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I. Introduction

To ensure steady and reliable flow rate (measured as the mass or volume of the material per unit time) it is crucial to accurately characterize the flow behavior of the bulk materials (*Kamath et al., 1994*) through the orifice of bins, cylinders, funnels, hoppers, and silos. The flow of granular materials through these storage structures constitutes a problem extremely important in the design of hoppers and bins, other handling equipment, grain drills, among others. Information on the flow rate of egusi-melon through orifices of various sizes, shapes and orientations and the functional design of bins, hoppers and other storage equipment is needed to determine its flow and properly size the opening for flow control during transfer of grain from storage (*Gregory and Fedler, 1987; Wilcke et al., 1992; Wang et al., 1995a; Sahay and Singh, 2001).*

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Chang and Converse (*1988)* found that the flow rates of wheat and sorghum increased as moisture content decreased*.* Using two grains (wheat and barley) and two oil seeds (flax and rapeseed) through circular, square and rectangular orifices, *Moysey et al. (1988)* noticed that the flow rates were affected by moisture content but not by bulk density of grain in the bin. These go to show that moisture is a key parameter when considering flowability of any granular material *(Bhadra et al., 2008*), because most agricultural materials tend to gain or lose moisture with changing environmental factors, thereby affecting cohesive strength, arching and the frictional properties of bulk grains and seeds (*Marinelli and Carson, 1992). Seifi and Alimardani (2010)*posited that coupled with surface properties, moisture influences adherence properties between particles and materials handling equipment such as storage tanks, bins, hoppers, etc., leading to flowability problems.*Raymus (1984)* said that moisture content is one of the most common and controllable flow factors. And that most materials can safely absorb moisture up to a certain point; however, the further addition of moisture can cause significant flow problems.

Discharge rates increase with increase in orifice size, more rapidly for smaller orifices, and appear to approach a power law for larger orifices (*Beverloo et al., 1961; Wang et al., 1995b; Sheldon and Durian, 2008; Janda et al., 2009*).The Beverloo law (Eqn. 1) is the most accepted law that predicts the flow rate of grains through an orifice with one most important and interesting issue: the dependence of flow rate on a 5/2 power of the diameter of the orifice, if the orifice is large (*ASAE, 2003; Mankoc et al., 2007).*

$$W_m = C_d \rho_b g^{1/2} (D - kd_e)^{2.5} \quad (1)$$

Where,
W_m = mass flow rate, g/min;
C_d = friction or discharge coefficient (0.55 < C_d < 0.65);
ρ_b = bulk density, g/cm^3;
g = gravitational constant, cm/s^2;
D = orifice diameter, cm;
d_e = equivalent particle diameter, cm;
k = shape coefficient (1 < k < 2);
kd_e = empty annulus, cm.

The Beverloo equation can describe the relationship between discharge rate and orifice size, however the constants in the equation may vary with the wall friction coefficient, particle friction and damping/moisture coefficients (*Zhu and Yu, 2004*). Volume flow rate is chosen by many researchers instead of mass flow rate as the parameter to express flow rate as a function of orifice diameter because an orifice has direct effect or control over volume flow rate rather than mass flow rate (*Chang and Converse, 1988*) and eliminates the differences in densities (*Moysey et al., 1988*).

Based on some prediction equations for flow rate through orifices taken from *Gregory and Fedler (1987), Chang and Converse(1988), Moysey et al.(1988) and Chang et al.(1990; 1991*), the American Society of Agricultural and Biological Engineers (ASABE) developed a Standard for flow of grains and seeds through orifices (*ASAE, 2003).*The Standard gave the equation for predicting volumetric flow rate of grains and seeds as Eqn. (2).

$$Q = C_o A D_h^n \tag{2}$$

Where,

Q = volume flow rate, m^3/h;

A = area of the orifice, cm^2;

D_h= hydraulic diameter of the orifice, cm;

C_o= coefficient, $m^3/cm^{(n+2)}h$, varying for different crops *at* different moisture contents and different orifice hydraulic diameters;

n = exponent with value between 0.5 and 1.0.

Since the constants and exponents of the predicting flow rate equations vary at different seed moisture contents and orifice diameters, this work intends to determine experimentally these constants and exponents foregusi-melon seeds as they flow through horizontal circular and square hopper orifices.

II. Materials and Methods

One hundred (100) kilograms of egusi-melon seeds were purchased from the Eke Onunwa Market, Owerri based on estimation from the experimental design for the actual tests. The sun dried egusi-melon seeds were cleaned manually to remove all foreign materials, empty and broken seeds. The initial moisture content of somerandomly selected 200 g seeds was determined by using the standard oven method at 105 ± 1 °C for 24 h (*Gupta and Das, 1997;Altuntaşet al., 2005)*. The initial moisture content of the seeds was 6.76% d.b. The seeds were then divided into six (6) batches of 18 kg each. Five (5) of the batches were conditioned to various moisture contents following the method of *Balasubramanian (2001),* Eqn. (3).

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

Where,

Q_m = mass of water added, kg;

W_i = initial mass of sample, kg;

M_i = initial moisture content of sample, % d.b.;

M_f = final moisture content of sample, % d.b.

The amount of distilled water used for the seed conditioning and the final moisture contents determined for the five batches are given in Table 1.

After the conditioning of the seeds, they were all put in high density polyethylene (HDPE) bags, tied tightly and labeled, and then put in a functional refrigerator at 5°C.

Table 1 : Amounts of distilled water for seeds conditioning

Egusi-melon seeds			
W_i (kg)	M_i(%)	Q_m (kg)	M_f (%)
18	6.76	1.18	12.5
18	6.76	1.50	13.9
18	6.76	1.91	15.7
18	6.76	2.03	16.2
18	6.76	2.69	18.9

Two hoppers with upper and lower orifices of areas 240 and 60cm^2 and circular and square shapes respectively, were constructed. Both hoppers have side slope of 70°, with heights of 12.0 and 10.63cm for the circular and square shapes, respectively. These give hopper volumes of about 900 and 800cm^3 for circular and square respectively. Two slide gates with orifices of areas 16, 20, 30 40 and 50cm^2 spaced 70cm each of circular and square shapeswere also constructed.

To determine the flow rate of the seeds at specific moisture content, a bag of the seeds was brought out from the refrigerator; left spread out on a cardboard sheet for 24 h to equilibrate to the room temperature of the laboratory, with their moisture content not significantly different from their original values. While this was going on, the hopper stand and the hoppers were brought out and one hopper mounted on the stand (Fig. 1), with the slide gate closed. The seeds were used to fill the mounted hopper, of known volume (V m^3). Three trial runs were made with each hopper to get used to and perfect the procedure for flow rate data collection from the different hopper orifices and also to condition the innerhopper surfaces for the experiment. With a stop watch ready, the slide gate was pulled out to open the orifice as the stop watch is started. At the end of the seeds discharge from the hopper, the stop watch was stopped and the time (t hr) to empty the hopper was read and recorded, and the slide gate was pushed back to close the orifice. Three replications were taken and averaged for each hopper orifice and moisture content. The volumetric flow rate (Q) was calculated from Eqn. (4).

$$Q = \frac{V}{t}(m^3/h) \tag{4}$$

(a)

(b)

Fig. 1 : Experiment set up with square orifice (a); Actual test going on for egusi-melon (b)

III. Results and Discussion

The results of this work showed that the overall volumetric flow rate, Q decreased as the moisture content increased (Fig. 2) due probably to the increase in internal friction as the moisture content increased as well as the change in bulk density with moisture (*ASAE, 2003).* For egusi-melon seeds, these decreases were 5.36% and 4.36% for circular and square orifices respectively as moisture increased from 6.76% to 18.90%.Even for vertical orifices *Chang et al. (1988)* found flow rate to decrease with increase in moisture content. Similar results were also observed by *Wang et al. (1995b)* who posited that for soybean meal, increased moisture increased the binding force at the surfaces of particles, thereby decreasing flowability.

Bokhoven and Lohnes (1989) are of the opinion that cohesion increased with increasing moisture content decreasing volumetric flow rate.The Q was observed to be higher for circular than for square orifice, because for the same orifice area, the orifice diameter is higher for the circular than for the square. Again, the height and the overall volume of the hoppers were higher for the circular than for the square. Also, the linear regression model of the effect of moisture on the overall volumetric flow rate had the highest $R^2 > 0.91$ and given as Eqns. (5)&(6). It may be argued that the low sphericity of egusi-melon (0.414 – 0.466) made it flow faster through round orifice than through square orifice.

$$Q_{cm} = -0.0171M + 3.7163 \quad (R^2 = 0.9146) \tag{5}$$

$$Q_{sm} = -0.0091M + 2.4159 \quad (R^2 = 0.9142) \tag{6}$$

Where,

Q_{cm} = volumetric flow rate of egusi-melon from horizontal circular hopper orifice, m^3/h.

Q_{sm} = volumetric flow rate of egusi-melon from horizontal square hopper orifice, m^3/h.

M = moisture content, % d.b.

The Q increased with power law as the hydraulic orifice diameter (D_h) increased, though it decreased with increase in moisture content as shown in Fig. 3a & b for circular orifice and Fig. 4a & b for square orifice.The curves plotted on log-log scale paper of volume flow rate vs orifice diameter or the length of orifice side were nearly linear for all tests*(Chang et al., 1984).* Thus the flow rate can be expressed as a function of orifice size in the following form (Eqn. 7):

$$Q = \alpha D_h^{\beta} \tag{7}$$

Where,

Q = volume flow rate, m^3/h

D_h = hydraulic orifice size (diameter or side length), cm

α & β = coefficients to be determined experimentally.

The function coefficients of the power regression models were determined using regression analysis and are given in Table 2 for horizontal circular and square orifices. At lower moisture contents of 6.76 – 13.9% d.b., the exponent on D_h for the volumetric flow rate of egusi-melon through circular orifice ranged between 2.8311 and 2.8705 while for higher moisture contents of 15.7 – 18.9% d.b. it ranged between 2.5405 and 2.5626.

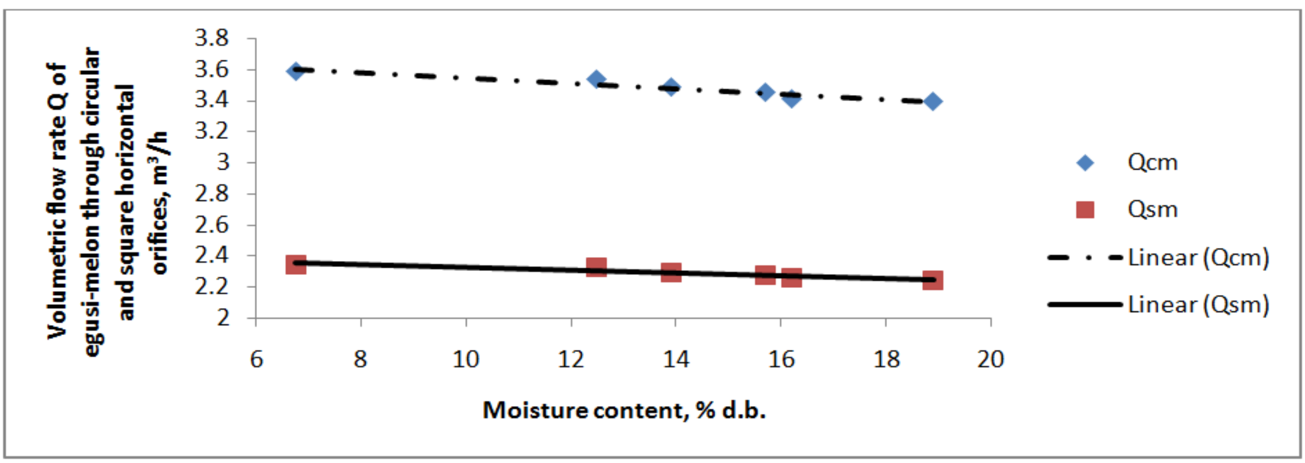
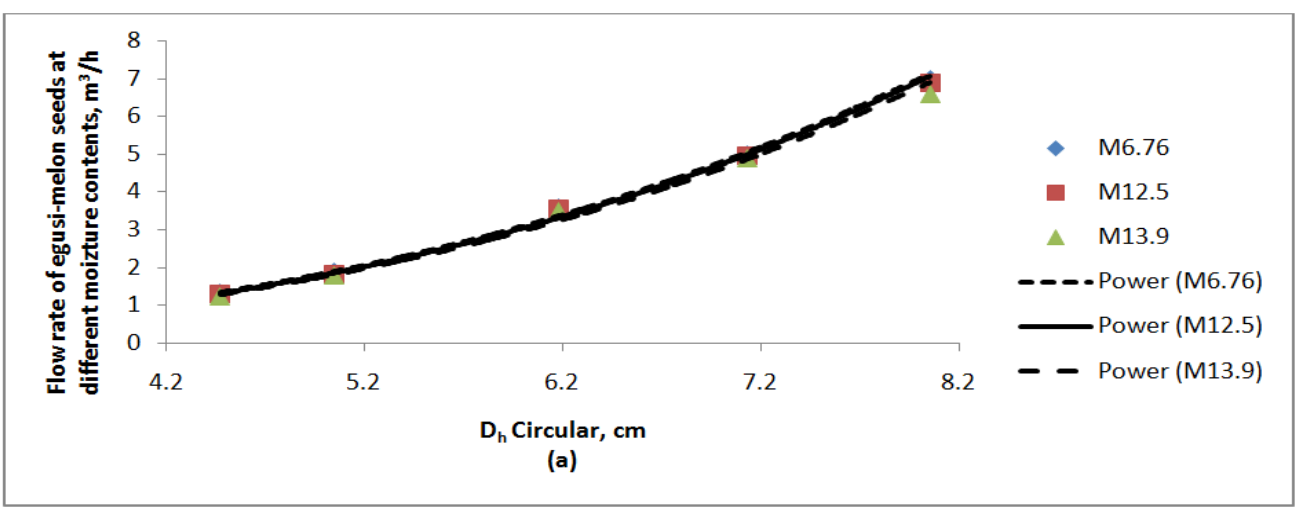


Fig. 2 : Effect of moisture on the volumetric flow rate of egusi-melon horizontal hopper orifices



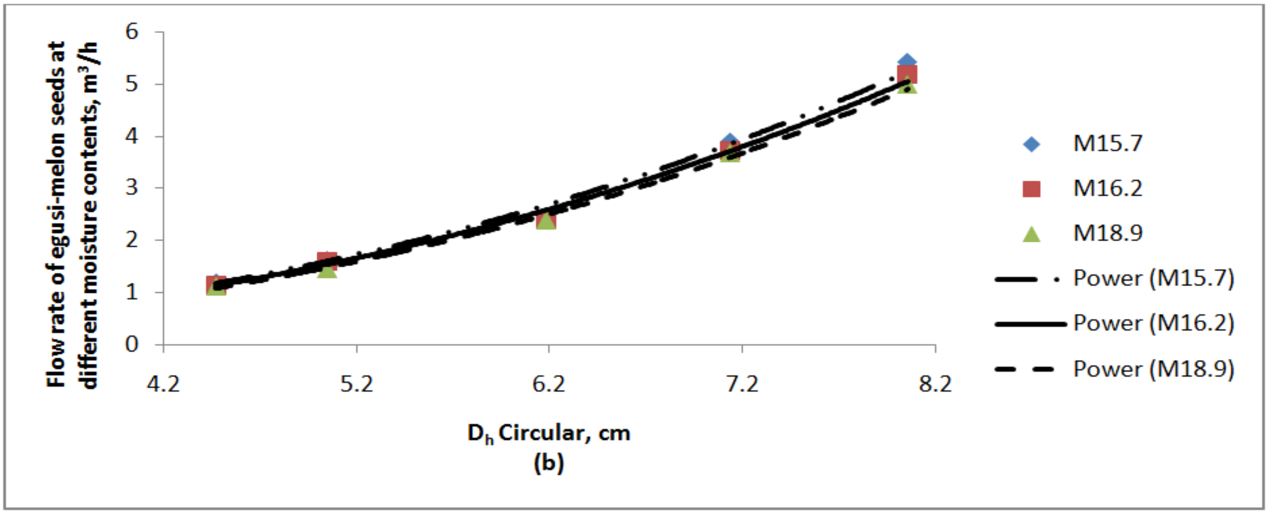


Fig. 3 : Effect of circular hydraulic orifice diameter on Q for different moisture contents

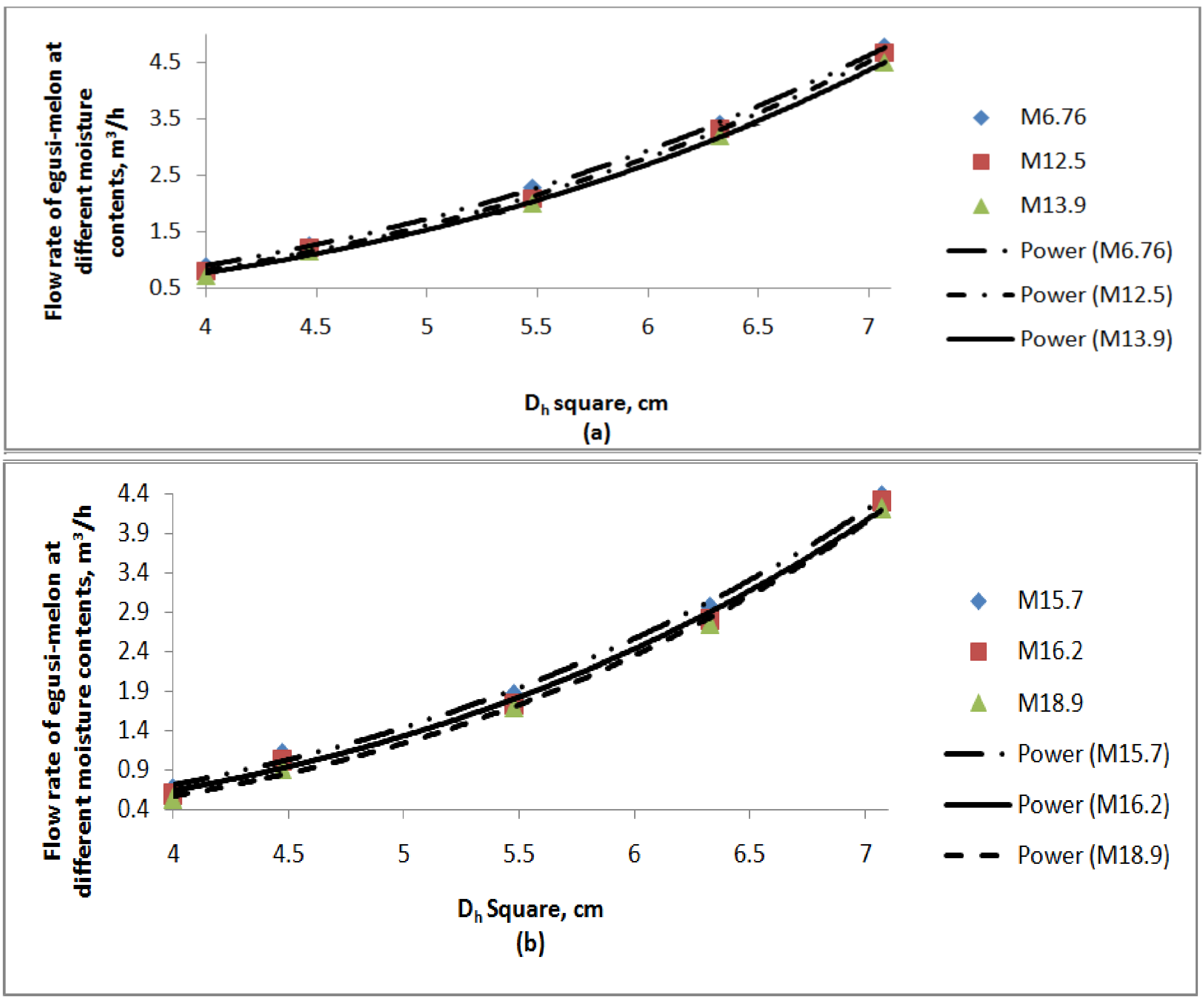


Fig. 4 : Effect of square hydraulic orifice diameter on Q for various moisture contents

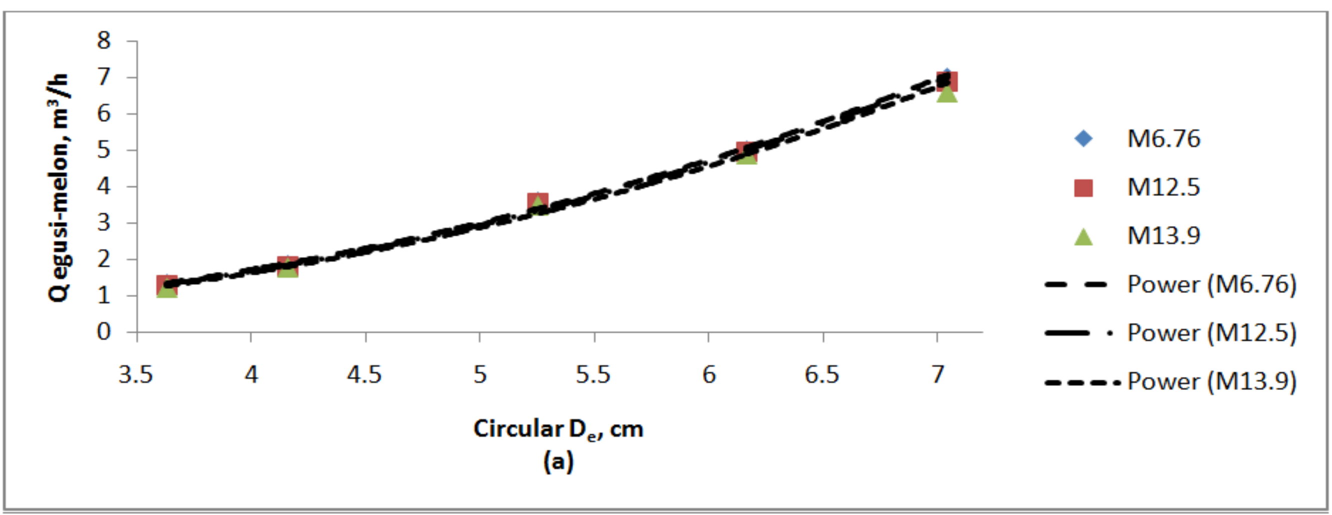
Table 2 : Coefficients of the equation* expressing volume flow rate of egusi-melon as a function of hydraulic orifice diameter

Moisture Content, % d.b.	Coefficients			
	Circular orifice		Square orifice	
	α	β	α	β
6.76	0.0194	2.8311	0.0159	2.9143
12.5	0.0180	2.8628	0.0124	3.0292
13.9	0.0173	2.8705	0.0102	3.1137
15.7	0.0261	2.5405	0.0088	3.1680
16.2	0.0259	2.5267	0.0065	3.3104
18.9	0.0234	2.5626	0.0045	3.4943

$$* Q = \alpha D_h^{\beta}$$

This is very informative as *Chang and Converse (1988)* working with wheat and sorghum at 12.9 – 15.1% and 11.2 – 17.7% w.b. respectively, got the exponent to range between 2.6394 and 2.6774 for wheat through the circular orifice. For the square orifice, the flow characteristics of egusi-melon seeds were similar to the circular orifice and the exponent on D_h ranged from 2.9142 to 3.4943 and higher than for circular orifice. For moisture content 13.9 – 18.9% d.b. the power exponent for the square orifice was high ranging from 3.1137 – 3.4943, quite above what were found in Literature. It is also higher than for wheat and sorghum for square orifice *(Chang and Converse, 1988)*. For wheat and sorghum, they found the flow higher for square than for circular orifice of the same diameter/side length at lower moisture contents.*Morsey et al. (1988)* working with wheat, rape, flax and barley within moisture content range of between 3.8 and 16.4% w.b. also found the flow rate of these crops to decrease with increase in moisture content.*Kusińska (2005)* reported that the flow intensity of rape seeds through square orifice increased with decrease in moisture content from 8.4 to 17.6% d.b.Working with Olejarczykthey got the overall Q's α as 0.0173 while its β is 2.829 for oat grains through circular orifice *(Kusińska and Olejarczyk, 2005)*. They found the flow rate to decrease with increase in moisture content between 8.9 and 13.8% d.b.

With the equivalent diameter, $D_e$the power law trend is similar to D_h as shown in Fig. 5a & b for circular and Fig. 6a & b for square orifices respectively. The coefficients are given in Table 3. Also the R^2 ranged from 0.9923 to 0.9981 for circular and from 0.9938 to 1.0 for square orifices. At high moisture contents of 15.7 – 18.9% d.b., the power exponents on D_e for Q of egusi-melon through circular hopper orifice were 2.2369 – 2.2693 which are lower than found in Literature.



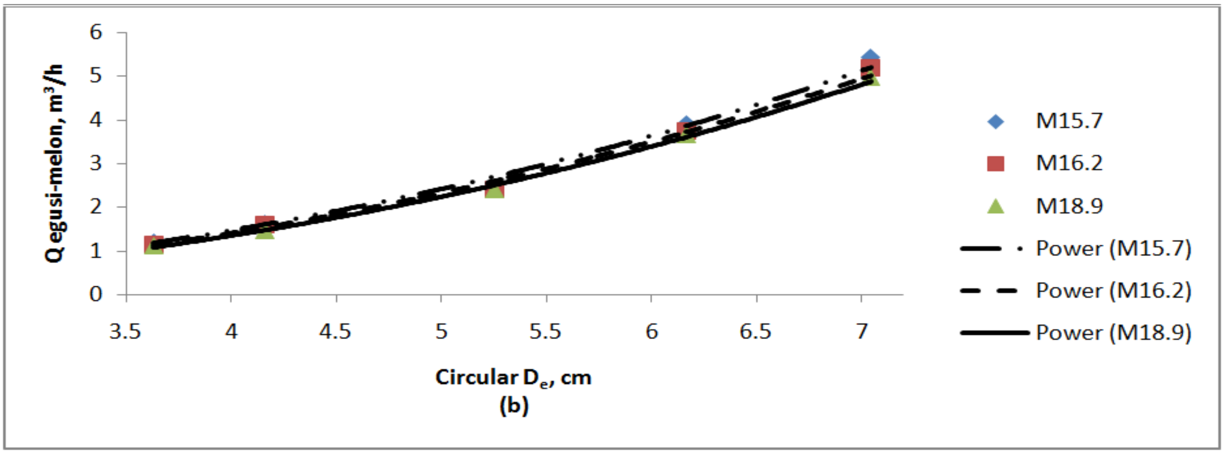


Fig. 5 : Effect of circular equivalent diameter on Q for various moisture contents

Table 3 : Coefficients of the equation* expressing volume flow rate of egusi-melon as a function of equivalent orifice diameter

Moisture Content, % d.b.	Coefficients			
	Circular orifice		Square orifice	
	α	β	α	β
6.76	0.0529	2.5085	0.0625	2.3727
12.5	0.0495	2.5368	0.0514	2.4662
13.9	0.0477	2.5440	0.0440	2.5356
15.7	0.0645	2.2489	0.0388	2.5801
16.2	0.0635	2.2369	0.0305	2.6961
18.9	0.0582	2.2693	0.0231	2.8459

$$* \, Q = \alpha D_e^{\beta}$$

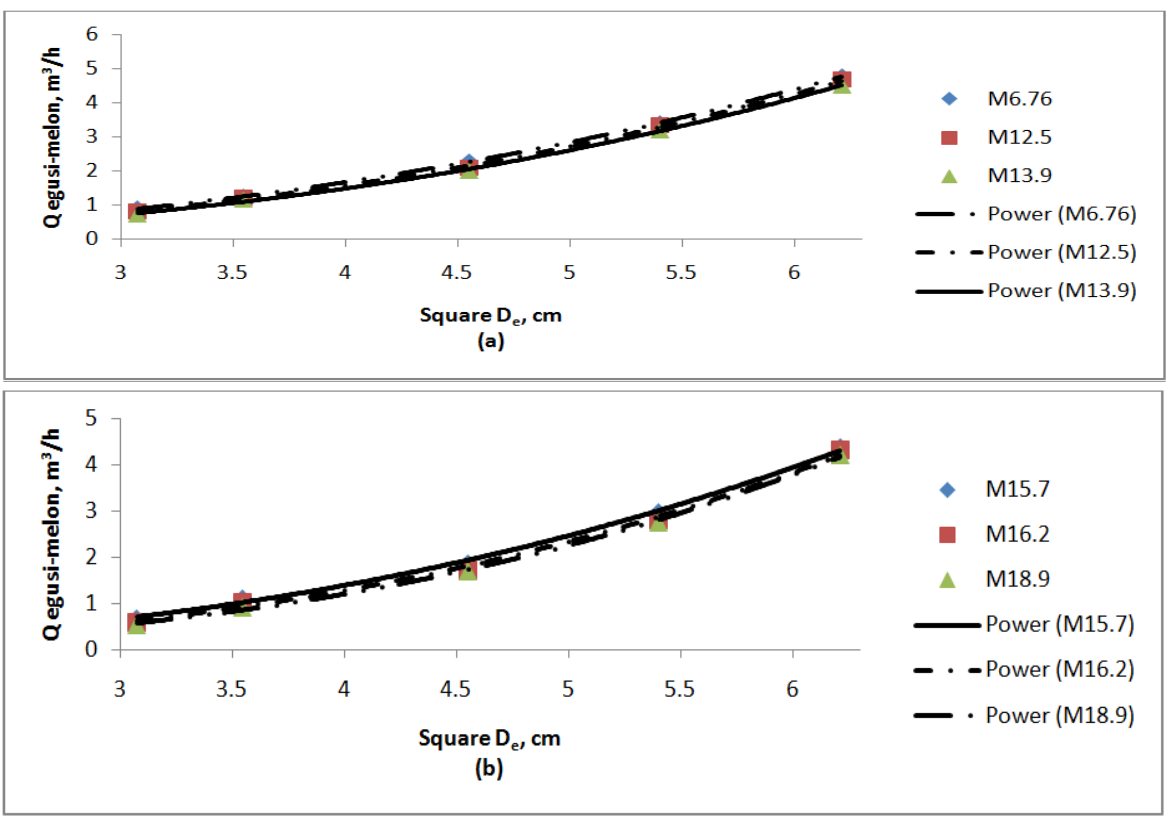


Fig. 6 : Effect of square equivalent diameter on Q for various moisture contents

For lower moisture contents of 6.76 – 13.9% d.b. they ranged from 2.5085 to 2.5440 which are within the range found in Literature. However, the opposite was observed for the square orifice where for moisture content range of 13.9 – 18.9% d.b., the exponent ranged from 2.5356 to 2.8439 as found in Literature. It may be said, therefore, that for circular orifice and within the range of moisture content under review, use could be made of D_h since the power exponent of the regression model is within the range found in literature. However, D_e is suitable with circular orifice for lower moisture contents and with square orifice for higher moisture contents.

Using the above Eqns. 5 & 6 for M = 7, 13 and 19% d.b., Table 4 shows the Q through the different orifice shapes. The differences in Q for the three moisture contents between circular and square orifices were 34.6, 34.2 & 33.9% respectively, decreasing as the moisture contents increased.

Table 4 : Volumetric flow rates of egusi-melon through circular and square orifices at M =7, 13 & 19% d.b.

Parameter	Moisture content, % d.b.		
	7	13	19
Q_{cm}	3.5966	3.4940	3.3914
Q_{sm}	2.3522	2.2976	2.2430

For circular and square orifices of the same diameter/side length (D_h = 4.472 cm), it is observed that flow rate was higher through the circular orifice as seen in Eqns. (8)&(9)and Fig. 7. The differences between the orifices increased with increase in moisture content from 5.26 to 18.75% as the moisture increased from 6.76 to 18.9% d.b.

$$Q_{cm} = -0.0011M^2 + 0.0100M + 1.3185 \quad (R^2 = 0.9397) \quad (8)$$

$$Q_{sm} = -0.0031M^2 + 0.0486M + 1.0724 \quad (R^2 = 0.9716) \quad (9)$$

For same hopper orifice diameter/side length (D_h = 4.472 cm), it is observed that Q has a polynomial relationship with moisture content with R^2> 0.93 (Eqns. 8 & 9).

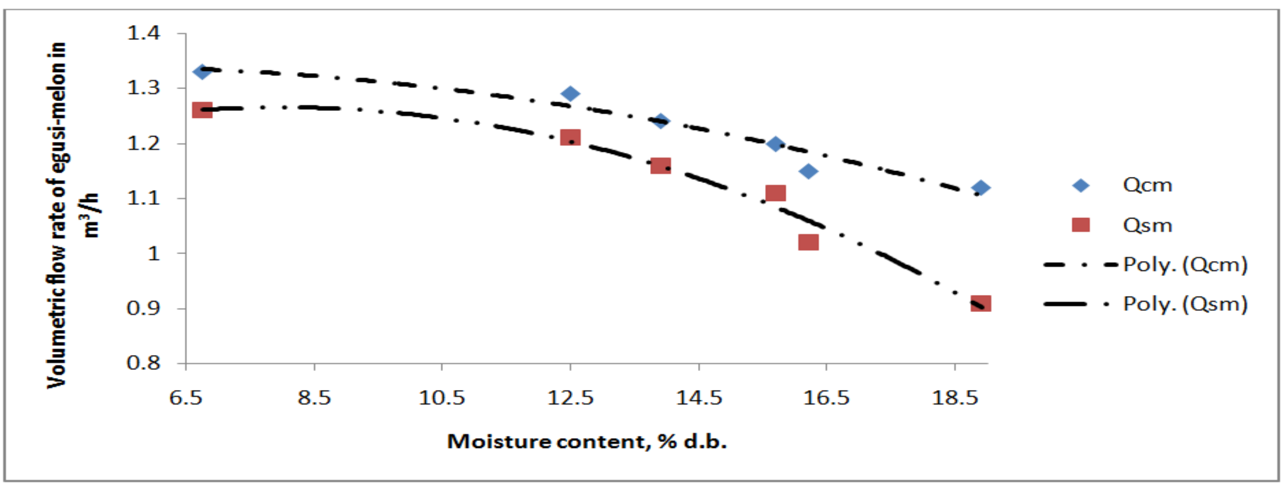


Fig. 7 : Effect of moisture content on the volumetric flow rate of egusi-melon through circular and square orifices of the same diameter/side length (D_h = 4.472 cm)

IV. Conclusions

For egusi-melon seeds, the volumetric flow rate generally decreased with increase in moisture content, linearly with R^2> 0.91. However, for the same hopper orifice diameter/side length, the decrease was polynomial with R^2> 0.93. Also, the flow rate is more through circular hopper orifice than square. As the hopper diameter/side length increased, the volumetric flow rate increased with power regression with the exponent ranged between 2.5267 to 2.8705 for D_h for circular orifice; 2.5085 to 2.5440 for D_e for circular at lower moisture content and 2.5356 to 2.8459 for higher moisture content for D_e.

References Références Referencias

1. Altuntaş, E., E. Özgöz and Ö.F. Taşer. 2005. Some physical properties of fenugreek *(Trigonellafoenum-graceum L.)*seeds. *Journal of Food Engineering*71: 37–43.
2. American Society of Agricultural Engineering. 2003. *Flow of Grain and Seeds Through Orifices*. ASAE Standards D274.1 Feb. 2003 published by

American Society of Agricultural Engineers. St. Joseph. MI 49085 – 9659.

3. Balasubramanian, D. 2001. Physical properties of raw cashew nut.*Journal of Agricultural Engineering Research***78** (3): 291–297.
4. Beverloo, W. A., H. A. Leninger and J. Van De Velde. 1961. The flow of granular solids through orifices. *Chemical Engineering Science***15**: 260 – 269.
5. Bhadra, R., K. A. Rosentrater and K. Muthukumarappan. 2008. Understanding and modeling flowability of DDGS. ASABE *Paper No. 083808*, St. Joseph MI. American Society of Agricultural and Biological Engineers.
6. Bokhoven, W. H. and R. A. Lohnes. 1989. Preconsolidation effects on flow characteristics of soybean meal. *Transactions of the* ASAE 32(5): 1779-1784.
7. Chang, C. S., H. H. Converse, and F. S. Lai. 1984. Flow rate of corn through orifices as affected by moisture content. Transactions of the American Society of Agricultural Engineers **27** (5): 158 – 1589.
8. Chang, C. S. and H. H. Converse. 1988. Flow rates of wheat and sorghum through horizontal orifice. *Transactions of the American Society of Agricultural Engineers***31** (1):300–304.
9. Chang, C. S.; H. H. Converse and J. I. Steele. 1990. Flow rate of grain through vertical orifices. *Transactions of the American Society of Agricultural Engineers* **32** (2):601–606.
10. Chang, C. S.; H. H. Converse and J. I. Steele. 1991. Flow rates of grain through various shapes of vertical and horizontal orifices. *Transactions of the American Society of Agricultural Engineers* **34** (4): 1789 – 1796.
11. Gregory, J. M. and C. B. Fedler. 1987. Equation describing granular flow through circular orifices. *Transactions of the American Society of Agricultural Engineers***30**(2):529–532.
12. Gupta, R.K. and S.K. Das. 1997. Physical properties of sunflower seeds, *Journal of Agricultural Engineering Research***66**(1): 1–8.
13. Janda, A., R. Harich, I. Zuriguel, D. Maza, P. Cixous and A. Garcimartin. 2009. Flow rate fluctuations in the outpouring of grains from a two-dimensional silo. *Physical Review E 79, 031302* (2009) *The American Physical Society.* DOI:10.1103/PhyRevE. 79.031302.
14. Kamath, S., V. M. Puri and H. B. Maubeck. 1994. Letter; flow property measurement using Jenike Cell for wheat flour at various moisture contents and consolidation times.*Powder Technology***81**(3): 293 – 297.
15. Kusińska, E. 2005. Effect of the size and position of square hole on flow intensity of rape seeds. *InzynieriaRolnicza.* Nr. **11**(71) S. 275 – 282.
16. Kusińska, E. and P. Olejarczyk. 2005. Effect of selected geometrical hole parameters on the flow intensity of oat grains. *InzynieriaRolnicza*. Nr **11**(71) S. 283 - 290.
17. Mankoc, C., A. Janda, R. Arévalo, J. M. Pastor, I. Zuriguel, A. Garchimartin and D. Maza. 2007. The flow rate of granular materials through an orifice.*Granular Matter***9**: 407 – 414.
18. Marinelli, J. and J. W. Carson. 1992. Solve solid flow problems in bins, hoppers, and feeders. *Cheminal Engineering Progress* p. 22 – 28.
19. Morsey, E. B., E. W. Lambert and Zhijie Wang 1988. Flow rates of grains and oil seeds through sharp-edged orifices. *Transactions of the American Society of Agricultural Engineers***31**(1): 226 – 231.
20. Raymus, G. J. 1984. Handling of bulk solids and packaging of solid and liquid. In *Perry's Chemical Engineering's Handbook,*6th Ed., eds. R. H. Perry and D. O. Green, 7-1 to 7-63. New York: McGraw-Hill Book Company.
21. Sahay, K. M. and K. K. Singh. 2001. *Unit Operations of Agricultural Processing* (Second Revised Edition).Vikas Publishing House PVT LTD, p. 174 – 181.
22. Seifi, M. R. and R. Alimardani. 2010. The moisture content effect on some physical and mechanical properties of corn (Sc 704). *Journal of Agricultural Science***2**(4):125 - 134.
23. Sheldon, H. G. and D. J. Durian. 2008. Granular discharge and clogging for tilted hoppers. *arXiv:0810.0495v1 (cond-mat.soft). PACS numbers*: **45**.70.-n.
24. Wilcke, W. F., C. S. Chang and G. H. Hetzel. 1992. Grain flow through guarded horizontal orifices. *Applied Engineering in Agriculture***8**(1): 65-75.
25. Wang, Y. J., D. S. Chung and K. C. Behnke. 1995a. Flowability of soybean meal in a round model hopper bin. *Applied Engineering in Agriculture***11**(3): 421 – 425.
26. Wang, Y. J., D. S. Chung and C. K. Spillman. 1995b. Gravity flow characteristics of soybean meal. *Transactions of the American Society of Agricultural Engineers***38**(4):1179 – 1186.
27. Zhu, H. P. and A. B. Yu. 2004. Steady-state granular flow in a 3-D cylindrical hopper with flat bottom: microscopic analysis. *Journal of Physics D*: *Applied Physics***37**(10):1497 – 1508.

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