Flow Rates of Wheat and Sorghum through Horizontal Orifices

C. S. Chang, H. H. Converse
MEMBER ASAE MEMBER ASAE

This article is reprinted from the TRANSACTIONS of the ASAE (Vol. 31, No. 1, pp. 300-304, 1988)
Published by the American Society of Agricultural Engineers, St. Joseph, Michigan

ABSTRACT

THE flow rates of wheat and sorghum through circular and square horizontal orifices were measured. Orifice sizes ranged from 10.2 to 25.4 cm in diameter or side length. Moisture contents (w.b.) of the grain lots ranged from 12.9 to 15.1% for wheat and from 11.2 to 17.7% for sorghum. The flow rate of sorghum for a given size of orifice increased as the moisture content increased, but the flow rate of wheat was not significantly affected by the moisture content. An empirical equation was obtained to predict volume flow rate of grains.

INTRODUCTION

Information on the flow rate of grain through various sizes and shapes of orifices is needed to properly size the opening for flow control during transfer of grain.

The flow rate of grain through an opening is independent of the depth of grain above the opening if the mode of flow remains the same (Ketchum, 1919; Fowler and Glastonbury, 1959). Stahl (1950) indicated that flow of grain through a horizontal opening was proportional to the cube of the diameter, or the product of length and width of the opening. Chang et al. (1984) conducted experiments with corn of various moisture contents and found that the flow rate was proportional to the orifice diameter raised to the 2.6 to 2.8 power depending on the moisture content. The flow rate decreased as the moisture content of corn increased.

Based on a dimensional analysis, Beverloo et al. (1961) suggested that the flow rate of granular material was proportional to the diameter raised to the 2.5 power and proposed a general equation for calculating the flow rate through various shaped orifices:

$$Q = 0.75\, A_e \sqrt{gD_e} \quad \ldots\ldots [1]$$

where
Q = volume flow rate, m^3/s
g = gravitational acceleration, m/s^2
D_e = D_h — 1.4d, effective hydraulic diameter, m
D_h = hydraulic diameter, m
d = average size of particles, m
A_e = effective orifice area calculated from D_e, m^2

Article was submitted for publication in May, 1987; reviewed and approved for publication by the Food and Process Engineering Institute of ASAE in October, 1987.

Mention of firm names or trade products does not constitute endorsement by the U.S. Department of Agriculture over others of a similar nature not mentioned.

The authors are: C. S. CHANG and H. H. CONVERSE, Agricultural Engineers, USDA-ARS, U.S. Grain Marketing Research Laboratory, Manhattan, KS.

They conducted experiments using sand and several types of small seeds and found that the maximum deviation of calculated values from the test data was 10%.

Based on a balance of downward force causing flow and upward force resisting flow, Gregory and Fedler (1987) derived an equation to predict the granular flow through orifices:

$$Q = \frac{\pi g}{16k}\, \rho\, D^3 \quad \ldots\ldots [2]$$

where
Q = volume flow rate, cm^3/s
D = orifice diameter, cm
ρ = bulk density of material, g/cm^3
g = gravitational acceleration, cm/s^2
k = coefficient of drag, $g/(s \cdot cm^2)$

Orifice sizes ranging from 1.9 to 7.6 cm in diameter were tested with several types of grain for verification. The derived equation fitted measured data well.

The flow of wheat through orifices has been tested by Whited (1901) and Moysey et al. (1985). Their experiments were limited to openings of 5 cm or smaller. Openings larger than 10 cm in grain handling systems for grain flow control are common. However, performance data for these larger openings are limited.

The objectives of these experiments were to determine the flow rates of wheat and sorghum through large circular and square horizontal openings, and to measure the effect of moisture content on the flow rates.

EQUIPMENT AND PROCEDURE

Three varieties of wheat and four hybrids of sorghum were used in the experiments. Moisture contents of the three wheat varieties, Newton, Mustang, and Hawk were 12.9, 14.4, and 15.1% (w.b.), respectively. All four hybrids of sorghum were freshly harvested at relatively high moisture content. Each hybrid was tested soon after harvest and then dried to a lower moisture content for further tests. Two moisture contents each for the Cargill, Dekalb, and Funk hybrids, and three moisture contents for the Hoegemeyer hybrid were used in the tests. Moisture contents for each grain lot are given in Table 1. A grain lot referred to a batch of particular variety or hybrid of grain at a certain moisture content. A test lot referred to a desired amount of grain from a grain lot for a particular test.

Seven sizes of circular orifice ranging from 10.2 to 25.4 cm in diameter and six sizes of square orifice ranging from 10.2 to 22.9 cm square with increments of 2.5 cm for both sets of orifices were used in the experiments (Table 2). Orifice sizes of 10.2 cm circular and square were used only for sorghum.

TABLE 1. MOISTURE CONTENT, TEST WEIGHT, KERNEL DIAMETER AND BNFM OF TEST GRAIN LOTS

Grain	Variety or hybrid	Mean equivalent kernel diameter, mm	Moisture content, % w.b.	Test weight, kg/m^3	Test weight, (lb/bu)	BNFM* %
	Newton	3.4	12.9	744	57.8	0.8
Wheat	Mustang	3.5	14.4	756	58.7	2.3
	Hawk		15.1	766	59.5	1.1
	Hoegemeyer 688		11.2	786	61.1	4.4
Sorghum	Hoegemeyer 688		13.8	795	61.8	4.2
	Hoegemeyer 688		17.7	779	60.5	3.7
	Cargill 70	3.4	12.6	770	59.8	5.0
	Cargill 70		15.8	763	59.3	3.4
	Dekalb 42Y	3.3	12.8	774	60.4	5.0
	Dekalb 42Y		16.1	770	59.8	3.1
	Funk G-522DR	3.4	11.6	707	54.9	9.7
	Funk G-522DR		15.6	687	53.4	5.9

*Broken kernels and foreign material

Before a given test, a test lot of grain was transferred to a holding bin (Fig. 1) by means of a bucket elevator. The amount of grain used for a given test depended upon the orifice sized and was determined based on the amount required for a 3 to 10 min test. The quantities of grain used for each size of orifice are given in Table 2. For a given grain lot, the smaller orifices were tested first using a smaller test lot. As the orifice size increased, additional grain was added to obtain desired test lot size. Two replicated tests were conducted with each orifice. Before and after a series of tests for each grain lot, samples were taken by an automatic sampler (Carter-Day, CHCI132) during the transfer of grain to the holding bin. These samples were analzyed for moisture content, test weight, and broken kernels and foreign material (BNFM). The equivalent kernel diameter was also determined for each sample from the average kernel volume which in turn was determined by measuring the volume of a 600-kernel sample using an air pycnometer.

The holding bing (Fig. 1) was 2.4 x 2.9 x 7.6 m high with a hopper-bottom sloping toward the central opening at an angle of 40 deg from horizontal. The test orifice was installed at the bottom of the slide gate spout. The sliding gate was opened to permit grain to flow through the orifice to a receiving bin and the time required for the holding bin to empty was measured with a stopwatch. The mass flow rate of grain was determined from the test lot weight and flowing time of the test lot. The volume flow rate was calculated from the mass flow rate and test weight.

TABLE 2. QUANTITY OF GRAIN USED WITH EACH ORIFICE SIZE

Orifice diameter or side, cm	Test lot weight, kg Wheat	Sorghum
10.2		3,050
12.7	5,180	3,050
15.2	5,180	4,840
17.8	5,180	4,840
20.3	8,180	7.640
22.9	8,180	7,640
25.4	8,180	7,640

RESULTS AND DISCUSSION

Moisture content, test weight, mean kernel diameter, and BNFM of grain lots are given in Table 1. The flow rates of wheat through circular and square orifices are given in Table 3. The flow rates of sorghum through circular and square orifices are given in Tables 4 and 5, respectively. Each flow rate value shown in the Tables was the mean of two replicated tests. All coefficients of variability of replicated tests were less than 1%.

Effect of Orifice Size

Since log-log scale plots of volume flow rate vs orifice diameter or side length were nearly linear for all tests on wheat and sorghum, the flow rate was expressed as:

$$Q = C1\ U^{C2} \quad \ldots\ldots [3]$$

where

Q = volume flow rate, m^3/h

U = orifice size (diameter or side length), cm

C1 and C2 are coefficients

Volume flow rate was chosen instead of mass flow rate to

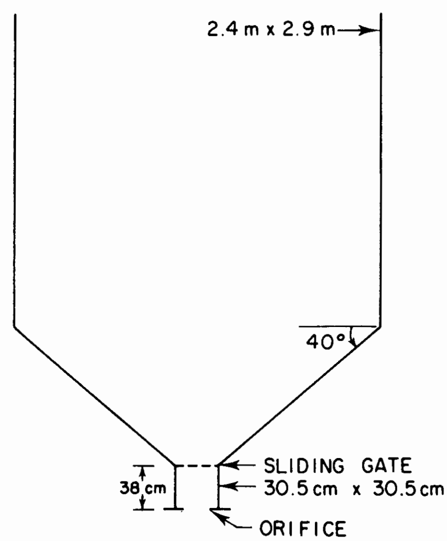

Fig. 1—Schematic of holding bin.

TABLE 3. FLOW RATES (m^3/h) OF WHEAT THROUGH HORIZONTAL ORIFICES

Orifice type	Variety	Moisture content, % w.b.	Orifice diameter or side length, cm					
			12.7	15.2	17.8	20.3	22.9	25.4
Circular	Newton	12.9	38.1	58.2	85.0	120.4	170.4	242.4
	Mustang	14.4	37.2	55.7	81.6	117.9	164.3	234.5
	Hawk	15.1	37.9	57.6	85.7	122.9	175.1	243.5
Square	Newton	12.9	49.6	77.5	115.2	166.5	241.0	
	Mustang	14.4	47.7	74.5	109.8	161.3	234.3	
	Hawk	15.1	48.5	75.9	114.7	166.0	241.6	

TABLE 4. FLOW RATES (m^3/h) OF GRAIN SORGHUM THROUGH HORIZONTAL CIRCULAR ORIFICES

Hybrid	Moisture content, % w.b.	Orifice diameter, cm						
		10.2	12.7	15.2	17.8	20.3	22.9	25.4
Hoegemeyer	11.2	21.5	39.4	60.3	85.7	118.4	157.2	211.4
	13.8	21.5	39.4	59.7	84.9	118.5	160.9	219.7
	17.7	22.0	39.6	60.8	88.0	122.9	167.9	231.7
Cargill 70	12.6	22.1	40.3	61.4	86.7	121.0	159.9	216.5
	15.8	21.7	40.1	61.0	87.7	123.5	169.6	232.4
Dekalb 42Y	12.8	21.7	39.8	60.6	85.8	121.7	161.2	220.3
	16.1	21.7	39.4	60.4	87.4	123.1	167.3	233.4
Funk G-522R	11.6	18.5	35.0	54.2	77.1	104.9	139.4	193.8
	15.6	19.8	37.8	57.2	82.1	113.3	153.8	215.4

be the parameter expressed as a function of orifice size, because an orifice has direct effect or control over volume flow rate rather than mass flow rate.

Wheat

For wheat, the flow rates for Newton and Hawk were similar and were slightly higher than for Mustang, but the differences were not significant at the 0.05 level. Therefore, data from all three wheat lots were combined for regression analysis to obtain coefficients C1 and C2 (Table 6) in equation [3] for both circular and square orifices. The correlation coefficients for the regression were 0.99 or higher and the standard error of estimate ranged from 5.2 to 6.9 m^3/h. Regression curves and six data points for each orifice size for the circular and square orifices are shown in Fig. 2. The flow rates of wheat through 13 and 25 cm diameter orifices were about 40 and 220 m^3/h, respectively. The flow rate of wheat was not affected by its moisture content probably because the changes in surface characteristics of wheat kernels were small within the moisture range (12.9 to 15.1%) tested.

Sorghum

The flow rate increased as the moisture content increased for all four hybrids of sorghum. Data for sorghum were divided into two moisture groups, lower than 14% and higher than 15%. Within a group, the flow rates for Hoegemeyer, Cargill, and Dekalb hybrids were very similar. However, the flow rate for the Funk hybrid was about 10% lower. Lower flow rates for the Funk hybrid were probably due to its low test weight and

TABLE 5. FLOW RATES (m^3/h) OF GRAIN SORGHUM THROUGH HORIZONTAL SQUARE ORIFICES

Hybrid	Moisture content, % w.b.	Orifice side length, cm					
		10.2	12.7	15.2	17.8	20.3	22.9
Hoegemeyer 688	11.2	28.3	49.5	76.5	108.6	151.5	208.4
	13.8	28.2	49.5	75.8	110.0	155.2	218.5
	17.7	28.6	50.4	78.4	114.0	161.8	228.9
Cargill 70	12.6	28.9	50.3	77.9	110.3	155.1	213.2
	15.8	28.8	50.3	79.0	114.3	163.2	229.7
Dekalb 42Y	12.8	28.6	49.7	77.0	109.7	156.6	217.8
	16.1	28.4	49.4	78.4	113.0	161.8	229.2
Funk G-522R	11.6	24.6	44.5	68.4	98.4	133.1	188.3
	15.6	26.4	47.7	72.9	105.6	147.2	210.8

TABLE 6. COEFFICIENTS OF THE EQUATION* EXPRESSING VOLUME FLOW RATE OF GRAIN AS A FUNCTION OF ORIFICE SIZE

Grain	Moisture content range, % w.b.	Coefficients			
		Circular orifice		Square orifice	
		C1	C2	C1	C2
Wheat	12.9 to 15.1	4.198×10^{-2}	2.656	5.033×10^{-2}	2.693
Sorghum	11.2 to 13.8	7.056×10^{-2}	2.467	9.216×10^{-2}	2.461
Sorghum	15.6 to 17.7	6.076×10^{-2}	2.531	7.844×10^{-2}	2.532

*$Q = C1\ U^{C2}$

sprouted kernels, which might increase surface friction.

Regression analyses were performed for each moisture group to obtain coefficients C1 and C2 (Table 6) for each type of orifice. The correlation coefficients were 0.99 or higher and the standard error of estimate ranged from 5.9 to 6.9 m³/h. Fig. 3 shows the regression curves for circular and square orifices. For a given size of orifice, the flow rate of high moisture sorghum was about 5% higher than that of lower moisture sorghum. The effect of moisture content on the flow rate of sorghum was opposite to the effect of moisture content on the flow rate of corn (Chang et al., 1984). A possible explanation for the higher flow rates of sorghum at the higher moisture contents is that the fine trichomes (hair) on kernel surfaces would become softer at the higher moisture contents. The softer hair might have reduced the friction between kernels during movement, which might have resulted in higher flow rates.

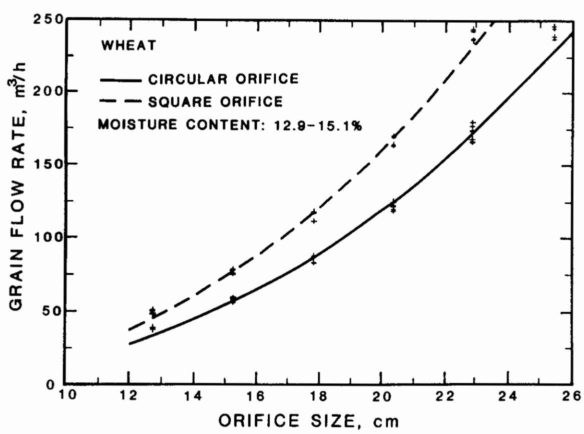

Fig. 2—Volume flow rates of wheat through horizontal orifices.

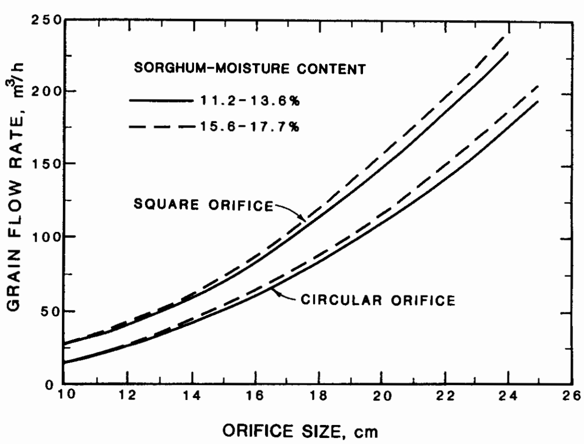

Fig. 3—Volume flow rates of sorghum through horizontal orifices.

The flow rates of low moisture sorghum through the 13 and 25 cm diameter orifice were about 40 and 200 m³/h, respectively. The flow rates of wheat and sorghum were very similar for orifice sizes smaller than 16 cm. The difference in flow rate between wheat and sorghum increased as the orifice size increased. For a 25 cm diameter orifice, the flow rate of wheat was about 5 to 10% higher than that of sorghum.

Comparison

Using the mean equivalent kernel diameter of 3.4 mm for wheat and sorghum (Table 1), the flow rates calculated from equation [1] (Beverloo et al., 1961) were about 3 to 9% lower for wheat and 1 to 10% lower for sorghum as compared with flow rates obtained from these experiments.

Using the k values of 23.7 for wheat and 24.6 for sorghum in equation [2] (Gregory and Fedler, 1987), the flow rates calculated from this equation were 21 to 51% higher for wheat and 13 to 65% higher for sorghums as compared with flow rates obtained from these experiments for orifice diameters ranging from 12.7 to 25.4 cm. As stated by Gregory and Fedler (1987), equation [2] was intended for small orifices and might not be valid for large orifices.

It should be noted that the short spout at the bottom of the hopper (Fig. 1) may affect the flow rate if the size of orifice approaches the size of the spout. The slope of hopper may also have some effects on the flow rate particularly when the slope is above 60 deg from horizontal (Williams, 1977).

SUMMARY AND CONCLUSION

Experiments were conducted to determine the flow rates of wheat and sorghum through various sizes of circular and square horizontal orifices and to measure the effect of moisture content on the flow rates. Three wheat varieties with moisture contents ranging from 12.9 to 15.1% and four sorghum hybrids with moisture contents ranging from 11.2 to 17.7% were tested. The orifice sizes ranged from 10.2 to 25.4 cm in diameter and from 10.2 to 22.9 cm square with increments of 2.5 cm for both sets of orifices.

The observed relationships between the volume flow rate and the orifice diameter or the side length for both wheat and sorghum were log-linear. Consequently, the flow rate predicting equation is of the form of the equation [3].

The flow rate of sorghum increased as the moisture content increased within the range of moisture content tested, but the flow rate of wheat was not significantly (at the 0.05 level) affected by moisture content. The differences in flow rates between wheat and sorghum were small at orifice sizes smaller than 16 cm but increased as the orifice size increased. For a 25 cm diameter orifice, the flow rate of wheat was about 5 to 10% higher than that of sorghum.

References

1. Beverloo, W. A., H. A. Leniger, and J. van de Velde. 1961. The flow of granular solids through orifices. Chem. Eng. Sci. 15:260-269.
2. 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 ASAE 27(5):1586-1589.
3. Fowler, R. T. and J. R. Glastonbury. 1959. The flow of granular solids through orifices. Chem. Eng. Sci. 10:150-156.
4. Gregory, J. M. and C. B. Fedler. 1987. Equation describing granular flow through circular orifices. TRANSACTIONS of the ASAE 30(2):529-532.
5. Ketchum, M. S. 1919. Design of walls, bins, and grain elevators. McGraw-Hll, NY.
6. Moysey, E. B., E. W. Lambert, and J. Wang. 1985. Flow rtes of grains and oilseeds through orifices. ASAE Paper No. 85-3530, ASAE, St. Joseph, MI 49085.
7. Stahl, B. M. 1950. Grain bin requirements. USDA Circular No. 835 (Based on data in Engineering Data on Grain Storage, Agricultural Engineering Data 1:1-11, 1948).
8. Whited, Willis. 1901. The flow of semi-fluids through orifices. Proc. Eng. Soc. Western Penna. 17:113-129.
9. Williams, J. C. 1977. The rate of discharge of coarse granular materials from conical mass flow hoppers. Chem. Eng. Sci. 32:247:255.