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Hydro-sorting of Apple using Terminal Velocity in Water

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Abstract: The possibility of using the terminal velocity of fruit through water as a means of hydro-sorting of apples was studied. In this study, the rising time of Redspar apples was theoretically formulated and was then was determined experimentally using water column. Some effective characters of apple on rising time were determined using standard methods. Experimental curves showed that fruit will reach terminal velocity within a few centimeters of starting from rest. In this study the best model for rising time of Redspar apples was $T_r = 6681(\rho_w - \rho_f)^{-0.83} V^{-0.88} + 1.6$ with R^2=0.78. The difference of fruit density minus the density of water and volumes of fruit had major effect on rising time of apple. But the fruit shape had only a small effect on it. It was concluded that on online sorting system; terminal velocity has potential to remove poor quality fruit from apple with approximately constant volume.
Key words: Sorting; Redspar apple; Terminal velocity; Rising time.

INTRODUCTION

As electrical sizing mechanisms are overly expensive and mechanical sizing mechanisms are slow to react (Tabatabeefar and Rajabipour, 2005) and fruit graders that employ near-infrared technologies, are applying expensive method, and, perhaps more importantly, the calibrations and maintenance they require tend to remain outside the skills of packing house staff (Jordan and Clerk, 2004).

Density, a good indicator of fruit dry matter (Richardson et al., 1997; Jordan et al., 2000) thus becomes an interesting tool for fruit quality sorting because of its inherently lower cost and simpler operation. Density sorting of produce is not new, and patents and publications in the potato industry extend from the 1950s through to the present day (Kunkel et al., 1952; Wilson and Lindsay, 1969; Bajema, 2001). Other products (e.g., citrus, blueberries, and tomatoes) have also been sorted by flotation techniques for quality or defects (Perry and Perkins, 1968; Gutterman, 1976; Patzlaff, 1980).

According to Jordan and Clerk, an approach to fruit sorting is to use the terminal velocity of fruit moving in a fluid that has a density above or below the target density. Fruit with different terminal velocities will reach different depths after flowing a fixed distance in a flume and may be separated by suitably placed dividers. This approach could use water as a sorting medium, which provides huge advantages in terms of the resulting low corrosion and disposal difficulties, and the fact that it does not need any density adjustment. Additionally, this approach allows purely mechanical setting of the separation threshold by adjusting the divider positions and does not require changing the fluid density itself.

Terminal velocity at first appears to be a complex function of fruit shape, fruit size, both water and fruit temperature (not studied here) and density. The authors embarked on a study to test terminal velocity of apple in water column to determine if there was potential for terminal velocity methods in sorting industry. In particular, fruit size and density over the random ranges expected for Redspar apple variety was investigated.

In this study, fruit rising from the bottom of a water column whose density is higher than that of the fruit, was considered; but the theory and methods used are equally applicable to situations where fruit are introduced into a less dense fluid through which they fall.

MATERIAL and METHODS

Consider a fruit of mass *m*, volume *V*, diameter d, and density ρ_f (= *m*/*V*), rising in a liquid with density ρ_w (ρ_f < ρ_w) such that the largest cross-sectional area of fruit (*A*) is perpendicular to the direction of motion. The forces acting on it will be a gravitational force (F_w) downward, a buoyant force (F_b) upward, and a drag force (F_d) opposite to motion. The combination of these forces will accelerate the fruit at a rate (*a*) proportional to its mass (Crowe et al., 2001):

$$F_{tot} = ma = F_w + F_d - F_b$$

$$ma = mg + 0.5\rho_w v^2 C_D A - \rho_w V g \qquad (1)$$

where v is the fruit velocity. Dividing equation 1 by $m = V\rho_f$, gives:

$$a = g\left(1 - \frac{\rho_w}{\rho_f}\right) + 0.5\rho_w v^2 C_D A/\left(V\rho_f\right) \qquad (2)$$

In equation 2 is C_D, drag coefficient. But Mohssenin 1986 applied bellow formula for N_R>1:

$$C_D = \frac{const}{N_R^n} \qquad (3)$$

With using formula 4 in 3, equation 5 will be:

$$N_R = \frac{vD\rho_w}{\mu_w} \qquad (4)$$

$$C_D = \frac{K_4 \mu_w^n}{v^n D^n \rho_w^n} \qquad (5)$$

Replacing 5 in equation 2; equation 6 will result:

$$a = g\left(1 - \frac{\rho_w}{\rho_f}\right) + K_5 v^{(2-n)} \mu_w^n \rho_w^{(1-n)} A/\left(V\rho_f D^n\right) \qquad (6)$$

For a spherical object, *A*/*V* can be computed directly as a function of the diameter, but an apple is more hyper-ellipsoidal than spherical. According to Jordan and Clerk, by separating *A*/*V* into two parts: S_h and S_i Thus:

$$\frac{A}{V} = \frac{S_h}{S_i} = \left[A \Big/ V^{\frac{2}{3}}\right] \Big/ \left[V^{\frac{1}{3}}\right] \qquad (7)$$

and by knowing that

$$d = e\left(\frac{6V}{\pi}\right)^{\frac{1}{3}} \qquad (8)$$

Using formulas 7 and 8, in equation 6, equation 9 will result:

$$a = g\left(1 - \frac{\rho_w}{\rho_f}\right) + K_6\left(\frac{\mu_w^n \rho_w^{(1-n)} v^{(2-n)} S_h}{V^{\left(\frac{n+1}{3}\right)} \rho_f}\right) \qquad (9)$$

Setting acceleration to zero in equation 9, the terminal velocity of the fruit will be:

$$v_t = K_7 \frac{\left(\rho_w - \rho_f\right)^{\left(\frac{1}{2-n}\right)} V^{\left(\frac{n+1}{3(2-n)}\right)}}{\mu_w^{\left(\frac{n}{2-n}\right)} \rho_w^{\left(\frac{1-n}{2-n}\right)} S_h^{\left(\frac{1}{2-n}\right)}} \qquad (10)$$

Assuming water density and viscosity, equation 11 will result as:

$$v_t = K_8 \frac{\left(\rho_w - \rho_f\right)^{\left(\frac{1}{2-n}\right)} V^{\left(\frac{n+1}{3(2-n)}\right)}}{S_h^{\left(\frac{1}{2-n}\right)}} \qquad (11)$$

Formula 17 shows that the terminal velocity is directly proportion to the difference between the fruit and water densities, with unit power $\left(\frac{1}{2-n}\right)$, and volume, with $\left(\frac{n+1}{3(2-n)}\right)$ power, and shape factor, with $\left(\frac{-1}{2-n}\right)$ power, of fruits in $N_R > 1$ condition.

Redspar apple cultivar, new-planted variety in Iran were randomly hand-picked in 2007 summer season from orchard located in Horticultural Research Center, Department, Faculty of Agriculture, university of Tehran. This cultivar is also late season, red-color variety with large size and very sweet and delicious in taste.

The 40-50 fruits were transferred to the laboratory in polyethylene bags to reduce water loss during transport. The initial moisture content of fruits was determined by using dry oven method (Yagcoglu, 1999). The rest of apples were kept in cold storage at 4 ºC. All of the experiments were carried out at a room temperature, in the Biophysical laboratory and Biological laboratory of university of Tehran, Karaj, Iran.

Fruit mass was determined with an electronic balance of 0.1 g sensitively. Volume and fruit density were determined by the water displacement method (Mohsenin 1986). Projected area of the apples was determined from pictures of the fruits taken by Area Measurement System-Delta Tengland, Fig 1.

Fig. 1. Apparatus for measuring dimensional characteristics. Apple is positioned on the center of horizontal plate, directionally, under the vision of camera.

A glued Plexiglas column was constructed, height = 1200 mm and cross-section = 400 × 400 mm, shown in Fig. 2. This column was optimal, fruit diameter approximately 20% of column diameter, (Vanoni, 1975). The column was filled with tap water to a height of about 1100 mm.

Each fruit was placed on the bottom of column using a nondestructive fruit holder as shown in Fig. 2, and if any bubbles appeared on them; it was removed by rubbing the fruit. Fruit were then positioned flat (i.e., with their largest two dimensions oriented horizontally) on the bottom of column.

In order to determine rising times and terminal velocities of fruits, a digital camera, JVC (770) with 25 frames per second, recorded the moving of fruits from releasing point to the top of water column, simultaneously. Each fruit was tested three or four times. Video to frame software were used to change video film to images, subsequently to calculate coming up times and terminal velocities of fruits by knowing the fact that each picture takes 0.04 s. Then information on the trajectory of fruit moving through the water was plotted in Microsoft Excel Worksheet. Determined data were considered for modeling rising time using SPSS Software.

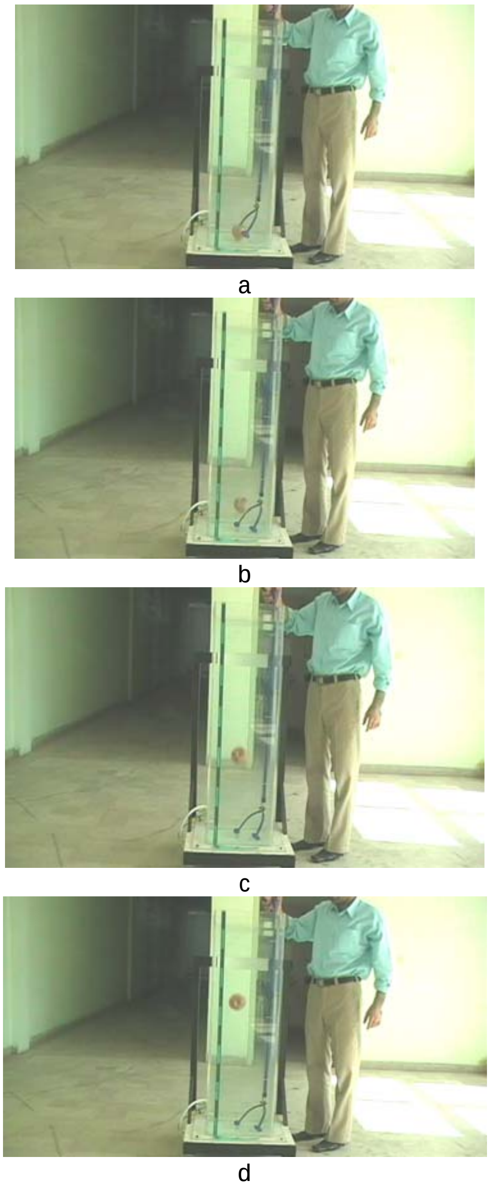

Fig. 2. Apple position in water column at four different times a: at the rest, b: after 0.5 s, c: after 1 s, and d: after 1.5 s.

RESULTS and DISCUSSION

Figure 3 shows the curves of acceleration, velocity, and depth of an 816 kg/m^3 388.8 cm3 apple rising through water column from the images. Terminal velocity (0.542 m/s) is reached in around 0.5 s, and from there the depth trajectory follows a smooth linear path. Most fruit showed little tendency to move significantly in horizontal directions.

Given the terminal velocity formula (Eq. 10) and making observation from figure 3 that v_t is reached quite quickly, one can estimate the time (T_r) taken to drop depth *x* as:

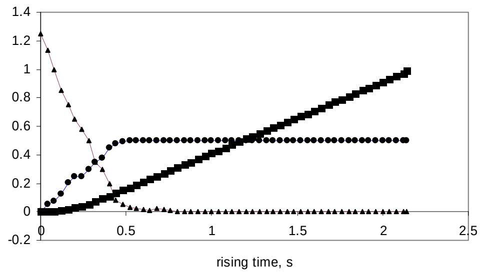

Fig. 3. Acceleration (▲), velocity (●), and depth (■) of fruit rising in water. Fruit density was set to 816 kg/m^3 and volume to 388.8 cm^3.

$$V_t = \frac{X}{T_r}$$

$$T_r = BX\left[S_h \left(\rho_w - \rho_f\right)^{(-1)} \left(V^{\left(\frac{-2}{3}\right)} \right) \right] \qquad (12)$$

where *B* is a general amplitude constant, and X is the displacement. This can be generalized to equation 11 as:

$$T_r = A\left(\rho_w - \rho_f\right)^{-b} V^{-c} S_h{}^{d} + E \qquad (13)$$

Where the parameters A, b, c, d and E take appropriate values. Parameter E is added to allow for the fact that fruit do not reach terminal velocity immediately. This model was optimized by adjusting various combinations of these five parameters to fit of the model to maximize correlation factor.

A number of models were tested, and the results are summarized in table 1. Where parameters *A*, *b*, *c*, d and E have fractional values in the table, they have been fixed to that value. The eight models investigated in table 1 have been placed in order of increasing coefficient of determination R^2.

Table 1. Comparison of models developed with different parameters and corresponding correlation factors.

Model	A	b	c	d	E	R^2
1	2.883			3.700	1.528	0.050
2	42.048	-0.930			-23.800	0.640
3	198.155		-0.977		1.444	0.750
5	9.714	-17.368		-10.262	2.329	0.000
6	92.302		-0.979	-2.579	1.336	0.770
4	170.400	-0.418	-0.597	-1.795	0.977	0.790
7	6681.034	-0.829	-0.884		1.595	0.780

All models had an offset term (*E*). Model 1, 2 and 3 were studied to found most effective parameter among volume, differences between water and fruit densities and shape factor of fruits, and were individually plotted versus rising time showed in figures 4, 5 and 6.

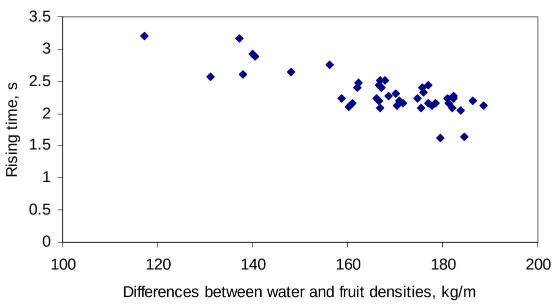

Fig. 4. Time to rise top of water column versus fruit density minus density of water for all fruit. Each fruit was measured thee or four times.

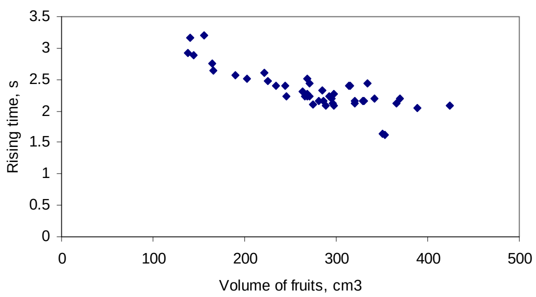

Fig. 5. Time to rise top of water column versus fruit volume for all fruits.

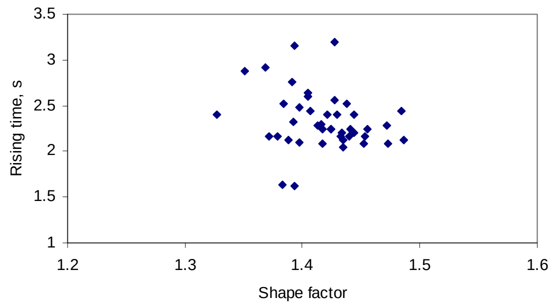

Fig. 6. Time to rise top of water column versus fruit shape factor.

Model 3 with higher R^2 (0.75) than that of model 2 (0.64) and consequently figure 4 with more regular plots than that of figure 5 showed the higher effectiveness of volume than that of differences between water and fruit densities. As shown in table 1, model 1 has the lowest correlation factor (R^2=0.05) that showed the lowest effectiveness of shape factor, irregular plots in figure 6 depicted this fact.

The effectiveness of both shape factor and differences between water and fruit densities was studied in model 4 but it was not acceptable because of R^2=0.

Model 5 had the acceptable R^2 and model 4 was that developed from the theory above and had the highest R^2, but shape factor in both models had the coefficient with negative sign (-) against that of equation 11. By abstracting shape factor in this model (model 7), there is no significant reduction in R^2:

$$T_r = 6681.034(\rho_w - \rho_f)^{-0.829} V^{-0.884} + 1.595$$

R^2=0.78

Model 7 with acceptable R^2 showed that shape factor of Redspar apple had negligible effect on its rising time. A little more negative power of volume than that of differences between water and fruit densities in model above showed more effectiveness of volume than that of differences between water and fruit densities emphasized by models 2 and 3.

Above results show that the most effective characters of Redspar apple on its terminal velocity are volume and density. This research concludes that apple fruits with approximately constant volume can be sorted based on their densities.

CONCLUSION

In this study the best model for rising time of Redspar apples was decimal points must be corrected

$$T_r = 6681.034(\rho_w - \rho_f)^{-0.829} V^{-0.884} + 1.595$$

with R^2=0.78 as function of fruit and water density and volume. Density and volume of Redspar apples were found as the most effective characters. This research concludes that apple fruits with approximately constant volume can be sorted based on their densities, and vise versa. In order to hydro-sorting of apples may be required to decrease their terminal velocity, this is possible by decreasing the density of water.

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