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FLOW RATES OF GRAIN THROUGH VERTICAL ORIFICES

by

C. S. Chang, H. H. Converse and J. L. Steele
Agricultural Engineers
USDA-ARS-USGMRL
Manhattan, KS 66502

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SUMMARY:

Flow rates of wheat, corn, sorghum and soybeans through various sizes of circular and square vertical orifices were measured. The effect of grain moisture content on flow rate was also evaluated. Coefficients for an empirical equation to predict volume flow rate of grain through vertical openings were determined.

KEYWORDS:
Grain, flow rates, orifice

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Flow Rates of Grain Through Vertical Orifices

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C. S. Chang, H. H. Converse, and J. L. Steele[1]

ABSTRACT

Flow rates of wheat, corn, sorghum, and soybeans through circular and square vertical orifices were measured. Orifice sizes ranged from 10.2 to 30.5 cm in diameter or side length with increments of 2.5 cm. Moisture contents of the grain lots ranged from 10.2 to 23.0% for wheat, from 13.2 to 22.4% for corn, from 11.6 to 18.0% for sorghum, and was 12.3% for soybeans. For all grains and moistures, the flow rate increased geometrically with orifice size. For a given size of orifice, the flow rate was higher for sorghum and was lower for wheat and corn at the higher moisture content. Coefficients for an empirical equation to predict volume flow rate of grain through vertical openings were determined. Coefficients for each grain type, orifice shape, and a high versus low moisture range were presented.

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[1]Agricultural Engineers, U. S. Grain Marketing Research Laboratory, ARS, USDA, 1515 College Avenue, Manhattan, KS 66502.

INTRODUCTION

Information on the flow rate of grain through various sizes, shapes, and orientations of openings is needed to determine grain flow and to properly size the opening for flow control during transfer of grain. Flow of grain and other granular materials through horizontal openings has been investigated by a number of researchers (Beverloo et al., 1961; Chang et al., 1984; Chang and Converse, 1988; Gregory and Fedler, 1987; Moysey et al., 1988), however, little information is available regarding flow of grain through vertical openings.

Flow rate of grain through an opening is independent of the depth of grain above the opening (Ewalt and Buelow, 1963; Fowler and Glastonburg, 1959). It has been reported that the flow rate of granular materials through horizontal openings varies with the diameter raised to a power ranging from 2.5 to 3 (Chang et al., 1984; Gregory and Fedler, 1987). Beverloo et al. (1961) suggested that flow rate varies with the orifice area times the orifice hydraulic diameter raised to 0.5 power:

$$Q = 0.75\, A_e \sqrt{g D_e}$$

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

Ewalt and Buelow (1963) conducted experiments on the flow of dried shelled corn (11% w.b.) through vertical openings. They were able to correlate their results using the following expression:

$$Q = a \cdot D^b$$

where

Q = volume flow rate, bu/min

D = diameter or side length of opening, in

a and b are constants

Ewalt and Buelow's experimental data were limited to openings of 13 cm or smaller.

The objectives of this study were to determine the flow rates of grain through circular and square vertical openings and to evaluate the effect of moisture content on grain flow rate.

MATERIAL AND EQUIPMENT

Three test lots each of wheat and sorghum, two test lots of soybeans, and five test lots of shelled corn were used in the experiments. Each lot of wheat, sorghum, and soybeans was freshly harvested and tested for flow rate soon after harvest. Wheat, sorghum, and soybean lots with initial moisture content higher than 14% were dried to lower moisture contents for further tests. Drying was accomplished in a drying bin using forced air with no added heat. Three of the five corn lots were freshly harvested and tested soon after harvest. Corn lots with initial moisture content higher than 17% were dried to lower moisture contents for further tests. Two of the five corn lots were from storage where the grain had been held for about three months after harvest.

Grain variety or hybrid, moisture content, test weight (bulk density) and broken kernels and fines content for each grain lot are given in Tables 1 through 4. Moisture content and test weight were determined by a grain analysis computer (Model GAC II, Dickey-john Corporation, Auburn, IL). Broken kernels and fines content were determined by methods used by FGIS (USDA, 1980).

Fig. 1 is a schematic of the grain handling system used for the flow rate tests. A rectangular steel container (120 x 150 x 120 cm high) was used to hold test grain for experiments. A 30 x 30 cm square spout from the holding bin terminating at the top of the container supplied and maintained grain at a constant level in the container during all tests. Test orifices were installed in a vertical sidewall of the container with the center of all orifices located 23 cm above the bottom of the container. A sliding gate mounted outside the test orifice was used to control the start and stop of a given test. The container and holding bin were filled with test grain and then the gate was opened to permit grain to flow through the orifice to a receiving bin below the test container. Test times varied from 3 min for large orifices to 18 min for small orifices. After test completion, grain collected in the receiving bin was weighed and returned to the holding bin for replication. Grain weight and flowing time were recorded and used to determine the mass flow rate of grain for each test. Volume flow rate was calculated from the mass flow rate and test weight (bulk density) of the grain.

A set of circular and square orifices were used for all grain test lots. Each orifice shape consisted of nine sizes ranging from 10.2 to

30.5 cm diameter or square with increments of 2.5 cm.

Two replicated tests were conducted for each orifice size and shape. Before and after a series of orifice size and shape tests for each grain lot, samples were taken by an automatic sampler (Carter-Day, CHCI132) for moisture content, test weight, and broken kernel and fine material determinations.

RESULTS AND DISCUSSION

The rates of flow through various sizes of circular and square orifices for wheat, corn, sorghum, and soybeans are given in Tables 1, 2, 3, and 4, respectively. Each flow rate value shown in the Tables was the mean of two replicated tests. The coefficients of variability for all replicated tests were less than 2%.

Effect of Orifice Size

The logarithmic plots (Fig. 2) of volume flow rate vs. orifice diameter or side length were nearly linear for all tests on wheat, corn, sorghum, and soybeans, thus flow rate can be expressed as:

$$Q = k \cdot D^n \qquad (1)$$

where

Q = volume flow rate, m^3/h

D = orifice size, cm

k and n are coefficients

A regression analysis (SAS, 1985) was performed for each grain tested at each moisture group to determine the coefficients in equation (1) for both circular and square orifices. These values are shown in Table 5.

Wheat

Three lots of wheat at 5 levels of moisture content ranging from 10.2 to 23.0% were tested (Table 1). Flow rates of wheat at 23% moisture content were significantly (0.05 level) lower than those at the other four moisture levels. Therefore, flow rate data for wheat were divided into two moisture groups, lower than 15% and at 23%, for regression analysis. R-square values for the regression coefficients (Table 5) were 0.99 or greater and standard error of estimate ranged from 1.8 to 5.0 m^3/h. Regression results for both circular and square orifices are shown in Fig. 3. Flow rates of low moisture wheat through 10 and 30 cm circular orifices were about 10 and 160 m^3/h, respectively. Comparing flow rates (Table 1) for the two moisture levels of the same lot of grain showed flow rate increased as the moisture content decreased. Flow rates of high moisture wheat (23%) were about 30% lower than the flow rates of low moisture wheat for both orifice types. Wheat harvested at or above 23% moisture content is uncommon in most seasons.

Corn

Five lots of corn at 7 levels of moisture content ranging from 13.2 to 22.4% were tested (Table 2). Flow rates of corn with moisture contents of 20.3 and 22.4% were significantly (0.05 level) lower than those of corn at lower moisture levels. Flow rate data for corn also were divided into two moisture groups, higher than 20% and lower than 17%, for regression analysis. R-square values for the regression coefficients (Table 5) were 0.99 or greater and standard error of estimate ranged from 1.7 to 2.9 m^3/h. Regression curves for both circular and square orifices are given in Fig. 4. Flow rates of low moisture corn through 10 and 30 cm circular orifices were about 7 and 155 m^3/h, respectively. For the same lot of corn, flow rate increased as the moisture content decreased.

<u>Sorghum</u>

Three lots of sorghum at 5 levels of moisture content ranging from 11.6 to 18.0% were tested (Table 3). An analysis of variance indicated that flow rates of sorghum with 18% moisture were significantly (0.05 level) higher than those of sorghum at lower moisture levels. However, differences in mean flow rates were less than 5%, therefore data from all moisture levels were combined for regression analysis to determine coefficients (Table 5) in equation (1) for both circular and square orifices. R-square values for the regression were 0.99 or greater and standard error of estimate ranged from 2.1 to 2.7 m^3/h. Regression curves and data points for both circular and square orifices are given in Fig. 5. Flow rates of sorghum through 10 and 30 cm circular orifices were about 8 and 140 m^3/h, respectively. For the same lot of sorghum, flow rate decreased slightly when the grain was dried to a lower moisture content.

<u>Soybeans</u>

Two lots of soybeans at the same level of moisture content (12.3%) and similar test weight were tested (Table 4). Difference in flow rate between these two soybean lots was significant (0.05 level). Low flow rate for lot 1 was attributed to high contents of broken kernels and fines. Flow rate data were combined for regression analysis to determine coefficients (Table 5) in equation (1) for both sets of orifices. R-square values for the regression were 0.99 or greater and standard error of estimate ranged from 2.8 to 3.8 m^3/h. Regression curves and data points for both circular and square orifices are given in Fig. 6. Flow rates of soybean through 10 and 30 cm diameter orifices were about 7 and 145 m^3/h, respectively.

Comparison

Flow rates per unit area of vertical and horizontal openings for various types of low moisture grain (<15% w.b.) are given in Table 6. These flow rates were based on a circular and square openings of 400 cm^2, which was about the average orifice size in the tests conducted. Flow rate data for horizontal openings were from previous studies (Chang et al., 1984 and Chang and Converse, 1988).

Comparing circular and square vertical orifices, flow rate per unit area through circular orifices was greater for corn and soybeans, lower for wheat, and similar for sorghum. Comparing circular and square horizontal orifices, flow rate per unit area through circular orifices was greater for wheat, corn, and sorghum. Comparing vertical to horizontal orifices, the ratios of flow rate per unit area of vertical opening to horizontal opening were about 0.47, 0.50, and 0.43 for wheat, corn, and sorghum, respectively.

SUMMARY AND CONCLUSIONS

Tests were conducted to determine the flow rates of wheat, corn, sorghum, and soybeans through various sized circular and square vertical orifices. The effect of moisture content on grain flow rate was determined using three wheat lots ranging in moisture content from

10.2 to 23.0%, five corn lots ranging from 13.2 to 22.4%, three sorghum lots ranging from 11.6 to 18.0%, and two soybean lots at 12.3%. Orifice sizes ranged from 10.2 to 30.5 cm diameter or side length with increments of 2.5 cm.

The observed relationships between volume flow rate and orifice diameter or side length for wheat, corn, sorghum, and soybeans were log-linear. Consequently, flow rate of grain through vertical orifices was expressed as a power function of orifice diameter. Grain lots were grouped into high and low moisture regions and the power function coefficients were determined using regression analysis.

Flow rate of wheat and corn decreased as moisture content increased, but the flow rate of sorghum increased as moisture content increased within the range of moisture content tested. For a given size of orifice, flow rate of wheat was greatest and flow rate of sorghum was lowest among the four types of grain at the low moisture level (<15%). The flow rates of corn and soybeans were similar. Grain flow rates per unit of orifice area were slightly greater for circular compared to square orifices.

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Table 1. Flow Rates (m^3/h) of Wheat Through Vertical Orifices+

Orifice Type	Lot No.	Variety or Hybrid	Test Weight* kg/m^3	(lb/bu)	Moisture* Content % w.b.	Broken* Kernels & Fines %	Orifice diameter or side length, cm								
							10.2	12.7	15.2	17.8	20.3	22.9	25.4	27.9	30.5
Circular	1	Arkan	667	(51.8)	23.0	<1	6.1	11.4	18.2	28.1	39.9	54.6	71.8	91.9	111.0
			785	(61.0)	11.5	<1	9.8	18.8	28.9	42.7	59.6	80.7	103.0	128.8	154.6
	2	Pioneer 2157	794	(61.7)	14.4	<1	9.6	17.6	28.3	41.8	58.3	75.7	100.7	127.4	150.2
			826	(64.2)	11.3	<1	9.8	18.4	28.8	42.4	59.7	79.5	103.9	134.6	165.1
	3	Norkan	852	(66.2)	10.2	<1	10.2	18.8	29.4	42.4	59.3	80.4	105.7	136.7	167.1
Square	1	Arkan	667	(51.8)	23.0	<1	8.3	15.6	25.0	37.6	54.6	76.4	96.3	123.0	153.5
			785	(61.0)	11.5	<1	13.6	24.6	39.4	57.9	82.3	109.8	141.6	178.9	216.6
	2	Pioneer 2157	794	(61.7)	14.4	<1	13.0	23.8	38.4	57.7	77.0	103.5	135.1	171.1	205.4
			826	(64.2)	11.3	<1	13.4	24.5	39.5	58.2	80.5	107.7	143.5	184.2	225.9
	3	Norkan	852	(66.2)	10.2	<1	13.8	25.0	39.6	58.2	82.6	116.6	147.0	185.9	234.5

\+ Average of two replications.
* Average at beginning and end of tests.

Table 2. Flow Rates (m^3/h) of Corn Through Vertical Orifices[+]

Orifice Type	Lot No.	Variety or Hybrid	Test Weight* kg/m^3	(lb/bu)	Moisture* Content % w.b.	Broken* Kernels & Fines %	Orifice diameter or side length, cm								
							10.2	12.7	15.2	17.8	20.3	22.9	25.4	27.9	30.5
Circular	1	Dekalb 636	780	(60.6)	13.6	2.8	7.4	15.1	25.6	35.7	52.7	74.2	95.4	124.4	164.3
	2	Dekalb 636	785	(61.0)	14.0	3.3	7.1	14.2	23.9	35.4	51.4	72.7	92.7	122.6	154.6
	3	Dekalb 656	721 759	(56.0) (59.0)	22.4 13.3	2.0 5.1	6.5 7.3	12.6 14.3	20.7 23.6	32.8 36.6	47.0 52.2	64.1 72.0	81.5 94.3	107.6 122.4	133.9 154.5
	4	Dekalb 656	730 771	(56.7) (59.9)	20.6 13.2	1.9 4.0	6.8 7.1	13.5 14.2	22.6 23.3	34.6 36.1	49.3 51.9	66.5 72.3	88.2 95.2	112.2 125.8	140.7 156.9
	5	Dekalb 636	763	(59.3)	16.1	1.3	6.7	13.6	23.3	35.5	51.3	70.8	94.6	124.7	158.3
Square	1	Dekalb 636	780	(60.6)	13.6	2.8	9.9	19.7	34.4	47.5	70.5	96.5	127.4	171.7	223.2
	2	Dekalb 636	785	(61.0)	14.0	3.3	9.7	18.7	32.2	47.3	69.2	96.7	125.3	164.2	216.5
	3	Dekalb 656	721 759	(56.0) (59.0)	22.4 13.3	2.0 5.1	9.0 9.9	17.3 18.7	29.5 32.0	45.3 49.3	63.3 69.9	86.1 95.9	111.1 127.5	144.9 167.0	180.4 212.0
	4	Dekalb 656	730 771	(56.7) (59.9)	20.6 13.2	1.9 4.0	9.4 9.6	18.4 18.8	31.3 31.4	47.3 48.4	67.0 69.7	90.3 97.1	118.1 128.4	149.6 167.1	186.0 214.3
	5	Dekalb 636	763	(59.3)	16.1	1.3	9.6	18.4	31.9	48.8	69.5	96.1	128.2	168.2	215.0

\+ Average of two replications.
* Average at beginning and end of tests.

Table 3. Flow Rates (m^3/h) of Sorghum Through Vertical Orifices[+]

Orifice Type	Lot No.	Variety or Hybrid	Test Weight* kg/m^3	Test Weight* (lb/bu)	Moisture* Content % w.b.	Broken* Kernels & Fines %	Orifice diameter or side length, cm								
							10.2	12.7	15.2	17.8	20.3	22.9	25.4	27.9	30.5
Circular	1	Golden Harvest H-510B	762	(59.6)	12.9	5.5	7.6	14.3	22.8	34.3	48.1	65.8	87.7	111.8	137.4
	2	Garst 5511	722	(56.1)	14.7	2.4	8.5	15.6	24.8	36.4	48.4	64.4	85.5	110.4	136.7
			739	(57.4)	11.7	2.8	7.8	14.6	23.1	34.1	47.4	63.5	84.5	110.0	134.4
	3	Garst 5511	759	(59.0)	18.0	2.1	8.0	14.9	23.6	35.3	50.4	68.5	90.9	117.2	143.6
			767	(59.6)	11.6	3.1	6.8	13.4	21.6	33.4	48.3	66.5	88.6	115.0	141.9
Square	1	Golden Harvest H-510B	762	(59.6)	12.9	5.5	10.6	19.1	31.0	47.3	66.6	89.7	120.1	152.1	185.5
	2	Garst 5511	722	(56.1)	14.7	2.4	11.8	20.9	34.1	48.2	67.5	89.2	119.2	150.8	190.2
			739	(57.4)	11.7	2.8	10.8	19.8	31.9	47.7	65.3	88.4	117.5	148.5	184.9
	3	Garst 5511	759	(59.0)	18.0	2.1	10.8	19.7	32.8	48.6	68.4	92.2	124.5	159.1	197.6
			767	(59.6)	11.6	3.1	9.3	17.8	29.8	45.3	64.7	91.2	121.3	157.0	196.8

\+ Average of two replications.
* Average at beginning and end of tests.

Table 4. Flow Rates (m^3/h) of Soybeans Through Vertical Orifices[+]

Orifice Type	Lot No.	Variety or Hybrid	Test Weight* kg/m^3	(lb/bu)	Moisture* Content % w.b.	Broken* Kernels & Fines %	Orifice diameter or side length, cm								
							10.2	12.7	15.2	17.8	20.3	22.9	25.4	27.9	30.5
Circular	1	Ohlde 3431	720	(55.9)	12.3	11.8	7.0	13.4	21.8	33.4	47.9	66.0	88.6	117.4	145.7
	2	Ohlde 3431	722	(56.1)	12.3	5.7	7.5	14.3	23.2	35.4	51.0	70.7	94.8	125.0	156.1
Square	1	Ohlde 3431	722	(55.9)	12.3	11.8	9.7	18.0	30.2	46.3	65.1	88.9	118.5	155.9	199.1
	2	Ohlde 3431	722	(56.1)	12.3	5.7	10.5	19.6	32.3	48.6	69.2	95.2	127.8	167.1	213.3

\+ Average of two replications.

* Average at beginning and end of tests.

Table 5. Coefficients of the equation* expressing volume flow rate (m^3/h) of grain as a function of orifice size (cm).

Grain	Moisture Content range	Coefficients			
		Circular Orifice		Square Orifice	
		C1	C2	C1	C2
Wheat	Low (<15%)	0.0291	2.524	0.0380	2.542
	High (23%)	0.0129	2.662	0.0181	2.655
Corn	Low (<17%)	0.0117	2.783	0.0155	2.791
	High (>20%)	0.0121	2.738	0.0185	2.702
Sorghum	Low (<15%)	0.0182	2.619	0.0245	2.626
Soybeans	Low (12.3%)	0.0123	2.757	0.0182	2.730

* $Q = k \cdot D^n$

Table 6. Grain flow rates per unit area of openings ($m^3/h \cdot cm^2$) for 400 Cm^2 openings.

Orifice Orientation	Grain	Orifice Type: Circular	Orifice Type: Square	Flow rate difference between circular and square orifices %
Vertical	Wheat	0.190	0.193	-1.6
	Corn	0.171	0.166	2.9
	Sorghum	0.160	0.160	0.0
	Soybeans	0.166	0.162	2.4
Horizontal	Wheat	0.413	0.401	2.9
	Corn	0.347	0.331	4.6
	Sorghum	0.385	0.367	4.7

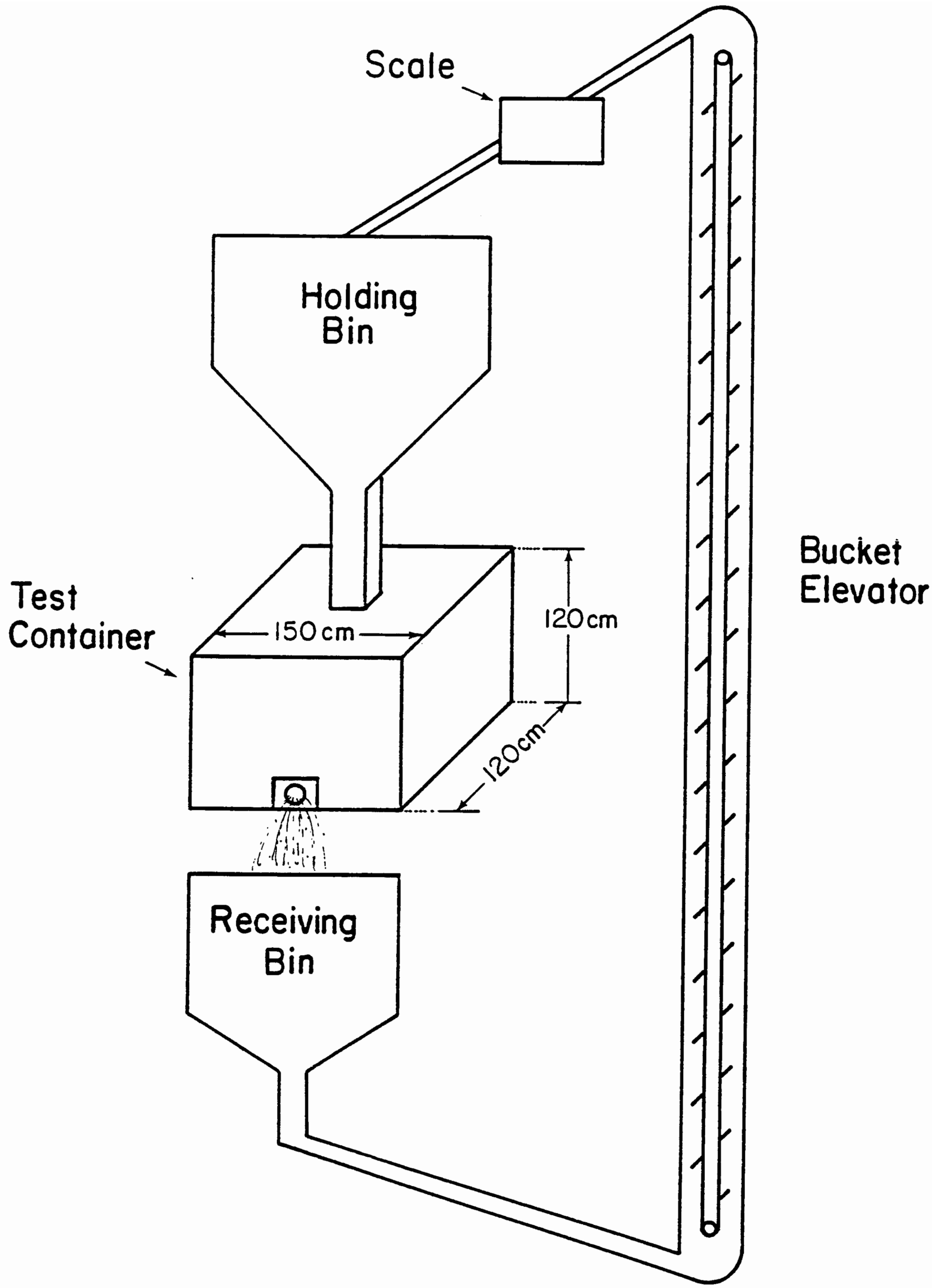

Fig. 1 Schematic of grain handling system for flow rate tests.

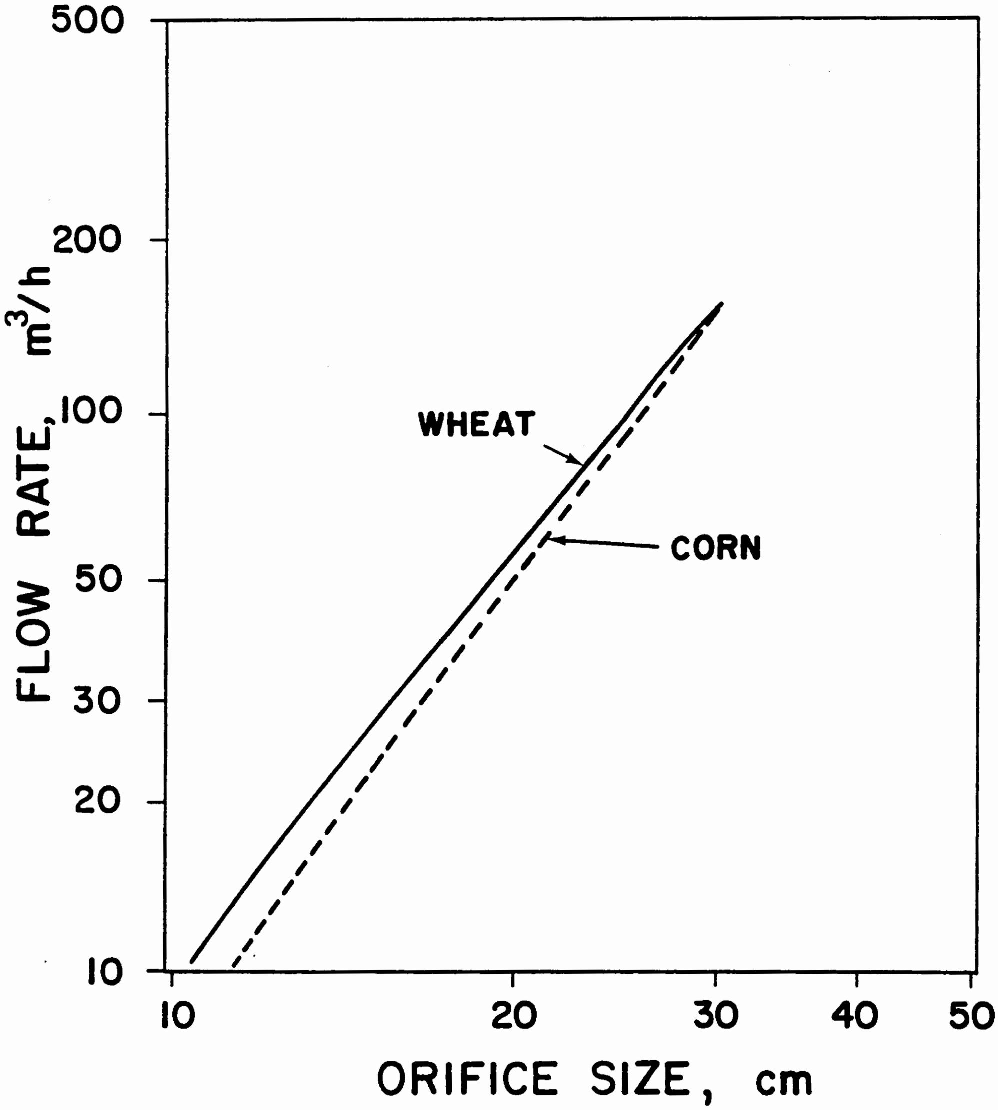

Fig. 2 Typical plots of flow rate versus orifice size.

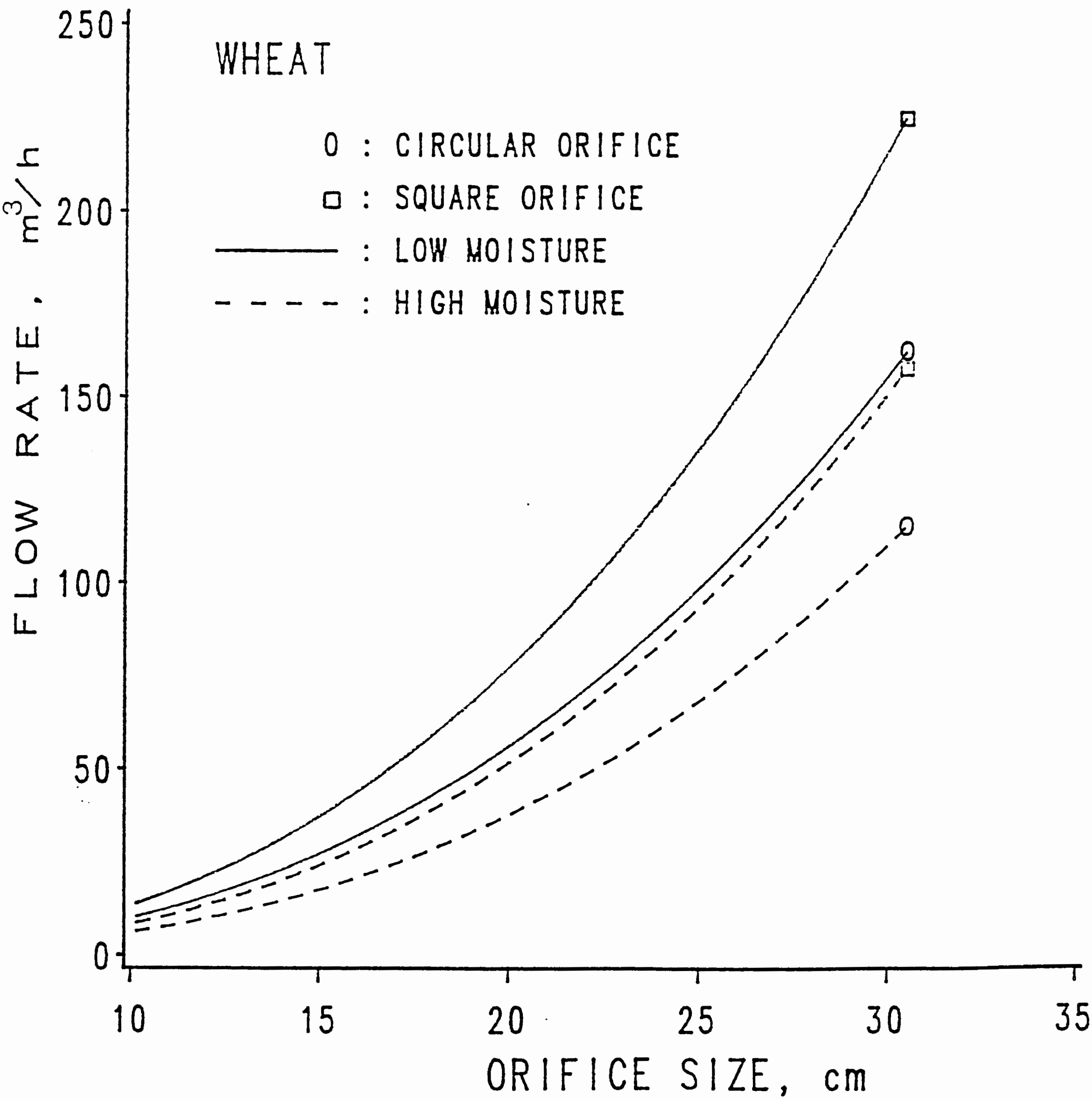

Fig. 3 Volume flow rates of wheat through vertical orifices.

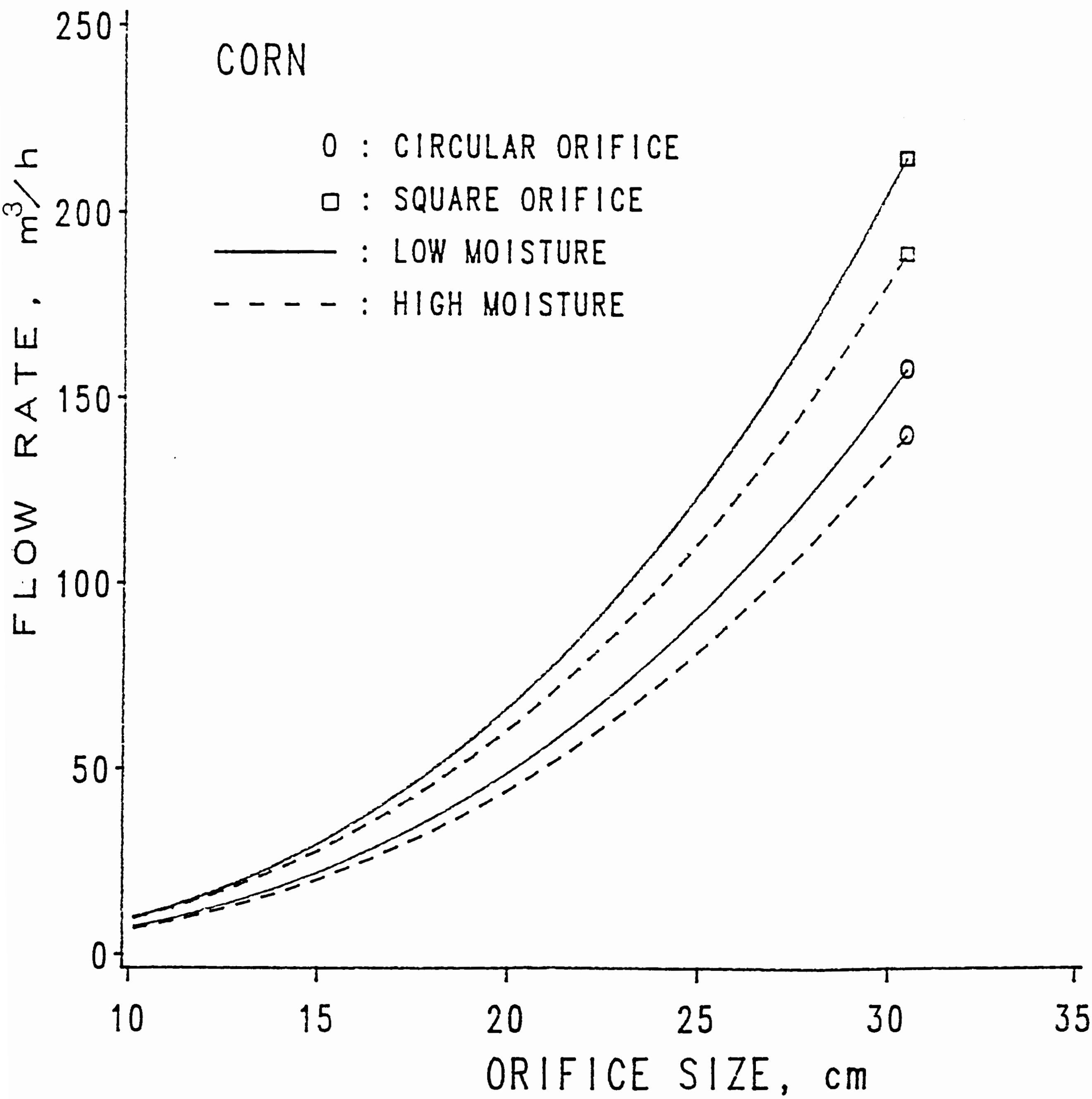

Fig. 4 Volume flow rates of corn through vertical orifices.

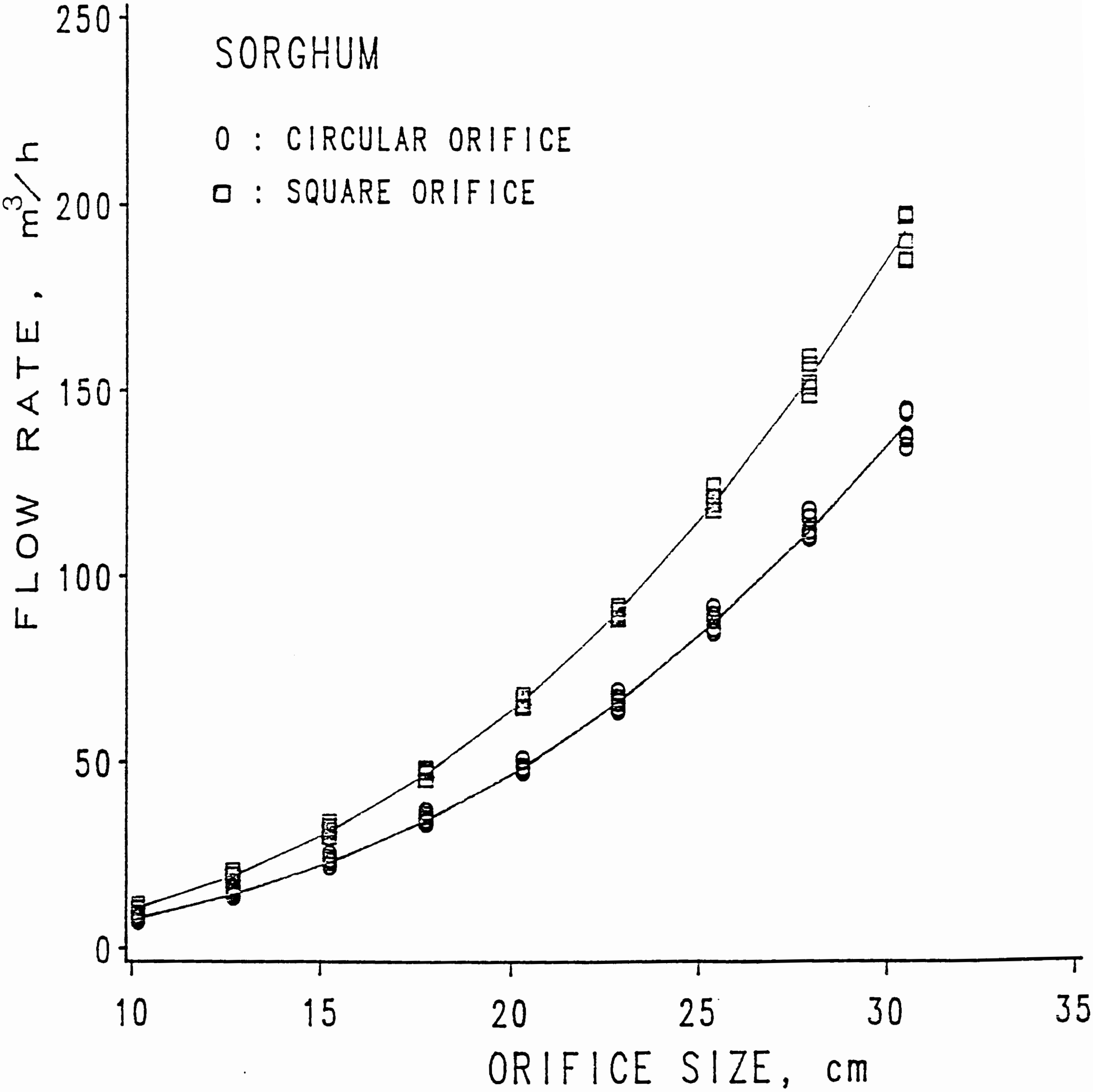

Fig. 5 Volume flow rates of sorghum through vertical orifices.

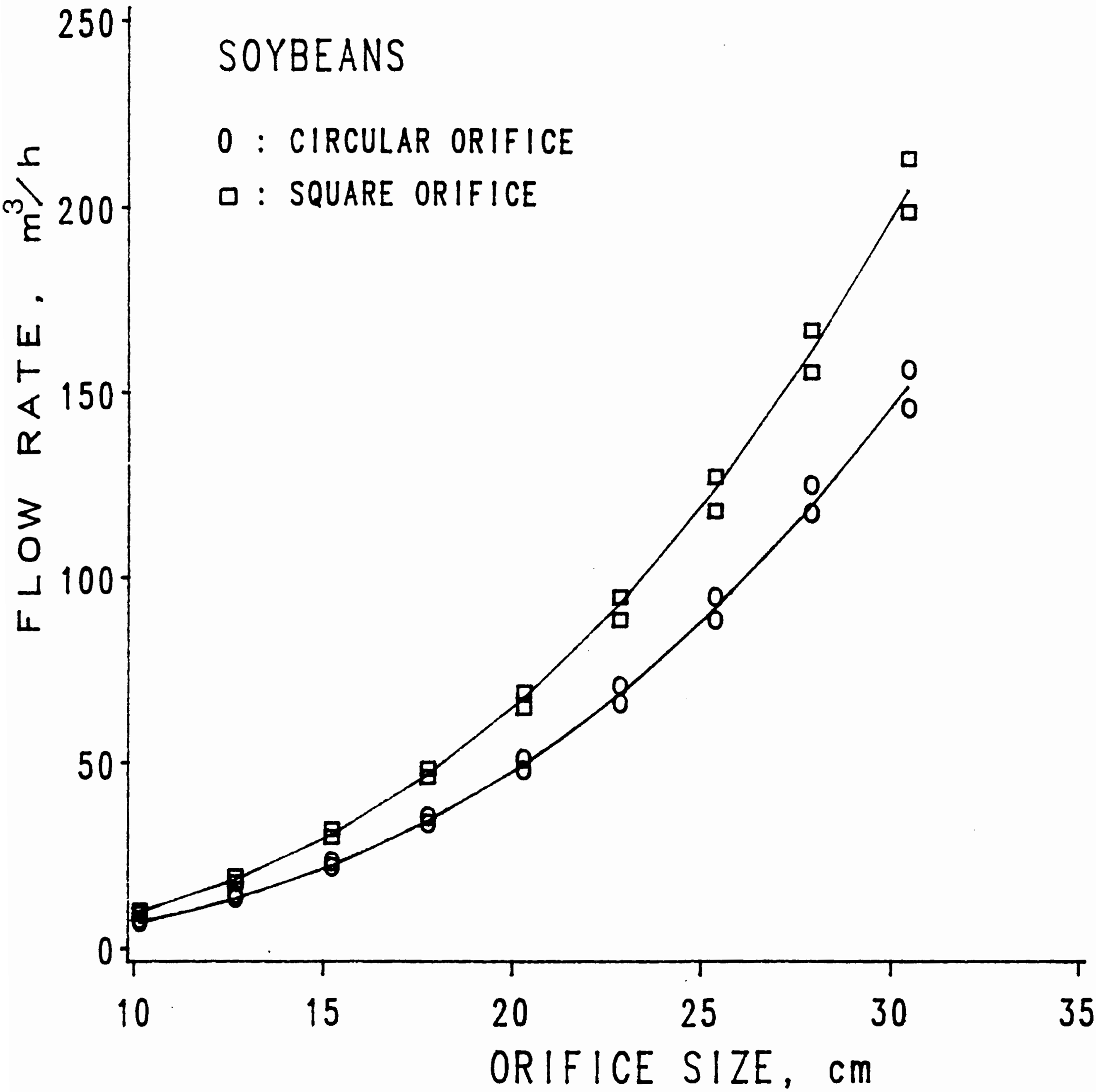

Fig. 6   Volume flow rates of soybeans through vertical orifices.