idea of introducing a major league team (The Colorado Rockies) to the Denver area was met with opposition in the early 1990's. Indeed, hitters counted on the so-called "Coors Field advantage" to help boost their hitting numbers, such as home runs (HR), runs batted in (RBI) and batting average (BA). On the other hand, pitchers dreaded throwing in Denver because the thin air was blamed for the lack of break of a curveball or slider, which are common tricks of the trade for any modern pitcher.

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 Baseball². So, starting in the 2002 season, the Rockies have stored their baseballs in a humidor behind the beer storage facility. This sealed room is maintained at a temperature of 70° F and 50% relative humidity (RH), consistent with the specifications of baseball manufacturer Rawlings.

The use of the humidor remains a matter of controversy within professional baseball, and a matter of fascination for the public that follows the sport. It is widely believed that Coors Field has yielded fewer home runs and fewer runs altogether in the humidor era. Indeed, the statistics for various offensive and defensive benchmarks at Coors Field do support a small but measurable correlation with the presence of the humidor, as shown in Table I. This table shows the various statistics for games played at Coors Field as compiled in the seven seasons before the humidor was installed (BH), and compared to the same statistics from the five seasons after (AH). For comparison, the same numbers for the entire National League (NL) are presented in the same two time frames. These data were obtained from Refs.^{3,4}

In all cases, there has not been a significant change for the NL as a whole. This fact

	BH	AH	BH – AH
Rockies ERA @ Coors	6.14(52)	5.34(52)	.80(74)
NL ERA @ Coors	6.50(47)	5.46(48)	1.04(67)
NL Avg. ERA	4.37(18)	4.28(12)	0.09(22)
HR/Team-Game @ Coors	1.59(19)	1.26(18)	0.33(26)
NL Avg. HR/Team-Game	1.06(09)	1.05(04)	0.01(10)
Runs/Team-Game @ Coors	6.94(49)	5.87(36)	1.07(61)
NL Avg. Runs/Team-Game	4.7(19)	4.58(12)	0.18(22)

TABLE I: Examples of run production numbers at Coors Field before (BH) and after (AH) the inception of the humidior in 2002. These are compared to the NL averages in the same two periods. Compare the NL averages to the Coors averages and note the deviation from zero. The quoted uncertainties are calculated using the year-to-year variance, as the counting statistics contribute negligibly to this uncertainty.

presumably represents an averaging over a host of other changes that may have taken place from one half-decade to the next. In all the categories for statistics at Coors Field, however, there is a definite trend toward lower ERA's and fewer runs (indicating more successful pitching), by more than one standard deviation. In a game as complex as baseball, it is impossible to attribute a cause-and-effect relationship between these results and the humidior. For example, Rockies pitchers may have been more talented since 2002, and the strike zone was enlarged in 2001⁵; however, consequences of these changes are difficult to quantify by means other than the very performance statistics we use to check the humidior's effect.

Nevertheless, one may wonder what possible quantifiable effects the humidior might have on the game. As early as the late 1980's, the president of the National League (NL), A. Bartlett Giamatti, asked Robert Adair, a Yale physicist, to test the effect of a humidior on baseballs. Adair found that under the most extreme conditions the humidified balls gained weight and were less elastic¹. Subsequent work by Kagan suggested that storing balls in an increased RH environment reduces the distance a well-hit ball travels by 3 feet for every 10% change in RH⁶. Another possible effect of the humidior is to make the horsehide surfaces of the balls more supple, enabling the pitchers to maintain a better grip and therefore pitch as they would with balls stored in higher RH elsewhere. This effect has been reported by

pitchers, but remains unexplored quantitatively.

In this article we will focus exclusively on 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 mass of baseballs as a function of RH. Strikingly, we find that this variation is less than the variation already allowed by the rules of Major League Baseball (MLB). Nevertheless, the lightest, smallest allowed balls, if dried out, will exceed the limits in the rulebook. To assess the effect of these changes in 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 *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. Our discussion suggests that if the humidor has altered the game at Coors Field, it does not do so by purely aerodynamic effects.

The rest of the paper is outlined as follows. Sec. II will provide the results of an experiment designed to measure the effect of RH on the size and mass of the ball. Sec. III discusses the approximate models of aerodynamic forces acting on a baseball in flight. Sec. IV evaluates the effects of RH on the aerodynamics for curve balls and well-hit baseballs. In Sec. V we summarize our results and present possibilities for future work.

II. EXPERIMENT

To assess the effect of RH on the baseballs, we measured the mass and diameter of a collection of balls stored at various RHs. We stored five Major League baseballs each in airtight containers in which the RH was held at the constant values 32%, 56%, and 74%. These humidities were maintained by including saturated salt-and-water solutions inside the containers⁷. The RH in each box was monitored and found to hold constant to within $\pm 1\%$, which was also our approximate measurement uncertainty. The temperature was not carefully controlled, but remained near 70° F during throughout the experiment.

The balls' masses were measured to $\pm 0.1\text{g}$ 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 found to be

± 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 between the diameters of dry and wet baseballs does not show the effect of RH. We therefore report the data as the *fractional change* in diameter from that of a dry ball held at 32 % RH, d/d_{dry} . Based on this measurement, we are unable to distinguish a difference in the expansion of the ball’s diameter measured on the hide as opposed to on the seams. We therefore averaged all five measurements 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 period exceeding two months. Two sets of balls were then moved into the “humid” (56% RH) and “wet” (74% RH) containers. The quantities d/d_{dry} and the mass ratio m/m_{dry} were recorded at weekly intervals, showing that they saturated on a timescale of ~ 2 weeks. For comparison, the balls at Coors Field are assumed to be stored for timescales long compared to this. The humididor stores 400 dozen baseballs and the stock is rotated bringing the oldest balls out first, as reported in Ref.³.

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

Fig. 2 summarizes the difference the humididor makes in the size of the ball. On one axis of this plot is the circumference of the balls, on the other is the mass. The region indicated by the solid lines shows the allowed limits on circumference and mass specified by the rules of MLB. By contrast, the dashed line shows what these specifications become if the ball is dried to 30% RH from 50% RH. Strikingly, drying out a baseball produces a smaller change than, say, substituting the smallest, lightest ball for the largest, heaviest one allowed by the

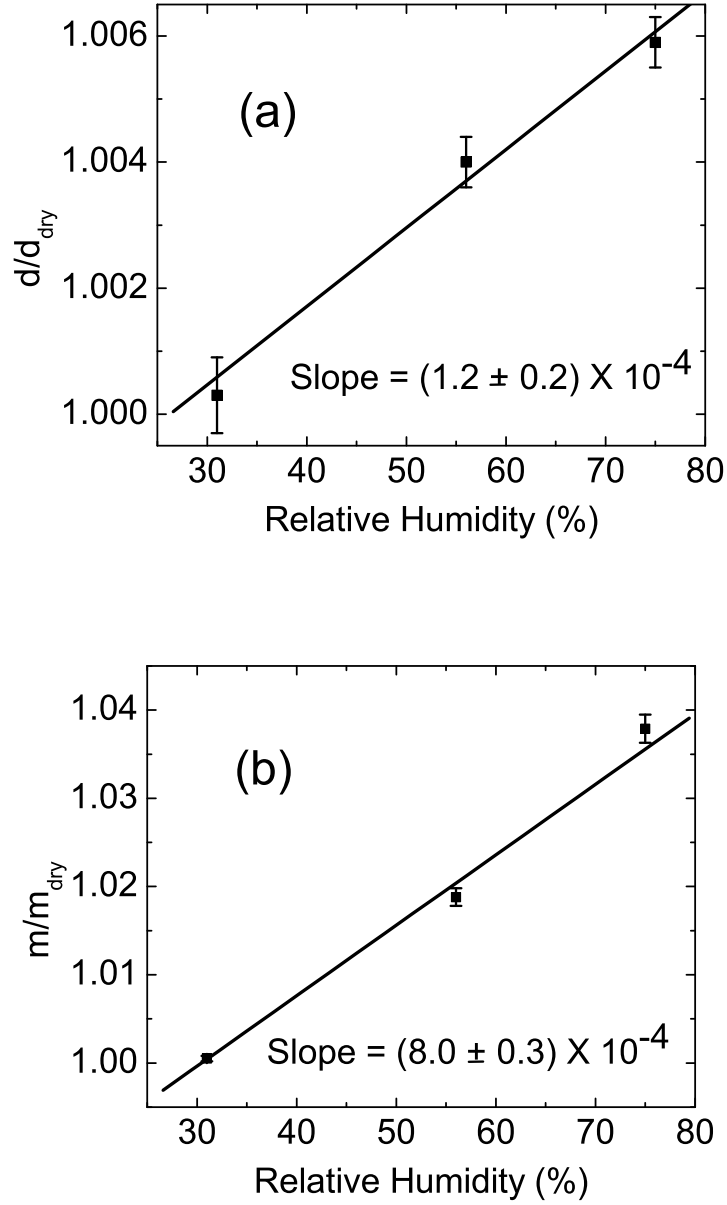


FIG. 1: (a) Relative diameter and (b) relative mass as a function of relative humidity (RH).

rules.

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

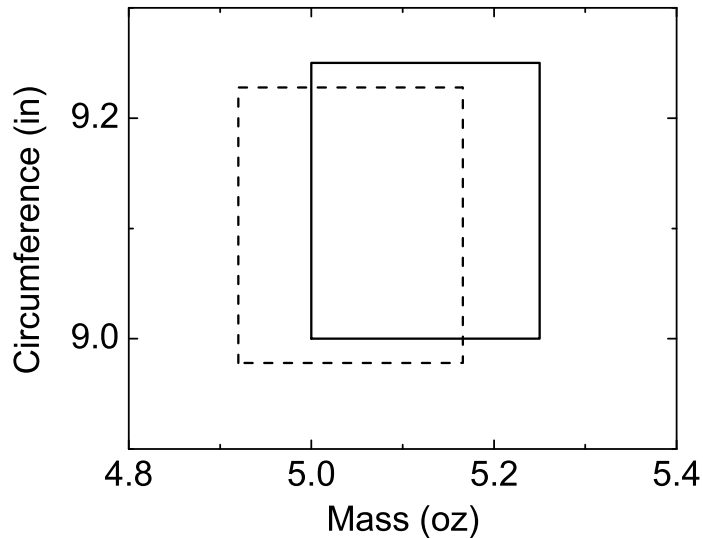


FIG. 2: The solid line represents allowed variations of ML baseballs, while the dashed line represents these same dimensions shifted to account for a 20% reduction in RH.

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 ball⁸. This force, along with the drag force, determine the trajectory of the ball in flight. A free-body diagram of a baseball in flight is shown in Figure 3. As shown, a baseball moving to the right with a counterclockwise spin (i.e., a backspin) experiences a lift force with an upwards vertical component.

While 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 simulations, below.

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 of the ball, A , and to the density of the air

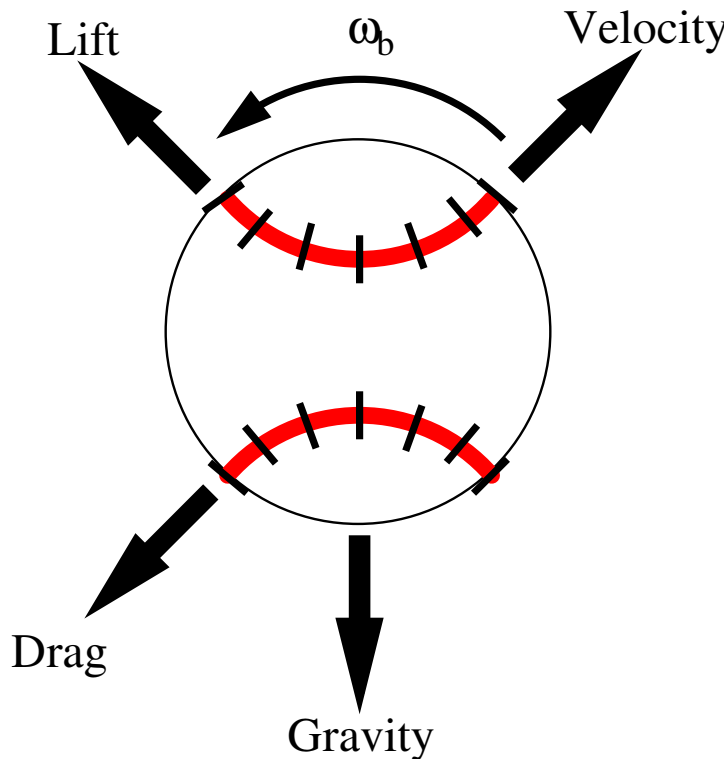


FIG. 3: Aerodynamic and gravitational forces acting on a baseball.

it displaces, ρ . From dimensional considerations, the drag force must then depend on the square of the velocity. Thus,

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

where the dimensionless drag coefficient C_D characterizes the strength of the drag force under particular circumstances. The direction of the drag force is such that it 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 is large. The Reynolds number is defined by

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

where v is the ball velocity, d the diameter of the ball, and ν the kinematic viscosity of the fluid. Baseball is played in a regime where $\mathcal{R} \sim 10^4 - 10^5$, and viscosity plays a fairly small role. For lower velocities, energy is dissipated into the environment, leading to a drag coefficient that diverges as $1/v$.⁹ For baseballs in flight, C_D as defined is roughly constant with velocity.

However, the drag coefficient for a spherical object changes dramatically in a certain range of \mathcal{R} . Near this “drag crisis,” C_D can drop by a factor of 2–5 over a narrow range of \mathcal{R} .⁹ This reduction is due to a change from laminar flow (i.e. smooth flow) to turbulent flow. 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 actually diminishes the total drag force, despite the quadratic dependence on velocity, for \mathcal{R} on the order of 10^5 .

Frohlich¹⁰ 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 Achenbach¹¹ on sand roughened spheres, Frohlich pointed out that the roughness of a baseball affects the Reynolds number at which the crisis occurs. Namely, a rougher ball reaches the onset of the drag crisis for a smaller value of \mathcal{R} , hence a lower velocity. For a baseball, Achenbach defined the roughness using the average height of the seam above the hide relative to the diameter of the baseball hide. This quantity is defined as ϵ . 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, i.e., get the ball to exceed the speed where the crisis occurs, then the ball would travel a greater distance when struck than expected using a constant drag profile.

Sawicki, Hubbard and Stronge (SHS)¹² extracted information on C_D versus \mathcal{R} from data taken at the 1996 Atlanta Olympic games¹³. They found a possible occurrence of the drag crisis. By contrast, experimental results of Nathan, *et al.*¹⁴ suggest that the drag crisis is less dramatic for baseballs than the SHS analysis. Because of this discrepancy, we perform trajectory simulations using several models of drag. Fig. 4 presents the four drag coefficient profiles considered in this paper, including a smooth ball that is not expected to represent a real baseball. The curve attributed to Frohlich¹⁰ represents a surface roughness of about $\epsilon = 5 \times 10^{-3}$.

As a point of reference, in Fig. 4 \mathcal{R} has been converted into v_s , which is the velocity of a standard baseball (5.125 ounces, 9.125 inches in circumference) in the atmosphere of Denver. Denver is located one 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 Nathan’s published data¹⁴ to account for air density at Denver. We stress that these curves

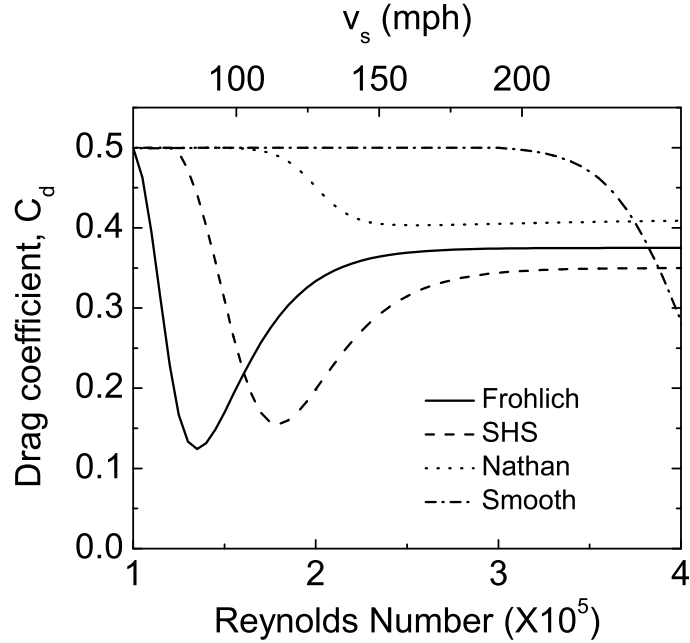


FIG. 4: Drag coefficient C_D as a function of \mathcal{R} . On the top axis \mathcal{R} is translated into a velocity for a standard ball (5.125 ounces, 9.125 inches in circumference) at representative Denver air pressure and kinematic viscosity. Each curve represents an approximate fit to the data from a given publication.

are approximate fits to published data sets and shifted according to the value of ν and d in the \mathcal{R} -value. Nevertheless, the general features and differences between the curves are represented. For analytical convenience, we have represented the drag coefficients in Fig. 4 using the following functional form:

$$C_D = a + b \tanh\left(\frac{\mathcal{R} - \mathcal{R}_d}{\Delta_d}\right) + c \tanh\left(\frac{\mathcal{R}_u - \mathcal{R}}{\Delta_u}\right), \quad (3)$$

where \mathcal{R}_d (\mathcal{R}_u) is the location of the drop (rise) in the drag coefficient and Δ_d (Δ_u) is the corresponding width. The data are consistent with two constraints: for $\mathcal{R} \ll 10^5$, $C_D \approx 0.5$ and for $\mathcal{R} \gg 10^6$, $C_D \approx \text{constant}$. Therefore, the fit has 7 parameters subject to two constraints given by

$$a - b \tanh\left(\frac{\mathcal{R}_d}{\Delta_d}\right) + c \tanh\left(\frac{\mathcal{R}_r}{\Delta_r}\right) = 0.5 \quad (4)$$

$$a + b - c = \text{Constant}. \quad (5)$$

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. However, the direction of the force is not in the direction of the drag force, but rather perpendicular to the direction of motion. This is 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 is given by

$$\mathbf{L} = -\frac{1}{2}\rho C_L A v^2 \hat{\mathbf{v}} \times \hat{\boldsymbol{\omega}}_b. \quad (6)$$

The lift coefficient C_L does not depend strongly on the value of \mathcal{R} since it arises from rotation shifting the wake region, not the size of the wake region or the eddies forming within it. Adair¹ uses a differential model of C_D to determine an approximate C_L . However, SHS¹² and Nathan¹⁴ find that C_L depends linearly on the spin parameter S , which is given by

$$S = \frac{r\omega_b}{v}, \quad (7)$$

where r and v are the radius and velocity of the ball respectively and ω_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 approximately¹²

$$C_L = \begin{cases} 1.5S, & S < 0.1 \\ 0.09 + 0.6S, & S > 0.1 \end{cases}, \quad (8)$$

In addition, the orientation of the seams has a noticeable effect, according to the unpublished work of Sikorsky and Lightfoot referenced in Alaways.¹³ We ignore this effect in the present work.

IV. TRAJECTORY CALCULATIONS

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

$$\dot{\mathbf{v}} = -\mathbf{g} + \frac{1}{m}(\mathbf{D} + \mathbf{L}), \quad (9)$$

where \mathbf{v} is the ball's velocity, m its mass, \mathbf{g} is acceleration due to gravity, and the aerodynamic forces \mathbf{D} and \mathbf{L} are given in Eqs. 1 and 6. 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 kg/m^3 (as compared to 1.0793 kg/m^3 at sea level) for a temperature of 70° F . We assume a kinematic viscosity for Denver at this temperature of $2.095 \times 10^{-5} \text{ m}^2/\text{s}$, as compared to $1.8263 \times 10^{-5} \text{ m}^2/\text{s}$ at sea-level.¹⁵

Using this equation of motion, we assess the difference between dry and humid baseballs with regard to two observable quantities. The first is the break of a pitched ball, i.e., the additional drop in elevation of a ball with forward motion due to a downward lift force. The second 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. Pitched Baseballs

A typical MLB pitcher releases the ball from a height of 6.25 feet and a distance from the plate of 53.5 feet at Coors Field¹⁶. A claim that has been made is that curveballs break more now that the balls have been stored in a humidity controlled environment, bringing them closer to curveballs in other Major League venues. 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, i.e., 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 mass 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.

This result is shown in Fig. 5. For all initial velocities, this quantity is positive, indicating that the drier ball actually breaks more than the standard baseball. It is moreover a small effect, changing the break of the ball by at most 0.25 in. This general result holds regardless of the specific drag curve used. As the speed of the pitch is increased, the difference in final height is diminished, and both balls break more similarly. This 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 shorter duration.

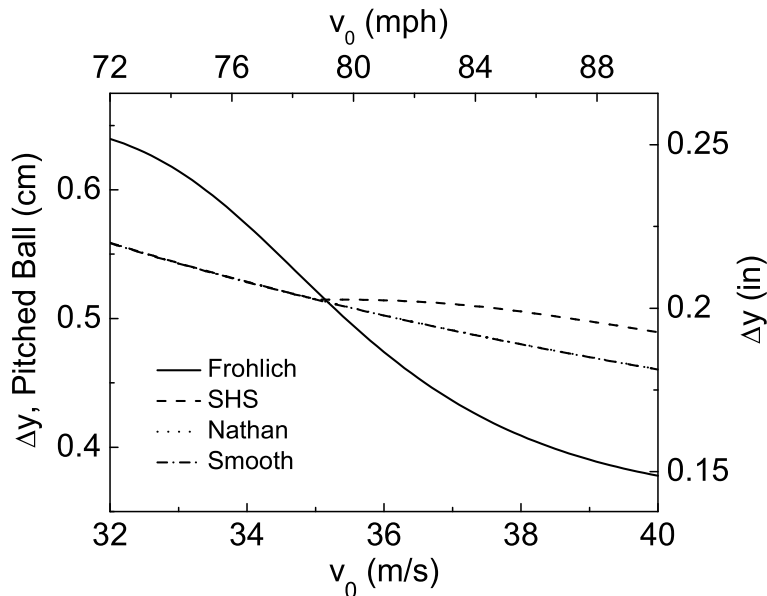


FIG. 5: Relative break of a curveball thrown at Coors Field versus velocity. Positive numbers mean that the “drier” baseball breaks more than the standard Rawlings baseball. For ease of comparing to baseball units, the top axis is labeled in mph and the right axis in inches.

The fact the the dry ball breaks more (for given initial conditions) follows directly from the equation of motion. The acceleration due to the lift force scales with ball parameters as

$$|a_{\mathbf{L}}| \sim \frac{A}{m} r \sim \frac{1}{\rho_b},$$

so that it is inversely proportional to ρ_b , the density of the ball. Because the dry ball is less dense it will experience a larger acceleration due to lift, thus will break more.

Nevertheless, reports from pitchers and batters alike assert that the humidified balls break more. Our result shows that this cannot be due purely to the aerodynamics. However, pitchers also report that the humidified balls are easier to grip. It is possible that they can put a greater spin on the ball. Since the lift force is also proportional to spin, it would take only an additional spin of 0.9% to overcome the aerodynamic effect arising from increased density of the humidified ball. Any additional spin the pitcher can provide beyond this will further overcome the aerodynamic tendency of the humid ball to break less. It may 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 humidior.

Another important item to note is the dependence on the type of drag curve describing the crisis. Each curve is fairly consistent for mid-range curveball speeds but it is clear that the sand-roughened sphere of Frohlich shows a wider variation with speed. Also, for higher speeds, the SHS drag curve would predict a larger break variation than a smooth ball or one using the results of Nathan. This 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 ν . A better understanding of the drag curve is imperative to fully understand the slight variations of the game due to RH changes.

B. Batted Baseballs

A batted baseball's final velocity 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.¹⁷ Here, 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° degrees from the horizontal.¹² In our calculations, we assume a range of initial speeds 35-45 m/s off the bat at this angle. Fig. 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 humidified ball actually travels slightly farther, but only by about 2 feet. Similar to the effect on lift, the acceleration due to drag is proportional to the ball's area, but inversely proportional to its mass. Since the fractional change in mass is greater than that in area, the mass effect wins. The change in RH may have other effects on the batted ball beyond aerodynamics. For example, Kagan⁶ found that a 20% increase in RH would reduce the ball's coefficient of restitution, resulting in about a 6 foot reduction on the distance of a batted ball. However, he made a simplifying assumption that the coefficient of restitution affected the total velocity whereas it only affects the component of velocity along the line joining the long-axis of the bat with the center of the ball.¹⁴ Thus, 6 feet is likely the *maximum* variation that can occur for a well-struck baseball.

Therefore, the effects of collision dynamics and aerodynamic effects have opposite consequences for the distance of a batted ball, and the two effects may nearly cancel each other out. This suggests that storing balls in humidity-controlled environments has little to no

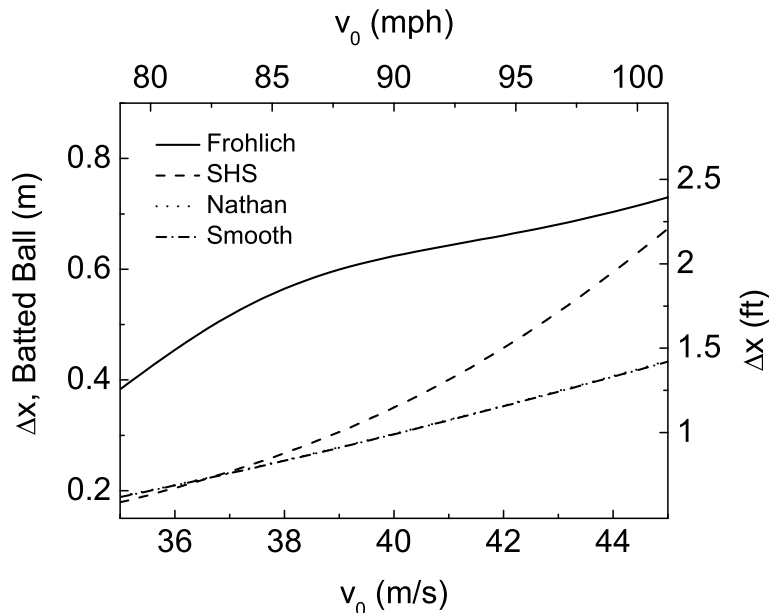


FIG. 6: Relative variation in the range of a well-struck baseball hit at Coors Field. Positive numbers mean that the “drier” baseball falls shorter than the standard baseball. For ease of comparing to baseball units, the top axis is labeled in mph and the right axis in feet.

effect on the range of batted baseballs. For the thin air of Denver, this conclusion depends weakly on which drag curve we consider. However, at sea level, typical baseball velocities are more likely to reach Reynolds numbers near the drag crisis, and humidity of the ball may play a somewhat larger role. This general conclusion is supported by the fact that Coors Field has experienced more HRs per game in the NL than all other stadiums save Wrigley Field in the 2007 season⁴. In fact, Coors Field has finished in the top 4 of all ML ballparks in park factor since the inception of the humidifier in 2002.

V. CONCLUSIONS

We have shown that storing baseballs in humidity controlled environments can slightly increase their size, mass, and density. This change, in turn, has small consequences for the aerodynamics of a ball in flight. Humidified balls will break slightly more, by about 0.2 in, while batted balls may travel further, on the order of a couple of feet. Both effects appear

at first counter-intuitive, but follow from the aerodynamics of spheres in air. Both effects are also common in experience: a baseball and wiffle ball are the same size, but the denser baseball curves far less and can be batted much further. Moreover, the effect on the batted ball may be largely negated by the decreased coefficient of restitution of the humidified ball. The search for the influence of the humidior on the game at Coors Field then shifts away from aerodynamics to other possible effects. 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. In addition, a batted dry-ball may be able to have more spin imparted in the collision, thereby allowing the drier ball to travel further. These will be topics for future study.

Acknowledgments

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¹ Robert K. Adair. *Physics of Baseball*, 3rd Ed. Addison-Weseley, 2002.

² Dan Agonistes. Coors field run facts. *Web Blog*, May 20, 2005. <http://danagaonistes.blogspot.com/2005/05/coors-field-fun-facts.html>.

³ Lee Jenkins. Mystery of coors field makes hitters paranoid. *International Herald Tribune: Sports*, August 17, 2006. <http://www.iht.com/articles/2006/08/17/sports/ROCKIES.php>.

⁴ Baseball Reference.com. <http://www.baseball-reference.com>, September, 30 2007.

⁵ William A. Murray et.al. *2001 Official Rules of Major League Baseball*. Triumph Books, Inc., 2000.

⁶ David T. Kagan. The coefficient of restitution of baseballs as a function of relative humidity. *Phys. Teacher*, 42:330–333, 2004.

⁷ L. Greenspan. Humidity fixed points of binary saturated aqueous solutions. *J. Res. NBS*, 81A:89, 1977.

⁸ I. Newton. New theory about light and colors. *Phil. Trans. R. Soc.*, 6:3078, 1671.

- ⁹ L. D. Landau and E. M. Lifshitz. *Fluid Mechanics*, 2nd Ed. Butterworth Heinemann, 1998.
- ¹⁰ Cliff Frohlich. Aerodynamic drag crisis and its possible effect on the flight of baseballs. *Am. J. Phys.*, 52:325–334, 1984.
- ¹¹ E. Achenbach. The effects of surface roughness and tunnel blockage on the flow past spheres. *J. Fluid Mech.*, 65:113–125, 1974.
- ¹² Gregory S. Sawicki, Mont Hubbard, and William J. Stronge. How to hit home runs: Optimum baseball bat swing parameters for maximum range trajectories. *Am. J. Phys.*, 71(11):1152, 2003.
- ¹³ L. W. Alaways, S. P. Mish, and M. Hubbard. Identification of release conditions and aerodynamic forces in pitched baseball trajectories. *J. Appl. Biomech.*, 17:63–76, 2001.
- ¹⁴ Alan M. Nathan, Joe Hopkins, Lance Chong, and Hank Kaczmariski. The effect of spin on the flight of a baseball. *ArXiv*, physics/(0605041), 2006.
- ¹⁵ Atmospheric properties calculator. Sep. 11, 2007. <http://www.aerospaceweb.org/design/scripts/atmosphere/>.
- ¹⁶ Baseball Analyst.com. <http://baseballanalysts.com/archives//001538-print.html>, September 18, 2007.
- ¹⁷ Alan M. Nathan. Dynamics of the baseball-bat collision. *Am. J. Phys.*, 68:979, 2000.