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Studies on Flow Rates of Wheat through Rectangular Orifices

Farhad Khoshnam[1], Moslem Namjoo[1]✉, Mohammad Reza Kamandar[1]

[1] Department of Mechanical Engineering of Biosystems, Faculty of Agriculture, University of Jiroft, Jiroft, Iran.

✉ Corresponding author: moslem.namjoo@gmail.com

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ABSTRACT

This experiment was conducted to examine how factors, including orifice area, aspect ratio, grain moisture content, and grain variety, influence the flow rate. Flow rates were measured for samples passing through rectangular horizontal orifices. An adjustable rectangular orifice with a maximum width of 50 mm and a length of 76 mm was used, with the shorter side varied in increments of 10 mm, ranging from 10 mm upward. The flow rate of wheat was significantly influenced by the orifice area and the moisture content. The decrease in flow rate with an increasing moisture content can be well described by a second-degree polynomial equation. The coefficients for several derived equations, which predict wheat flow rate through orifices based on measured parameters and their combinations, were determined. A linear relationship is found between the flow rate (m^3/h) and the product of the effective orifice area (A_e, cm^2) and the square root of ($g \cdot D_e$), i.e., $A_e\sqrt{gD_e}$. The flow rate of wheat varieties for a given dimension of orifice decreased as the aspect ratio increased. Flow rate increased as the area of the orifice increased from 1.15 to 23.15 cm2; however, a higher flow rate was obtained at a lower aspect ratio. The variation in flow rates among wheat varieties was minimal across the different orifice sizes. This study establishes a universal correlation based on the Beverloo and ASABE models that accurately ($R^2 > 0.99$) predicts the flow of wheat through rectangular orifices in a hopper.

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INTRODUCTION

The flow of granular materials discharging under their own weight from a hopper is a topic that has been widely studied in research. Therefore, the discharge of granular materials from hoppers has received considerable attention in previous research. Information on the flow rate of grain through an opening in a bin, hopper, or other grain-handling system is essential for correctly sizing the opening, ensuring proper control of grain movement to and from storage or holding bins. One of the most widely used correlations for predicting the discharge rate through flat orifices was proposed by Beverloo et al. and is expressed as follows (Beverloo et al., 1961):

$$Q = CA_e\sqrt{gD_e} \qquad (1)$$

Where Q= volume flow rate cm3/s; C= dimensionless empirical discharge coefficient (typically ~0.58, nearly universal for many materials), g= the acceleration of gravity, cm/s2; $D_e = D_h - 1.4d$ is effective hydraulic diameter, cm; Dh= hydraulic diameter, cm; d= average size of particle, cm; and Ae= effective (or net) orifice area calculated from De ,cm2. ASABE established a standard for the flow of grains and seeds through orifices, providing an equation to predict their volumetric flow rate, as shown in Eq. (2).

$$Q = C_0 A D_h^n \qquad (2)$$

Where, Q = volumetric flow rate, m3/h; A = orifice area, cm2; Dh = hydraulic diameter of the orifice, cm; Co = coefficient, m3/cm(n+2)h, which varies depending on the crop type, moisture content, and orifice hydraulic diameter; n = exponent ranging between 0.5 and 1.0. Rosentrater defined flowability as the capacity of granular solids and powders to flow freely during discharge from storage or transportation containers (Rosentrater, 2006). Flowability is an inherent property of a material, resulting from the combined effects of several interacting factors that simultaneously influence its flow behavior. Teunou and Fitzpatrick emphasized that a flow function, rather than a flow index, should be used to describe the effects of temperature and relative humidity on the flowability of food powders (such as tea, wheat flour, and whey permeate), since flowability is a multivariate phenomenon (Teunou & Fitzpatrick, 1999). The study by Teunou and Fitzpatrick on the flowability of food powders found that the instantaneous flow function increased with temperature and relative humidity (20-66%), although these factors had a less pronounced effect on the flowability of wheat flour (Teunou & Fitzpatrick, 1999). Chang et al. observed that the flow rates of sorghum and wheat increased as their moisture content decreased (Chang et al., 1984). Using two grains (barley and wheat) and two oilseeds (rapeseed and flax) through square, circular, and rectangular orifices, Moysey et al. observed that flow rates were influenced by moisture content but not by the bulk density of the grain in the bin (Moysey et al., 1988). Alizadeh et al. investigated the effects of orifice area, de-awning percentage, and paddy grain moisture content on the flow rate (FR) and variations in flow rate (VFR) of paddy grains through a horizontal hopper orifice (Alizadeh et al., 2012). The results indicated that both FR and VFR were significantly ($p < 0.01$) influenced by the orifice area, de-awning percentage, and paddy moisture content. An increase in orifice area from 12.08 to 34.81 cm^2 resulted in a higher flow rate (FR). Conversely, the maximum volumetric flow rate (VFR) was observed at the minimum orifice area. As the moisture content of the paddy increased from 8.67% to 15.06% (w.b.), the flow rate (FR) decreased for both awned (87% of grains) and de-awned (82% of grains) samples. Conversely, the volumetric flow rate (VFR) exhibited a positive correlation with moisture content. The relationship between moisture content and the volumetric flow rate (Q) of Egusi melon seeds (Colocynthis citrullus) in horizontal hopper orifices was established by Asoegwu et al. (Asoegwu et al., 2015). They observed an inverse relationship between moisture content and volumetric flow rate (Q). For both circular and square orifices, Q decreased as moisture increased from 6.76% to 18.9% d.b., with the circular orifice showing a greater reduction

(5.36%) but maintaining a higher absolute flow rate than the square orifice (4.36% reduction). A separate investigation analyzed the influence of particle size and moisture content on the flow characteristics of ground corn. Excess moisture also induces stickiness in flour, which hinders the inter-particle sliding necessary for flow. The influence of particle size and moisture content on the flowability of corn flour was investigated by Jadhav et al. (Jadhav et al., 2017). Using flow rate measurements, particle image velocimetry (PIV), and discrete element modelling (DEM), Fullard et al. investigated the dynamics of granular flow in a rectangular silo with two symmetrically placed exit openings (Fullard et al., 2019). Mustard seed flow within a Perspex silo was characterized by analyzing high-speed video recordings with Particle Image Velocimetry (PIV), yielding data on velocity, velocity divergence, and shear rate. Experimental measurements of grain discharge from an inclined quasi-2D silo were conducted, including the mass flow rate, average grain exit velocities, and the packing fraction along the orifice at different tilt angles. While a simple model is introduced to explain the observed behavior, a deeper analysis of the velocity vector fields could reveal the mechanisms through which inclination controls flow speed, extending beyond the mean-field framework presented here (Ali et al., 2012). This study aimed to determine the flow rate of wheat grains through rectangular orifices and to evaluate the effects of variety, orifice size (aspect ratio), and moisture content. Another purpose of this study is to compare the existing models to predict the mass flow or volume flow of wheat and also to present a new model if necessary. Volume flow rate was selected over mass flow rate as the dependent variable because an orifice directly controls volumetric flow.

MATERIALS AND METHODS

Sample Preparation

Mehregan and Setareh wheat varieties were prepared from the South Kerman Agricultural Research Center for testing. Before testing, the sample was purified by sieving to remove small foreign material and damaged grains, followed by the manual removal of larger foreign objects.

Moisture Content

Moisture content was determined by weighing 10 g of the wheat varieties, before and after drying in an oven at 130˚C for 19 hours. The moisture content of the wheat samples was deliberately varied to facilitate data collection at specific moisture intervals. Hydration was achieved by adding water directly to the samples and mixing them until a homogeneous consistency was attained. Following conditioning, all seeds were packaged in high-density polyethylene (HDPE) bags. The bags were sealed, labeled, and stored at 5°C. Equation 3 was used to calculate the amount of distilled water to be added (Sacilik et al., 2003).

$$Q_m = \frac{W_i\,(M_f - M_i)}{100 - M_f} \tag{3}$$

Where Qm = mass of water added, g; Wi = initial mass of the sample, g; Mi = initial moisture content of the sample, % w.b. and Mf = final moisture content of the sample, % w.b. To confirm the target moisture level was reached, the moisture content of the samples was tested after hydration using the standard method described above. Table 1 summarizes the distilled water quantities used for seed conditioning and the resulting final moisture contents for the two varieties. The moisture content was maintained below 43% w.b. to prevent the onset of surface moisture and particle adhesion.

Table 1. Quantities of distilled water added for seed conditioning.

Variety	Wi (g)	Mi (%)	Qm (g)	Mf (%)
Mehregan	3267	13.3	300	20.6
	3267	13.3	661	27.9
	3267	13.3	1104	35.2
	3267	13.3	1659	42.5
Setareh	3157	12.2	286	19.5
	3157	12.2	630	26.8
	3157	12.2	1049	34.1
	3157	12.2	1573	41.4

Experimental Procedure

The experimental apparatus is a cone-shaped hopper with a flat bottom (200 mm × 200 mm) and adjustable rectangular orifice with a maximum width of 50 mm and length of 76 mm. The hopper was made of Plexiglas with a thickness of 0.9 mm, the angle of the hopper wall was 71.5 degrees, the entrance opening was 300 × 300 mm and the height was 300 mm. The hopper was placed on a framework with a height from the ground and a pan underneath the sliding gate (Fig. 1). A movable rectangular plate was integrated into the hopper base to allow for adjustment of the gate size. The plate can move forward and backward to provide the desired gate width. The gate size of the hopper had constant length (76 mm) and variable width. Five width gates ranging from 10 to 50 mm with increments of 10 mm were used in the experiments. Therefore, the area of the orifice was obtained in five levels of 7.6, 15.2, 22.8, 30.4 and 38.0 cm2. The aspect ratio of a rectangular orifice is the ratio of the length of the longer side (76 mm) to the length of the shorter sides (10, 20, 30, 40, 50 mm). Preliminary tests showed that the selected wheat varieties flow well within this size range, without arching or clogging. Therefore, the aspect ratios were calculated 7.6, 3.8, 2.5, 1.9 and 1.5. The gate size was then set to a specific width, which was measured and controlled using a caliper. Following size adjustment, a slat was inserted to seal the gate and prevent material loss during the placement and compaction phases. The test was initiated by opening the gate (by remove the slat) to allow the material discharge. The gate was horizontal and centered at the bottom. A contributing factor is that particles near the orifice periphery overhang the edge, reducing the effective flow area compared to the physical orifice size.

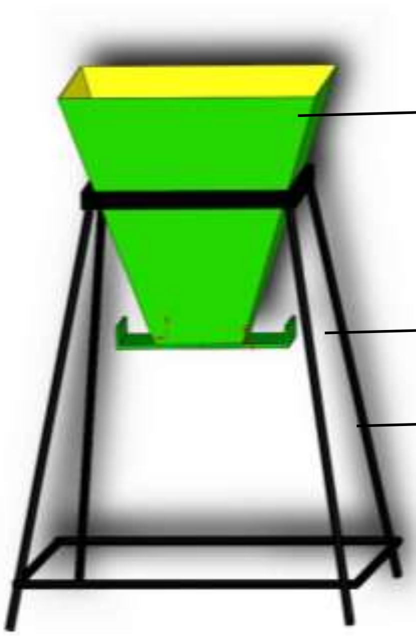

Figure 1. The developed experimental hopper

Mass Flow Rate

For flow rate testing, a sample was removed from 5°C storage and equilibrated on a flat surface for 24 hours to reach ambient laboratory temperature. Mass flow rate, defined as the mass of a substance passing a point per unit time, was measured in grams per second (g/s) in this study. To calculate the mass flow rate, the hopper was filled with material and discharged through the fully opened sliding gate (10 kg), with the time recorded by a stopwatch. The mass flow rate (g/s) was calculated by dividing the mass of the discharged sample by the recorded discharge time. Volumetric flow rate (cm3/s) is obtained from the ratio of mass flow rate (g/s) to bulk density (g/cm3) of seeds. To determine the bulk density of seeds, 50 g of each variety was poured into a graduated cylinder and the volume obtained by the cylinder was 41 cc for Mehregan variety and 42 cc for Setareh variety. Bulk density is obtained by dividing mass by volume. The bulk density of Mehregan and Setareh varieties was 1.22 g/cm3 and 1.19 g/cm3, respectively.

Experimental Design

The initial moisture content averaged 13.3% w.b. for the Mehregan wheat variety and 12.2% w.b. for the Setareh variety. Flow properties of wheat varieties were studied by making five levels of moisture content for them. In the first test, effects of the type of variety (at two levels of Mehregan and Setareh) and aspect ratio of orifice (at five levels of 7.6, 3.8, 2.5, 1.9 and 1.5) were evaluated at constant moisture content. The experiment was conducted using a randomized complete block design (RCBD) with a 10-treatment factorial arrangement and five replications. In the second test, flow rate was studied as influenced by the type of variety (at two levels of Mehregan and Setareh) and moisture content (at five levels of 13.3, 20.6, 27.9, 35.2 and 42.5%w.b. for Mehregan variety and 12.2, 19.5, 26.8, 34.1 and 41.4% for Setareh variety) at constant aspect ratio. Data were analyzed using analysis of variance (ANOVA) in SPSS 16, and mean comparisons were performed using Duncan's method at the 5% probability level.

RESULTS AND DISCUSSION

The analysis of variance (Table 2) indicated that the factors area (A) and moisture content (M) had a highly significant effect on the flow rate at the 1% significance level, indicating their dominant roles in determining flow characteristics. The interaction between variety and moisture (V×M) was significant at the 5% level, suggesting that the response of flow rate to changes in moisture varies among varieties. In contrast, the main effect of variety (V), as well as the interactions V×A, A×M, and V×A×M, were not statistically significant, indicating minimal contribution to variations in flow rate. Overall, the findings indicate that flow rate is mainly governed by the effects of area and moisture, with a secondary influence arising from the interaction between variety and moisture. The effect of grain flow rates for a common barley variety through square and circular orifices was investigated. The results showed that grain moisture content, as well as the shape and size of the orifice, had a significant influence on the grain flow rate(Haff, 1983). Kumar et al. investigated key factors affecting the design of seed boxes for grain planting machines (Kumar et al., 2022). Their experiments were conducted on wheat and oats using circular and square horizontal notches in three sizes: 12.56, 16.00, and 28.26 cm². The results indicated that the notch size, shape, and position, as well as the type of grain, had a statistically significant effect ($p < 0.05$) on the grain delivery rate.

Table 2. The analysis of variance for the effect of test factors on flow rate

Source of variations	DOF	Sum of squares	Mean squares	F Value
Variety (V)	1	2227.633	2227.633	0.056 ns
Area (A)	4	5882192.114	1470548.029	0.000**
Moisture (M)	4	383447.269	95861.817	0.000**
V×A	4	1626.215	406.554	0.604 ns
V×M	4	8002.271	2000.568	0.013*
A×M	0	.000	-	-
V×A×M	0	.000	-	-
Error	82	48588.979	592.549	-

** Significant at 1% level, * Significant at 5% level, ns Non-significant

Area of Orifice

Figure 2 presents the results indicating the effects of effective area of orifice and variety on flow rate. As the effective area of orifice increased for each variety, the flow rate values increased. Similar trends were obtained for flow rate as the effective area of the orifice was increased for each variety. Below are the equations that model how flow rate varies with the effective area of orifice for each variety.

For Mehregan $Qv = 0.149\ Ae$, $R^2 = 0.9984$ (4)

For Setareh $Qv = 0.150\ Ae$, $R^2 = 0.9994$ (5)

Where QV is the flowing rate of wheat grains (m^3/h) and A is area of orifice (cm^2).

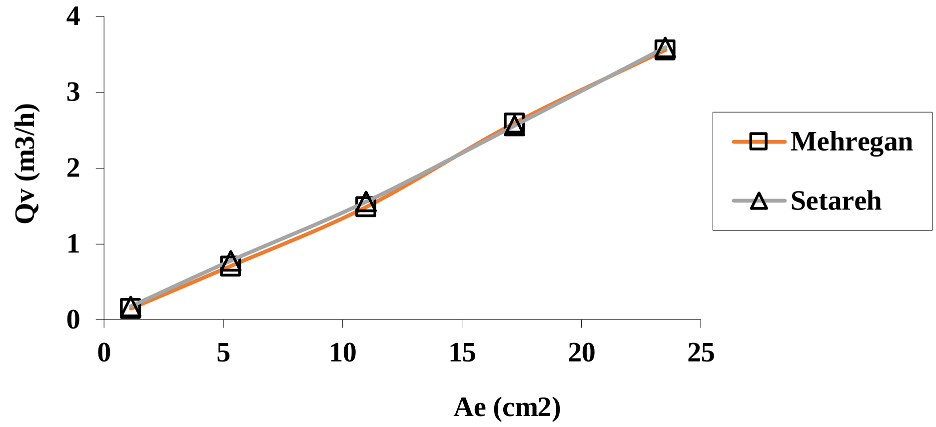

Figure 2. Flow rate variation with effective area of orifice and varieties

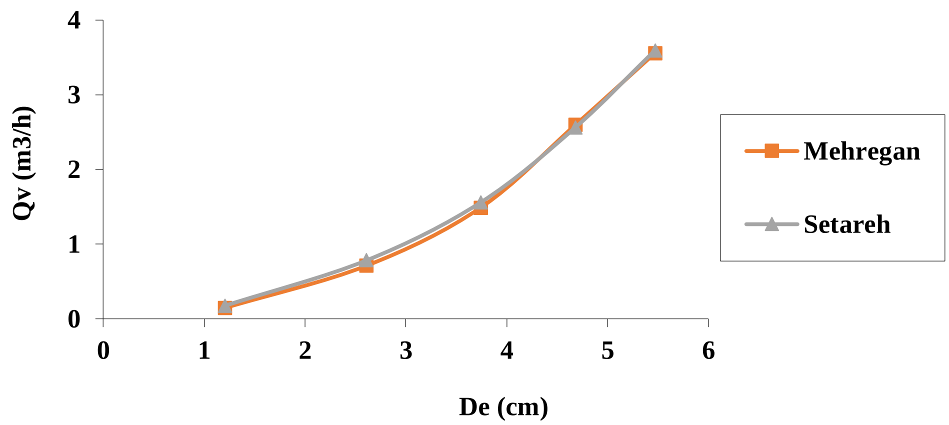

Figure 3. Flow rate variation with effective hydraulic diameter and varieties

The flow rate versus effective hydraulic diameter curves, plotted on log-log scales, were nearly linear for both wheat varieties. Consequently, the flow rate can be modeled by the following function of effective hydraulic diameter:

$$Q_v = \alpha D_e^{\beta} \quad (6)$$

where QV is the flowing rate of wheat grains (m3/h), De is effective hydraulic diameter (cm) and α & β are coefficients to be determined experimentally. It can be seen that the flow rate increases with the increase of hydraulic diameter for both varieties (Fig. 3). The presence of a larger orifice hydraulic diameter is often indicative of a larger orifice or flow passage. It allows more grains to move through without excessive friction or blockages. Additionally, a larger hydraulic diameter led to a reduction in the probability of arching or clogging in the orifice. This is due to the increased space available for grain flow, which decreases the likelihood of arch formation over the opening.

Flow rate- orifice hydraulic diameter relationships for each variety are expressed by the following equations.

For Mehregan	$Q_v = 0.096 D_e^{2.116}$,	$R^2 = 0.999$	(7)
For Setareh	$Q_v = 0.112 D_e^{1.979}$,	$R^2 = 0.998$	(8)

The coefficients for Equation (7), which models the volume flow rate of egusi-melon based on the equivalent orifice diameter, were obtained from Asoegwu et al. (Asoegwu et al., 2015). In range of moisture content 6.76 to 18.9% for square orifice the coefficients were obtained 0.0625<α<0.0231 and 2.3727<β<2.8459. These coefficients were obtained 0.0271<α<0.0566 and 2.571<β<2.835 for corn and square orifice in range of moisture content 12.3 to 22.3% (Chang et al., 1984).

Validity of Beverloo's law

If we plot flow rate (Q) against the $A_e\sqrt{gD_e}$, the slope of the resulting line will be the discharging coefficient (C), which can then be computed.

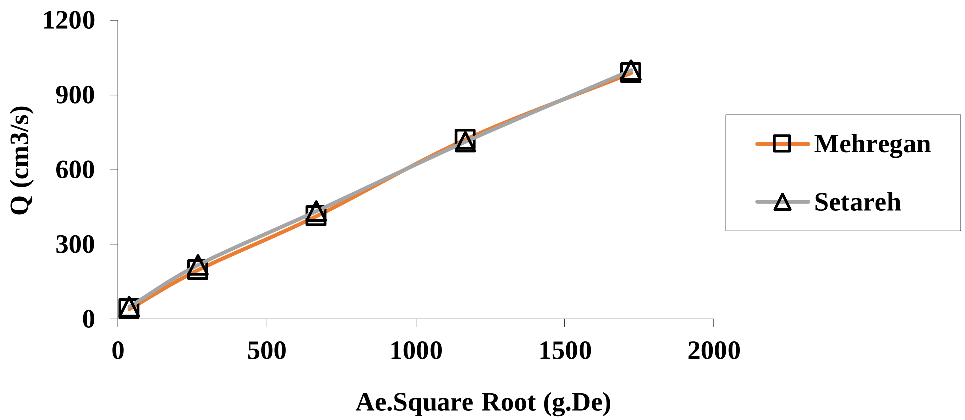

Figure 4. Flow rate vs. $A_e\sqrt{gD_e}$ using correlation recommended by Beverloo et al. (Beverloo et al., 1961).

For Mehregan	$Q = 0.593 A_e\sqrt{gD_e}$,	$R^2 = 0.998$	(9)
For Setareh	$Q = 0.598 A_e\sqrt{gD_e}$,	$R^2 = 0.996$	(10)

Both R2 values are extremely high, indicating excellent agreement between the empirical equation and measured data. The discharge coefficients (C) of 0.593 and 0.598 are very close in magnitude, suggesting that both structures exhibit similar hydraulic behavior and energy loss characteristics. The slightly higher C for Setareh implies marginally greater discharge efficiency compared to Mehregan. Overall, the consistency of these results confirms the reliability of the proposed equations in predicting discharge performance for similar hydraulic conditions.

ASABE Equation

The coefficients C_0 and n in Eq. (2) were determined by log-transforming the equation and fitting it via linear regression of log (Q) – log (Ae) against log (Dh). The resulting regression yielded the following coefficient and exponent values:

For Mehregan	$Q = 0.135 A_e D_h^{0.456}$,	$R^2 = 0.998$	(11)
For Setareh	$Q = 0.130 A_e D_h^{0.467}$,	$R^2 = 0.998$	(12)

The above relations show that the flow rate increases in proportion to the area of the orifice, but not in proportion to the hydraulic diameter. This suggests that optimizing flow rate by changing hydraulic geometry yields more benefit by increasing area than by increasing diameter - though both are beneficial to flow rate, the area has a stronger immediate impact. In other words, doubling Ae will double Q (all else being equal), but if Dh is doubled, Q increases by a factor of 2^0.4 (approximately 1.32), not by a full factor of 2.

Aspect Ratio

According to Fig. 4, for both varieties, the flow rate decreases significantly with an increase in aspect ratio. This dramatic reduction is primarily due to the smaller area of orifice and the different internal physical properties of the grains in the hopper's arching zone configurations. Near the orifice, there are stagnant zones and arching zones at higher aspect ratios (Narrower gates). In cases with lower aspect ratios (Wider gates), the grains are more mobile in the arching zone than in other cases. As shown in Fig. 4, when the aspect ratio increased from 1.5 to 7.6, the QV decreased by approximately 96% (from 3.555 to 0.146 m³/h) for the Mehregan variety and by approximately 95% (from 3.594 to 0.178 m³/h) for the Setareh variety, indicating a slightly higher QV for the Setareh variety. The following equations present the relationships between the flow rate, and aspect ratio of orifice for each variety.

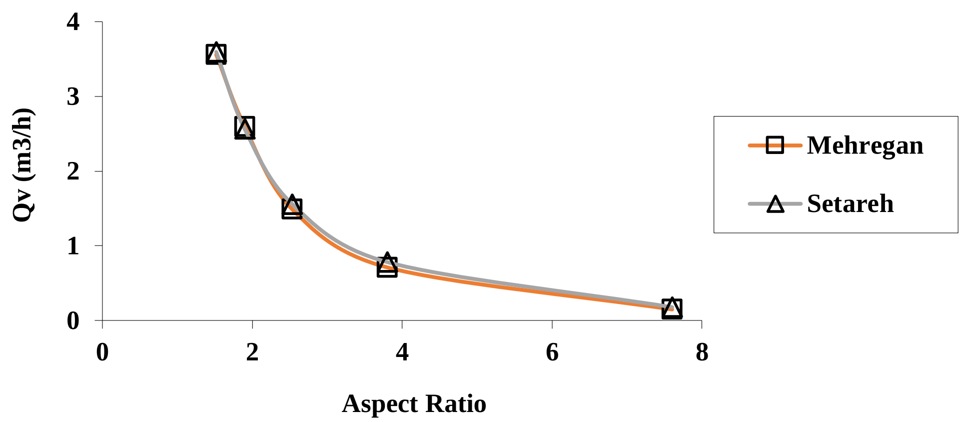

Figure 5. Flow rate variation with aspect ratio and varieties

For Mehregan	Qv = 6.30 e-0.511 AR ,	R^2 = 0.962	(13)
For Setareh	Qv = 6.02 e-0.48 AR ,	R^2 = 0.956	(14)

where QV is the flowing rate of wheat grains (m3/h) and AR is aspect ratio of orifice. The aforementioned fitting equations appear to conform to an exponential model, namely Qv = a e-b. AR, where a and b represent constant values. It is evident that as the Aspect Ratio (AR) value, denoted by b/a, increases, the grain flow rate experiences a decline. At elevated levels of AR, the flow rate approaches a state of zero. The maximum flow rate will occur at the minimum parameter AR (=1, i.e,. squared gate). Further research is required on agricultural grain products at varying moisture contents and sizes in order to determine the range of constants a and b. Through experimentation and modeling, To et al. demonstrated that the jamming phenomenon is a function of both the orifice size and the particle-to-orifice size ratio (To et al., 2001). The work of Zuriguel et al. established a demarcation between continuous flow and the jamming regime (Zuriguel et al., 2005; Zuriguel et al., 2003). This article defines the parameter R as the ratio of the aperture diameter to the bead diameter. The critical value of this ratio, denotedR_c, is reported to be 5. This criterion states that jamming requires an aperture-to-particle size ratio (R) ≤ Rc, where Rc = 5. This criterion specifies that the minimum gate width to prevent jamming is five times the maximum grain size. Consequently, the required minimum width is 10 mm.

Moisture Content

As illustrated in Fig. 5, increasing the moisture content to 26% results in a reduction of the flow rate of wheat grains for both varieties. Subsequent to this, the curves show fluctuations in the flow rate in relation to the moisture content. The flow ability and cohesiveness of wheat particles at higher moisture content were partly governed by biochemical mechanisms (e.g., water's plasticizing effect) and physicochemical mechanisms.

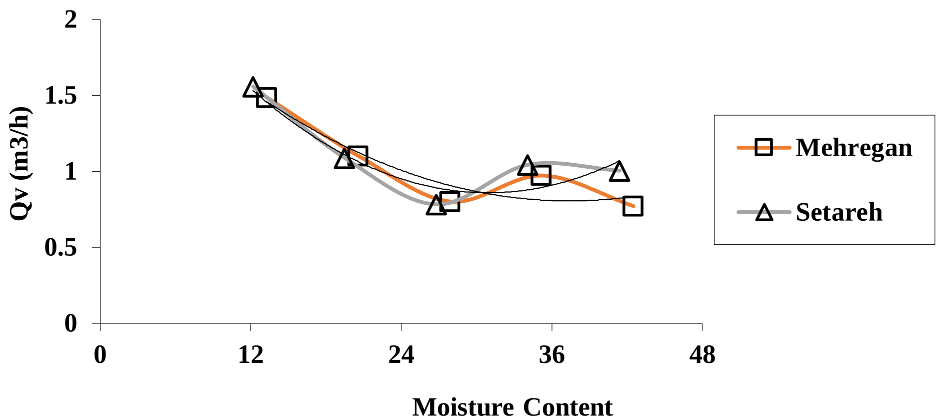

Figure 6. Flow rate variation with moisture content and varieties

The increase in grain cohesiveness due to moisture sorption is largely attributed to the formation of liquid bridges between particles. The regression model for moisture's effect on flow rate (Eqs. 8 and 9) achieved the highest R^2 value, exceeding 0.86.

For Mehregan	Qv = 0.0011 MC2 - 0.084 MC + 2.377,	R^2 = 0.873	(15)
For Setareh	Qv = 0.0019 MC2 - 0.119 MC + 2.691,	R^2 = 0.862	(16)

Where QV is the flowing rate of wheat grains (m3/h) and MC is moisture content. Raymus and Me identified moisture content as one of the most common and controllable factors affecting flow (Raymus & ME, 1997). Furthermore, he reported that while most materials can safely absorb moisture up to a certain level, exceeding this point causes significant flow problems. According to Chang et al., the mass flow rate of corn through square and circular orifices decreased appreciably when moisture content was increased from 12% to 23% (Chang et al., 1984).

CONCLUSIONS

The effects of orifice area, moisture content, and aspect ratio on the gravitational flow rate through horizontal orifices were tested using two grain varieties. Moisture contents of test wheat lots ranged from 13.3 to 42.5% for Mehregan variety and from 12.2 to 41.4% for Setareh variety. It was found that the factors area of orifice and moisture content had a highly significant effect on the flow rate at the 1% significance level. The flow rate increased with both effective orifice area and effective hydraulic diameter, showing strong correlations ($R^2 >$ 0.99) and following a power relationship with exponents ranging from 1.979 to 2.116 for De across both wheat varieties. Conversely, the flow rate decreased exponentially with increasing aspect ratio, exhibiting a strong correlation ($R^2 >$ 0.95). In contrast, the effect of moisture content followed a polynomial trend, with a coefficient of determination of $R^2 > 0.86$. The relationships between the flow rate of wheats and the effective hydraulic diameter of orifice were log-linear.

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