Tabled 12.02 pm EIC
20/3/13

The influence of temperature on bouncing balls

Introduction:

When a ball is bounced, a number of energy conversions occur. Initially, the ball has gravitational potential energy which is the energy of any object that is held above ground level and is determined by its height and mass (ScienceThinking, 2011). It can be described by the equation:

$$E_{gp} = mgh$$

As the ball falls, this gravitational potential energy is converted to kinetic energy, the energy of motion, which is described by the equation:

$$E_k = \frac{1}{2}mv^2$$

(University of Virginia, 2011).

In order to calculate the velocity with which the ball collides with the ground, it is assumed that at this point all the gravitational potential energy has been converted to kinetic energy. In the case of a ball dropped from a low height, this assumption is quite accurate. However, when talking about greater heights, the possibility of terminal velocity comes into play and this assumption becomes less accurate. Terminal velocity is occurs when the downward thrust is equal to the wind resistance. However, this is unlikely within the scope of this experiment. With this assumption, the equation of kinetic energy can be used to find the velocity. Once the ball hits the ground, it deforms and the kinetic energy is converted to elastic potential energy (Madden, 2011). However, as no ball is perfectly elastic, this conversion is not perfectly efficient and so some energy is lost to heat and sound. Eventually, the restorative force restores the ball to its previous shape and in doing so converts the elastic potential energy back to kinetic energy, which in turn is converted to gravitational potential energy as the ball rises (University of Virginia, 2011). However, the ball will not return to its original height, due to the energy lost to heat and sound. The difference between original and final height be analysed using the coefficient of restitution.

The coefficient of restitution is a measure of the change in velocity in a collision, and in the case of a bouncing ball it represents the ratio of the final velocity over the initial velocity:

$$e = \frac{v_2}{v_1}$$

It can also be calculated using:

$$e = \sqrt{\frac{h_2}{h_1}}$$ (Madden, 2011)

The coefficient of restitution can thus be used to compare how well different balls bounce. One factor that can influence the bounce of a ball is the temperature of the ball. A warmer ball will bounce higher than a cold one. The reason for this is twofold. In a hollow ball, the change in temperature causes a change in air pressure within the ball. In an enclosed situation, air pressure is directly proportional to temperature (Cook, 2011). Lowering the air pressure by lowering the temperature has an effect similar to deflating the ball. Increasing the temperature, and thus air pressure, has the effect of over-inflating (Portz, 2011). The other way in which temperature influences the height a ball bounces is by impacting its elasticity. Elasticity is a measure of how well the ball's kinetic energy is converted to elastic potential energy; the less energy lost to heat and sound, the more elastic the substance (Madden, 2011). The balls used in this experiment, squash balls, are made of rubber which is made from long polymer chains. These polymers are tangled and stretch upon impact. However, they will only stretch for a short time before their atomic interactions pull them back into their original shape, and thus transfer that elastic potential energy back to kinetic energy (University of Virginia, 2011). When the ball is heated, it becomes more elastic, as the bonds are able to move more freely and thus are able to stretch more than those in a cooler ball, and thus less energy is lost (Portz, 2011). This then means that the ball bounces higher. Under cold conditions the material can become so rigid that it becomes an 'energy sink' which absorbs energy rather than transferring it (Portz, 2011).

Aim: To investigate the influence of temperature on the coefficient of restitution of squash balls.

Hypothesis: It is expected that the higher the temperature, the greater coefficient of restitution as increasing temperature leads to increased elasticity and air pressure.

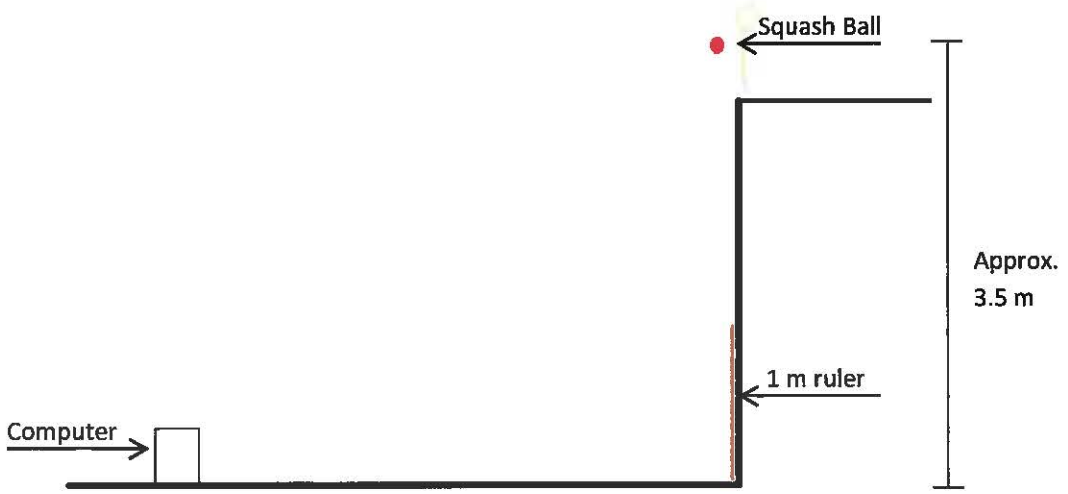
Materials:

3 x squash balls
1 x computer
1 x 1m ruler
1 x thermometer
1 x plastic bag
1 x large container
1 x metal tongs
1 x kettle
Water
Ice

Procedure:

1. The laptop was set up in front of drop site and computer program, Logger Pro, was opened.
2. The water in the water bath was brought to a temperature of 45°C using a combination boiling water and ice. The temperature was measured using a thermometer.
3. One squash ball was placed in the water bath and held under the water using the metal tongs for 5 minutes as shown in Figure 1.
4. The squash ball was removed from water bath using tongs and was placed in a plastic bag.
5. The ball was then transported to the drop site and held approximately 3.5 m above ground. A 1m ruler was held at base of drop site, to provide a point of reference as shown in Figure 2.
6. Logger Pro was started and the ball was dropped.
7. Logger Pro was used to calculate drop and bounce height (refer to Figure 3) which was recorded in Table 1 and used to calculate coefficient of restitution.
8. Steps 3-7 were repeated twice using two remaining squash balls as Trial 2 and 3.
9. Steps 2-8 were repeated for temperatures 5°C, 15°C, 25°C and 35°C.

Figure 1
: Set up of drop site



Results:

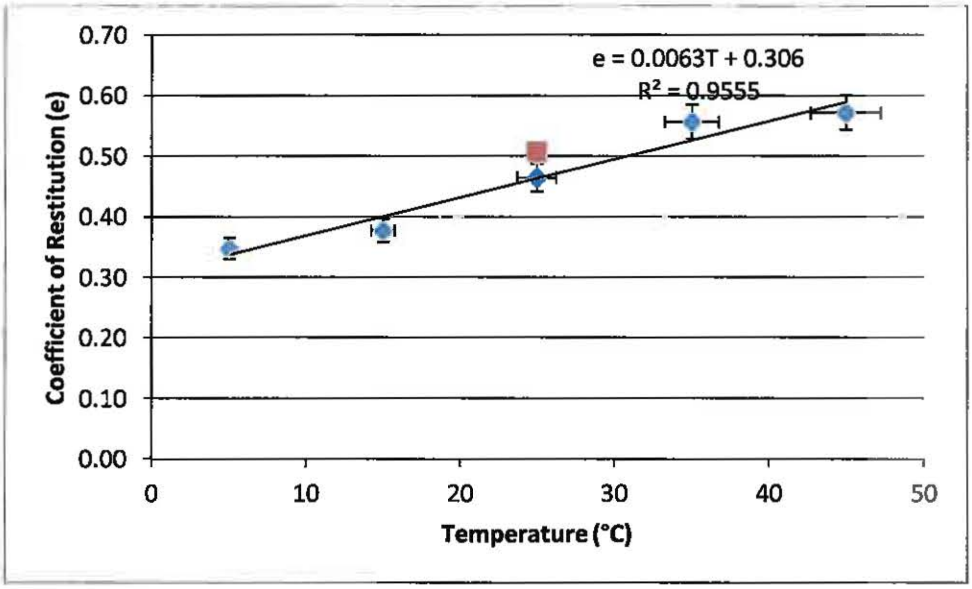
Table 1: Bounce height of squash balls at varying temperatures

Temperature (°C)*	Drop Height (m) (∓0.05)			Bounce Height (m) (∓0.05)			Coefficient of Restitution (m) (∓0.14)			
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Average
5	3.22	3.61	3.75	0.43	0.43	0.41	0.37	0.35	0.33	0.35
15	3.71	3.65	3.65	0.49	0.55	0.53	0.36	0.39	0.38	0.38
25	3.72	3.69	3.68	0.85	0.77	0.77	0.48	0.46	0.46	0.46
35	3.41	3.62	3.64	1.10	1.09	1.12	0.57	0.55	0.55	0.56
45	3.67	3.66	3.60	1.27	1.14	1.17	0.59	0.56	0.57	0.57
25#	3.61	3.47	3.54	3.54	0.96	0.90	0.91	0.92	0.51	0.51

* Temperature based on temperature of water/ice bath and may not correlate with the actual ball temperature.

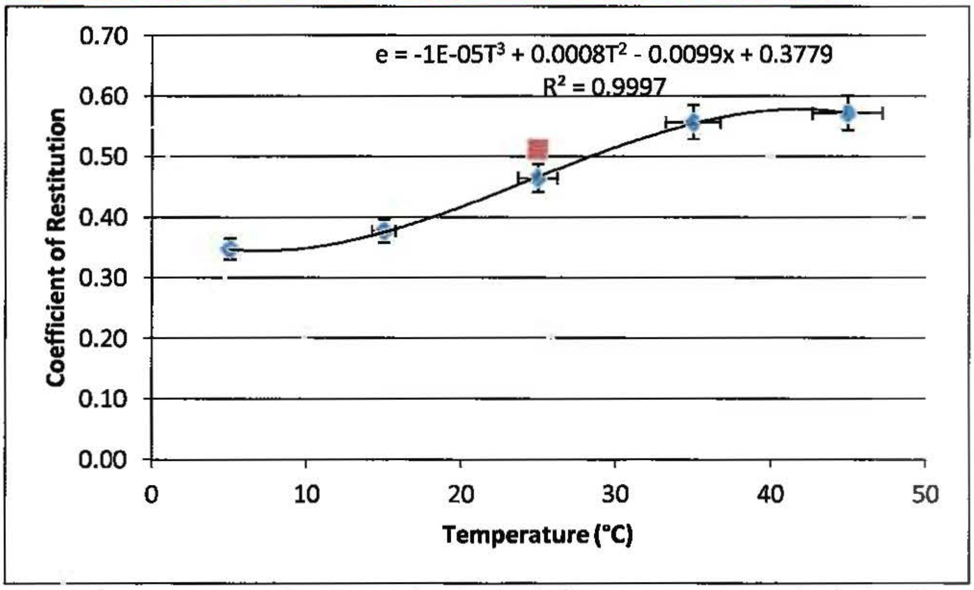
This trial was complete without the balls being soaked in a water bath, as temperature alteration was unnecessary and thus the ball was not wet which influenced the coefficient of restitution.

Graph 1: Coefficient of Restitution over Temperature (Linear Function)



Note: Red point represents the test completed with a ball at room temperature that had not been soaked in water.

Graph 2: Coefficient of Restitution over Temperature (Cubic Function)



Note: Red point represents the test completed with a ball at room temperature that had not been soaked in water.

Discussion:

As shown in Graph One, a linear trend when applied to the data is quite accurate. This is demonstrated by the R^2 value of approximately 0.96 which is very close to perfect correlation. The inaccuracy that prevents a perfect correlation (represented by an R^2 value of 1) could be due to the relatively large uncertainty in the data. This trend confirms that there is a relationship between temperature and elasticity; specifically that an increase in temperature leads to an increase in the coefficient of restitution. From the trend equation, $e = 0.0063T + 0.306$, it appears that for each degree of temperature increased, there is in an increase of 0.0063 to the coefficient of restitution. The trend also suggests that at 0°C, the coefficient of restitution would be 0.36; a reasonable prediction. However, it is not expected that this linear trend would continue indefinitely as ball's elasticity has a theoretical maximum and minimum; the maximum being perfect elasticity with a coefficient of restitution value of 1 (i.e. the ball bounces back to the drop height) and the minimum being no elasticity (i.e. the ball does not bounce), with a restitution value of 0. Therefore the trend is only valid for the range 0 to 1.

However, it is possible that a more appropriate model is a cubic one, as shown in Graph 2. This trend line is even more closely matches the data than the linear function, with an R^2 value of 0.9997, which represents almost perfect correlation. This trend suggests not only a theoretical maximum and minimum value, but also physical limits. It is possible that at the ball's minimum coefficient of restitution, which according to the model occurs around 0.36, temperature has little influence and thus there is little change from 0°C (predicted to have a coefficient of restitution of 0.36) to 15°C. From this point to approximately 35°C, temperature has a much greater influence shown by the almost linear increase before the ball reaches it physical maximum rebound ability with a coefficient of restitution of approximately 0.58 and once again plateaus. However, the cubic function produced would be valid only for a defined domain slightly outside that shown in Graph 2. At temperatures below 0°C the cubic experiences a sharp increase, which does not fit with the expected trend. Similarly, at temperatures greater than 45°C the trend declines sharply; far too sharply to be explained as the ball reaches a coefficient of restitution of 0 at only approximately 74°C. It would be necessary to complete further testing with temperatures greater than 45°C in order to verify the subsequent trend.

The positive correlation between temperature and coefficient of restitution is expected. An increase in temperature would have both increased the elasticity of the squash ball as well as the pressure inside the ball, and these two factors would have led to the observed correlation. However, explaining possible cubic model is more difficult and thus providing an accurate explanation is out of the scope of this experiment. It could be that the squash balls are made of a material that has a maximum and minimum elasticity and that these were reached within the ranged tested, thus producing the flattening out shown in Graph 2. It is also possible that there is a more complex relationship between the pressure within the ball and that outside, which could have influenced the trend. This could be explored by using solid balls, thus eliminating the influence of pressure on the experiment. Further experimentation is necessary to more accurately chart the trend beyond the temperatures tested and to determine the trend's causes.

Initially, the ball at room temperature (25°C) was dropped without being placed in the water/ice bath as its temperature did not require adjustment. The results that were produced by this test were anomalous within both functions plotted (Refer to Graphs 1 and 2). However, this anomaly was identified during the investigation, and thus trials were able to be performed with 25°C squash balls that were soaked in water. This eliminated the anomaly, and the dry ball was found to have a coefficient of restitution more than 10% higher than the wet. This is because soaking resulted in layer of water around the ball, which absorbed some of the force and thus the ball collided with the ground more slowly and consequently did not bounce as high. Other than this there are no anomalies, as all data point are within 10% of their expected values.

A number of other errors were also identified during the experiment. The first was that the drop height was not kept consistent during the trials, which meant that there was the possibility that some balls hit the ground with slightly greater velocity than others, with a drop height range of 0.53m. However, as can be seen from the results collated this did not have a great influence on the data, as the coefficient of restitution should not be affected by drop height. Regardless, this error could be easily corrected by identifying and marking a standard drop height for all tests.

Another error was that it was necessary to transport squash balls from the heating/cooling area to the drop site, in which time it is possible that the temperature of the ball could have been altered. Furthermore, the use of the water bath meant that the exact temperature of the balls could not be accurately determined. This gives the possibility that the scale of the graph, and therefore the rate of increase, is inaccurate. However, as these circumstances were consistent for all balls it is likely that, regardless of whether the balls were the exact temperatures intended their temperatures relative to one another were consistent. If this were not the case, this could provide an explanation for the trend complexities as described by the cubic, as the smaller difference in the coefficient of restitution could be due to a smaller difference in temperature between the two top and bottom recordings.

One limitation of the experiment was the use of Logger Pro to record drop and bounce heights. This technology provides the possibility for the data to lose accuracy, as the calculation of both drop and bounce heights required scales, origins and points of reference had to be identified manually which meant that there was a possibility for errors in judgement and therefore a decline in accuracy. If this requirement for human judgement could be removed, the reliability of the data could be improved.

Another limitation was the time frame of the experiment, which meant that a greater range of temperatures could not be tested and thus a more accurate trend of the correlation between temperature and the coefficient of restitution could not be determined. Testing more temperatures in future would correct this and give a more precise trend.

One extension to the experiment would be to test solid balls, as mentioned earlier, in order to isolate the influence of elasticity versus air pressure. Solid balls would not experience the influences of air pressure and would represent the influence of elasticity alone. This would assist in the development, and explanation of the trend.

Alternatively, different types of squash balls could be tested in order to determine if this trend is common to all squash balls, and then even further to all balls, or if it is a phenomena specific to type tested. Squash balls are made to different coefficients of restitution and this would be interesting to explore.

Conclusion: The results collected support the hypothesis that an increase in temperature of a squash ball leads to an increase in its coefficient of restitution, as described by both equations modelled; $e = 0.0063T + 0.306$ and $e = -1E\text{-}05T^3 + 0.0008T^2 - 0.0099x + 0.3779$.

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Appendix:

To calculate the coefficient of restitution:

For Trial One at 5°C,

$$e = \sqrt{\frac{h_2}{h_1}}$$

$$e = \sqrt{\frac{0.43}{3.22}}$$

$$e \approx 0.37$$

Anomaly Calculations

Percentage difference between wet and dry balls at 25°C

$$Difference\ (\%) = \frac{Dry - Wet}{Wet} \times 100$$

$$Difference\ (\%) = \frac{0.51 - 0.46}{0.46} \times 100$$

$$Difference\ (\%) \approx 10.9$$

Figure 2: Logger Pro calculations