International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org ||Volume 7 Issue 5 Ver VII || May 2018 || PP 72-78

Development of Prediction Models of Selected Hydrodynamic Properties of Plum Fruit (Prunus domestica L.) in Water

Turker Saracoglu[1]

[1](*Department of Biosystem Engineering, Faculty of Agriculture/ Adnan Menderes University, Turkey)*

Abstract:*In this study, some hydrodynamic properties of plum fruits in water were theoretically formulated. Generalized prediction equations were developed for drag force and terminal velocity of plum fruit in water using dimensional analysis and mathematical modelling methods. Reynolds number is the most significant term for drag force. Non-linear mathematical model which is relation to predict of terminal velocity, is the best due to has got high coefficient of determination. Shape factor and differences between water and fruit densities are most effectiveness than those of volume for terminal velocity. It can be concluded that plum fruit can be sorted based on their densities and shape factors.*

Keywords: *Plum fruit, terminal velocity, drag force, dimensional analysis, mathematical modelling*

Date of Submission: 18-05-2018 Date of acceptance: 04-06-2018

I. Introduction

Plum fruit is a source of essential nutrients, vitamins and minerals. The most common types of plums are grown in P. domestica L. (European plum) and P. salicina L. (Japanese plum). While European plums are usually used as a dried or canned, the Japanese plum is used for fresh consumption. P. cerasiferaEhrh. which is known as Japanese plums are used as rootstock in many countries. It has known as ‘‘Can plums’’ in Turkey [1].

In the world, plum production is about 11.3 million tons in 2014. Nowadays, China is the one of the most important plum-producing country in the world. Approximately, half of world plum production is done in the China which produces about 6.2 million tones. Then, Serbia, USA, Romania and Turkey, respectively [2]. Plum fruit is grown in Turkey with a production rate of 274,136 tones [3].

In handling and processing of agricultural products often air or water is used as a carrier for transport or for separating the desirable product from the unwanted materials. Use of water is more economical transport or less injury to such fruits and vegetables [4].

Many different methods are used for classification of agricultural products. Electrical sizing mechanisms are overly expensive and mechanical sizing mechanisms are slow to react. Also, near-infrared technologies are expensive, and the calibrations and maintenance they require tend to remain outside the skills of packing house staff. Density sorting of products is not new, and patents and publications in the potato industry extend from the 1950’s through to the present day. Other products, such as citrus, blueberries, and tomatoes have also been sorted by flotation techniques for quality or defects. In sorting based on density, fruit are placed in solution such as salt brine or alcohol-water [5].

The hydrodynamic properties such as terminal velocity and drag force are needed for hydro-conveying and hydrodynamic separation of materials.

Fruit with different terminal velocities would reach different depths after flowing a fixed distance in a flume and may be separated by suitable 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 separation threshold by adjusting the divider position and no change in fluid density is required [6].There are some researches on terminal velocity which has focused on apricot [6], kiwi [7] and tomato [8].

The objective of this study was to develop generalized prediction equations for drag force and terminal velocity of plum fruit in water using dimensional analysis and mathematical modelling methods. The results provide useful data to be used by engineers in the design of suitable equipment and machines

II. Materials and Methods

The plum fruits were randomly hand-picked in 2017 spring season from an orchard located at Sultanhisar-Aydin province. Samples were transferred to the laboratory in polyethylene bags to reduce water loss during transport.

To determine the average size, three linear dimensions, namely length, L, width, W, and thickness, T, and the projected area of the fruits digital images of each fruit (Fig. 1) were captured and then analyzed using Image Tool 3.0 image processing software.

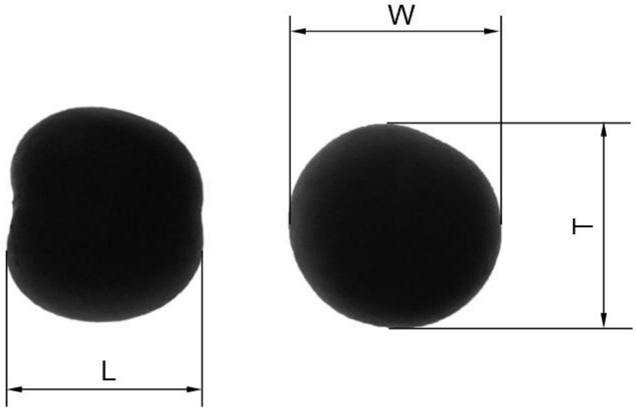

Figure 1 Three linear dimensions of the fruit on the digital image

The geometric mean diameter (D_g) in mm, sphericity (ϕ) in decimal, and shape factor (S_h) were calculated by using the following relationship [4,6].

$$D_g = (L \cdot W \cdot T)^{\frac{1}{3}} \quad (1)$$

$$\phi = \frac{(L \cdot W \cdot T)^{\frac{1}{3}}}{L} \quad (2)$$

$$S_h = \frac{A_p}{V^{\frac{2}{3}}} \quad (3)$$

where, L is length, W is width, T is thickness in mm, A_p is projected area of the fruit which is perpendicular to the direction of motion in m^2 and, V is fruit volume in m^3.

The average true density was determined using the water displacement method. The volume of water displaced was found by immersing a weighed quantity of quince fruit in the water [4]. The fruit mass was determined with an electronic balance of 0.1 g accuracy.

To determine some hydrodynamic properties of plum fruits, a 1500 x 400 x 400 mm^3 glued glass column was used (Fig. 2).

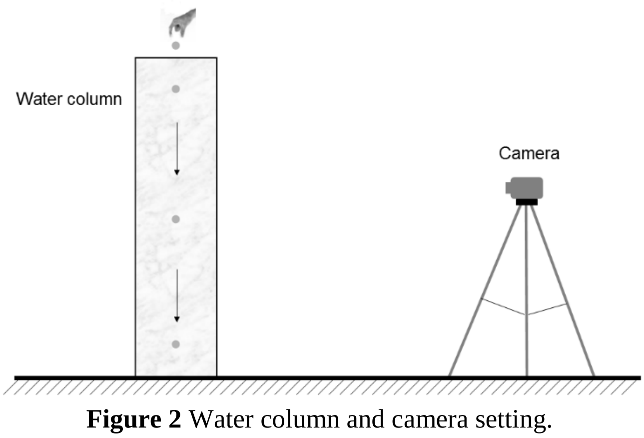

Figure 2 Water column and camera setting.

This column was suitable to fruit diameter in approximately 20% of tank diameter [5]. The column was filled with tap water to a height of about 1200 mm. Each fruit was placed on the top of column. Any bubbles appearing on them were removed by rubbing. The movement of the fruit in the water was recorded with a digital camera, Casio EX FH20. Video to frame software was used to convert the video film to individual images and, subsequently, to calculate fall down time in water and terminal velocity of fruits. In the tests 25 samples of plum fruits were used to determine some hydrodynamic properties.

Considering plum fruits in water, the forces acting on the sample will be the gravitational force (F_g) acting downward, buoyant force (F_b) acting upward, and drag force (F_d) acting opposite to the direction of motion. These forces were calculated using the following equations [4, 9].

$$F_g = m \cdot g \tag{4}$$

$$F_b = \rho_w \cdot V \cdot g \tag{5}$$

$$F_d = C \cdot A_p \cdot \frac{\rho_w \cdot {v_t}^2}{2} \tag{6}$$

where, m is the mass of fruit in kg, g is gravitational acceleration in m s^{-2}, ρ_w is water density in kg m^{-3}, C is the dimensionless drag coefficient, and v_t is terminal velocity in m s^{-1}. Drag coefficient was calculated from the following relationship [4].

$$C = \frac{2 \cdot m \cdot g \cdot (\rho_f - \rho_w)}{v_t^2 \cdot A_p \cdot \rho_f \cdot \rho_w} \tag{7}$$

where, $\rho_f$is the true density of the fruit in kg m^{-3}.

Dimensional analysis of drag force

Dimensional analysis develops general forms of equations that describe natural phenomena and is useful tool for developing prediction equations for complex physical systems. Dimensional analysis applied to a particular phenomenon is based on the assumption that certain defined variables, are the independent variables of the problem, and that all other variables, other than the dependent variable, are redundant or irrelevant. This is considered to be the initial step for studying physical phenomena. The second step in the process is formation of a complete set of dimensionless products of variables. This reduces the physical quantities pertinent to a system to dimensionless group called π terms [10].

Buckingham's π theorem was used to predict the drag force and this theorem requires the pertinent, non-redundant quantities affecting the physical system. The quantities affecting drag force are listed in Table 1.

Table 1. Variables affecting drag force

Type of variable	Symbol	Variable	Dimension	Unit
Dependent	F_d	Drag force	M L T^{-1}	kg m s^{-1}
	v_t	Terminal velocity	L T^{-1}	m s^{-1}
	D_g	Geometric mean diameter	L	m
Independent	υ_w	Kinematic viscosity of water	L^2 T^{-1}	m^2 s^{-1}
	ρ_w	Water density	ML^{-3}	kg m^{-3}
	L	Length of the fruit	L	m

Considering variables which related drag force, the relation can be written as in the following form

$$F_d = f(v_t, D_g, \upsilon_w, \rho_w, L) \tag{8}$$

The resulting dimensionless groups are given in Table 2.

Table 2. Dimensionless group for predicting the drag force and their significance

Dimensionless terms		Significance
π term	**Function**	
π_1	$F_d / \rho_w v_t^2 D_g^2$	Ratio of drag force to inertia force
π_2	$v_t D_g / \upsilon_w$	Reynolds number, R_e
π_3	D_g / L	Sphericity, ϕ

The dependent π term, drag force, can be written as a function of dimensionless groups as in the following theoretical form:

$$\frac{F_d}{\rho_w v_t^2 D_g^2} = f(R_e, \phi) \tag{9}$$

The motion of the fruit disturbs the fluid around it, and causes fluid flow. This fluid flow results in friction, and this frictional drag exerts a force on the fruit.

Since the frictional resistance to flow is due to viscous effects, it is expected that the viscosity will be important in determining the frictional force. In addition, the drag coefficient is expected to depend on the velocity of the fruit v_t, since a higher speed could result in a larger force.

Mathematical modelling of terminal velocity

Kheiralipour et al. [5] have been reported that the terminal velocity is directly proportional to the difference between fruit and water densities, volume, and shape factor of fruits in Re>1 condition. Accordingly linear and non-linear mathematical models which are relation to predict of terminal velocity based on the difference between water and fruit density, fruit volume and shape factor values as independent variables were developed. The relationship between results of these models and values of measured terminal velocity was determined.

The models have been created based on the hypothesis which linear and non-linear relationship between terminal velocity and other variables. Logarithmic transformation has been applied for all variables to the development of the non-linear model

III. RESULTS AND DISCUSSIONS

Dimensional analysis of drag force

The following prediction model was developed for drag force

$$F_d = 12641.54\,(R_e)^{-1.271}(\phi)^{-0,458}\rho_w v_t^2 D_g^2 \tag{10}$$

The results from the regression analysis are given in Table 3. As seen from the table, developed model is significant and each term in the regression equation is significant at 99% probability level. Reynolds number is the most significant term since it was the first term that was brought into the model and it helps to explain 82.87% of the variation in the data alone.

Table 3. Result of multiple regression analysis for the drag force

π term	Exponent	Standard error	R^2, %
Log (constant)	4.102	0.443	-
$v_t D_g / \upsilon_w$	-1.271	0.123	82.87
D_g/L	0.458	0.789	88.27

The drag force model developed can be written in a simplified form by taking the water density as 998.2 kg m^{-3} and the kinematic viscosity of water as υ_w=1.01x10^{-6} m^2 s^{-1} for 20°C water temperature:

$$F_d = 0.30\, v_t^{0,729} D_g^{0,271} L^{0,458} \tag{11}$$

As seen from the model, the drag forces are affected by the terminal velocity and dimensions of fruit. The model gives satisfactory result within the range of operational drag force variables and it is valid for the following conditions:

$0.100 \le v_t \le 0.168$ m s^{-1}
$0.0266 \le D_g \le 0.0343$ m
$0.0254 \le L \le 0.0326$ m

The prediction model was verified against the data obtained in the laboratory and the comparison is illustrated in Fig. 3. As can be seen, close agreement between the model and the measured data exists with a correlation of 95.3%.

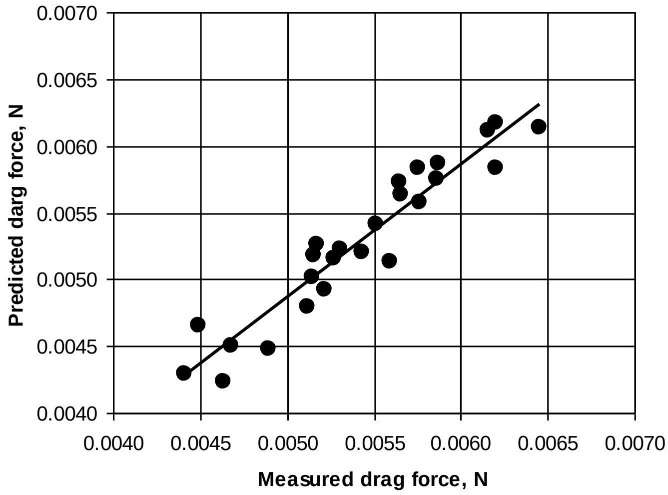

Figure 3 Comparison of the measured and predicted drag force values

Mathematical modelling of terminal velocity

Fig. 4-6 shows the relationship among shape factor, differences between water and fruit densities and fruit volume versus terminal velocity of fruit. Shape factor and differences between water and fruit densities are high effectiveness than those of volume.

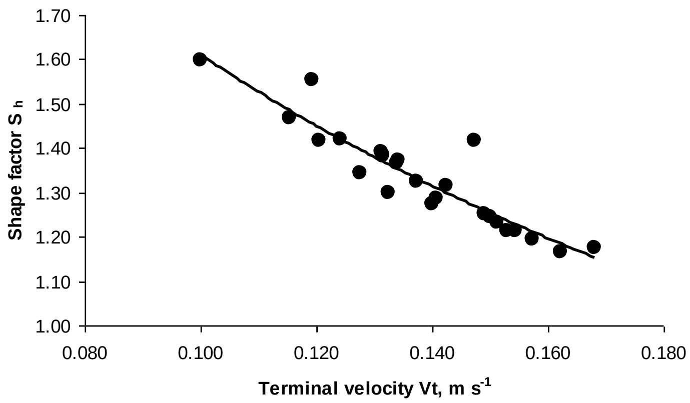

Figure 4 Shape factor versus terminal velocity of fruits

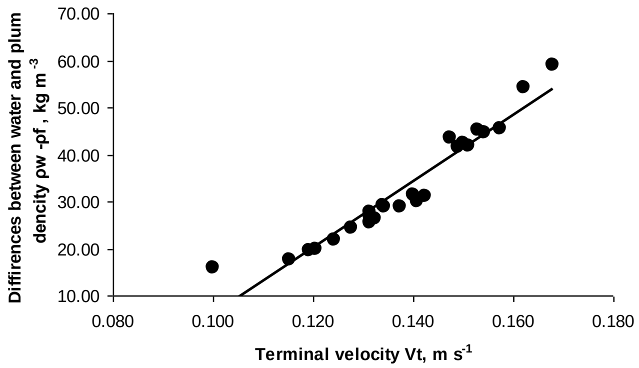

Figure 5 Differences between water and fruit density versus terminal velocity of fruits

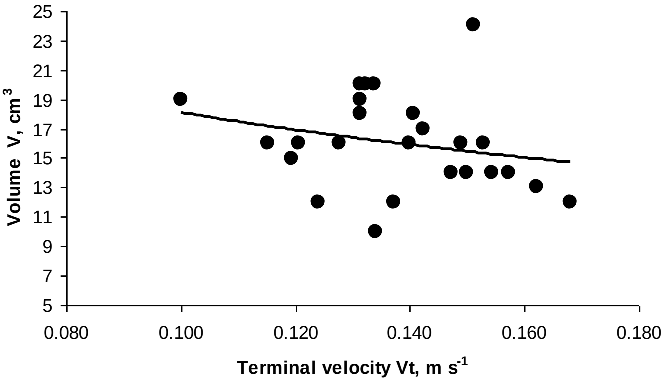

Figure 6 Fruit volume versus terminal velocity of fruits

The results from the regression analysis are given in Table 4. As seen from the table, developed model is significant and each term in the regression equation is significant at 95% probability level. Differences between water and fruit densities is the most significant term since it was the first term that was brought into the model and it helps to explain 94.9% of the variation in the data alone.

Table 4. Result of multiple regression analysis for the terminal velocity

Terms	Exponent	Standard error	R^2, %
Log (constant)	1.144	0.07053	-
ρ_w-ρ_f	0.237	0.029838	94.9
V	-0.019	0.024423	94.9
S_h	-0.404	0.124673	96.6

Non-linear mathematical model which is relation to predict of terminal velocity, is the best due to it has got high coefficient of determination (R^2=97%). This model is presented as

$$v_t = 0.0585\,(\rho_f - \rho_w)^{0.237} V^{-0.019} (S_h)^{-0.404} \qquad (12)$$

As seen from Fig. 7, good agreement between the model and the measured data was achieved with a correlation coefficient of 98.6%. It is clear that the model shows a good agreement between the predicted data and measured terminal velocity.Mirzae et al. [6] the similar model was developed for three apricot varieties with 71%, 71%, and 73% determination coefficients.

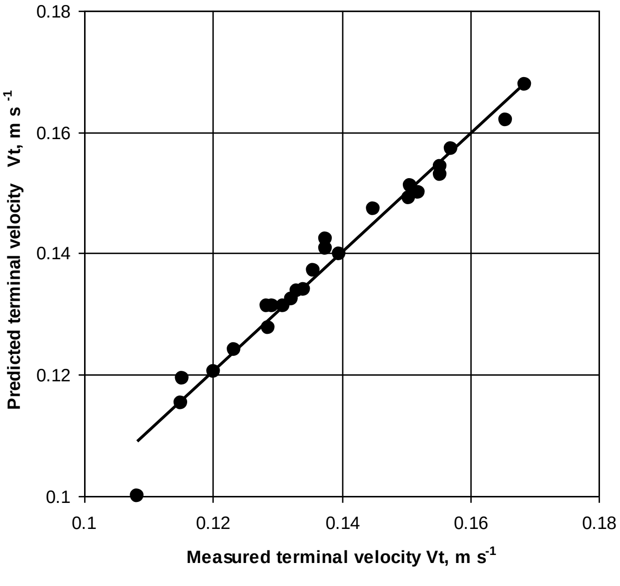

Figure 7 Comparison of the measured and predicted terminal velocity values

In this study, it has been shown that drag force and terminal velocity can be estimated based on the data obtained from two orthogonally taken photographs, measured mass and volume of plum fruit.

IV. CONCLUSIONS

The following conclusions were drawn from this study:

i. In this study, drag force and the terminal of plum fruit in water were theoretically formulated and determined experimentally using water column.
ii. Reynolds number is the most significant term for drag force. It helps to explain 82.87% of the variation in the data alone.
iii. Non-linear mathematical model which is relation to predict of terminal velocity, is the best due to has got high coefficient of determination.
iv. Shape factor and differences between water and fruit densities are most effectiveness than those of volume for terminal velocity.
v. This research concludes that plum fruit can be sorted based on their densities and shape factors.

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Turker Saracoglu "Development of Prediction Models of Selected Hydrodynamic Properties of Plum Fruit (Prunus domestica L.) in Water "International Journal of Engineering Science Invention (IJESI), vol. 07, no. 05, 2018, pp 72-78