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THE RATE OF BURNING OF CRIBS OF WOOD

by

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ABSTRACT

Because cribs of wood are widely used to produce experimental fires it is sometimes necessary to predict their burning behaviour especially when their burning rate is not controlled primarily by some other factor such as the window opening in a compartment. If the window is large enough the behaviour of the compartment fire is strongly influenced by the crib design and it is desirable to compare the behaviour of the crib in the compartment and in the open to assess the influence of, say, heat loss to the walls.

Several sets of crib data for burning in the open are available and in this report some attempt is made to correlate their behaviour.

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SUMMARY

Assemblies of wooden sticks known as cribs or cross-piles are often used in fire experiments as a standard fire. They usually consist of two or more layers of parallel sticks, the sticks in each layer being at right angles to those in the layers immediately above and below. The sticks in alternate layers are usually directly above each other, but this is not always so, for example, Bryan has used cribs with three sticks in each layer arranged as an equilateral triangle.

The rate at which such cribs burn and the way it depends on the design of the crib are important for planning and interpreting experiments, and for relating them to fires in which, furniture, say, is the fuel. This note shows how two sets of data obtained at the Fire Research Station, Boreham Wood, for over sixty cribs can be correlated reasonably closely by a simple empirical formula. An earlier study by Gross who included a much wider range of stick size in his experiments, but who did not vary the overall size of the crib and the stick size independently showed that there were two regimes of burning. In the first, the porosity of the crib or its voidage ratio could control the rate of burning, but once the spaces between the sticks became large enough in relation to the stick size the burning rate appeared to reach a limiting value depending only on the stick size and the overall weight of the crib. There are some discrepancies between Gross's correlation and that described in this paper and some suggestions are made as to the origin of this. Generally speaking all the information including Gross's for cribs larger than about 30 cm linear size up to 200 cm can be correlated by one formula which is

$$\frac{r}{A_V\sqrt{H}} \doteqdot k.\left(\frac{A_S}{A_V}\right)^{0.5} \quad \text{i.e.} \quad \frac{r}{\sqrt{A_V \; A_S H}} \doteqdot k$$

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in which r is the rate of weight loss, A_v is the horizontal cross sectional area of the vertical passages in the crib, A_s is the surface area of the exposed wood and H is the height of the crib.

As the cribs become larger k decreases slightly but no one simple form for k has been found which is justified for all three sets of data. Employing the variables A_s and A_v, which have the best justification for the main variation in r, k is roughly

$$\frac{0.0017}{(A_s A_v)^{0.052}} \text{ c.g.s. units.}$$

KEYWORDS: Wood, crib, burning rate.

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INTRODUCTION

The earliest experiments to study the behaviour of cribs appear to have been those by Folk[1]. The problem of scale effects in cribs was used as an example by Emmons[2] in a discussion of modelling fires and following some suggestions of Emmons, Gross[3] conducted a systematic study of cribs most of which however were cubical, the smallest having a side of 1.6 cm and the largest one of 91 cm. Each crib was made of sticks ten times longer than their thickness and was usually ten thicknesses high. He varied the number of sticks per layer, i.e. the horizontal spacing, and made a few experiments in which the number of layers was altered. By and large, tightly packed cribs burnt faster the wider the spacing between the cribs. Beyond a certain spacing, the burning rate depended on the total weight of the crib and the stick thickness according to simple power law and at very large spacings the crib failed to burn properly. In this paper we shall refer to other quantities which are obtainable from the basic properties referred to above. These are the surface area of exposed wood A_s, the fraction of a side of a crib which is open f, the horizontal cross sectional area of vertical shafts of a crib A_v, and the weight of the crib W.

In this note we have collected together details of a number of experiments in which wooden cribs were burned in the open. In addition to the experiments of Gross, we have made use of data obtained by O'Dogherty[4] who designed cribs in order to obtain a range of burning rates in his study of the behaviour of sprinklers. We have also used the data obtained by Webster and his collaborators[5] who used cribs to study the height of flames. O'Dogherty himself tried to present his data using the parameters given by Gross, but found many discrepancies between his and Gross's data.

We have already mentioned how most of Gross's experiments were conducted with cubes and how all of them were conducted with cribs having sticks ten times longer than their thickness. Consequently all but one of the independent design parameters of the cribs (for a given species of wood) are virtually perfectly correlated together and the only one which is not so correlated is the fraction f which is directly related to the number of sticks per layer which Gross varied systematically. Although O'Dogherty's cribs were not all cubical there is considerable correlation between the various pairs of design parameters, though as with Gross's data the fraction f is only weakly correlated with the others. However, in addition to f stick thickness b is also only weakly correlated with the others, there being some correlation however between f and b. Although Webster and his collaborators mainly used one stick thickness they did vary this in some cases and stick thickness is not too strongly correlated with the other parameters. In addition the height of the crib is only weakly correlated with the other design parameters. There are experimental differences between the three groups of tests.

The method of ignition is slightly different, but it is doubtful if this is of major significance though one might expect it to be so for very tightly packed cribs.

ANALYSIS OF DATA

Table 1 lists the maximum rate of burning r together with the dimension of the sticks and the cribs (L, H, b and W) L being the length of the sticks. Gross supported his cribs on two single sticks at the edge so that the calculation of the dependent terms such as f is not the same for his data as for the others and the following two formulae have been used:

for O'Dogherty and Webster

$$f = 0.5 - \frac{nb}{2L}$$

and for Gross

$$f = \frac{N(10-n) + 16}{20\,(N + 1)}$$

where n = no. of sticks per layer

N = no. of layers

A_s and A_v are also listed. We have not included those experiments by Gross in which wood other than Douglas Fir was used. Neither have we included the experiments using 1.6 mm sticks.

Although Gross found two separate regimes some preliminary attempts at finding correlations suggested that one could use power laws and accordingly several multiple regression analyses were carried out on a computer using linear regressions of the logarithm of the variables. In each of these the rate of burning was treated as the dependent variable. It is found for each experimental group that a maximum of three independent variables accounted almost completely for all the variation. Adding further variables made negligible improvement. Table 2 lists for each experimental group the five most significant sets of independent variables. These five together with several less significant sets gave almost equally good correlations. The only pair of variables which are perfectly correlated are L and b in Gross's experiments, but in all the data there are many pairs of variables which are very highly correlated together and several alternative correlations were therefore equally good. The choice between these had to be governed therefore to some extent by comparing the three different sets of experiments where independent variables are differently correlated to each other. W (the weight of a crib) is present in each of the five sets of correlation of Gross's and Webster's data but in only one set of O'Dogherty's data whereas H (the height of the crib) is present in all sets for O'Dogherty's data but in only two of those for Gross's data and one for Webster's and is not so important for the data as a whole. Since the decomposition of wood is largely the result of processes taking place in the gas phase within the crib, and the surface layers of the wood, the weight of the crib does not seem to be a physically meaningfull term to include and moreover may or may not, according to the experimental conditions, include materials other than wood such as glue and possibly nails. For any one species of wood, weight is uniquely determined by the other parameters and it was decided to exclude it for these reasons from the analysis. The most significant sets of independent variables (taken in sets of three independent variables) for each experimental group are those given in Table 3, and it is noticeable that one set (a) comprising H, A_V and A_S is common to all groups and, perhaps fortuitously, is the most significant set for all groups taken together. The indices in the relationship

$$r \propto H^x A_V^y A_S^z$$

are interesting.

In no case could the index of H, 'x', be regarded as significantly different from 0.5, the index of A_V, 'y', was only slightly less than 0.5, and the negative of the index of A_S, 'z', is only slightly greater than 0.5, and most important, the indices of each variable were consistent between the three sets of data. It was therefore decided to investigate the relations of the form

$$\frac{r}{A_v\sqrt{H}} \propto A_v^{\,y}\,A_s^{\,z}$$

Two other sets of independent variables (b) and (c), having overall correlation coefficients only slightly lower when all the data were taken together, had indices which were not consistent between the three groups of experiments.

If the frictional resistance to the flow of air in a crib is low, the velocities of the gases within the crib will be determined by the buoyancy and the inertia of the gas and consequently the volumetric flow rate of the gas moving vertically would be proportional to $A_v\sqrt{H}$*. Accordingly correlations were made for each group using a fuel to air ratio as the dependent variable and A_s and A_v as the two independent variables. The results are shown in Table 4. The consistency of the indices is encouraging. However, in most cases the difference from a numerical value of 0.5 is significant, so that $\frac{r}{\sqrt{A_v\ A_s H}}$ cannot strictly be treated as a constant. However, in view of the close correlation between A_v and A_s in some cases, and between one or other of them and other design parameters of the cribs, it would be rash to attach undue importance to the variations of this quantity as being associated with a surface area of wood or a vent area or with any other parameters to the exclusion of the rest.

DISCUSSION

In Fig.1 Gross's data are shown plotted in terms of the regression equation and it is seen that we are in effect putting a single line through points which quite clearly are better represented by two lines as Gross himself has shown. However before this approach is rejected it is as well to consider Fig.2 which shows all the data plotted in terms of $\frac{r}{A_v\sqrt{H}}$ and $\frac{A_s}{A_v}$. O'Dogherty's and Webster's data lie very close to a straight line through the origin and this line is a lower bound to Gross's data, some of which lie close to the line, but many of which, particularly those for small cribs, burn much faster than would be predicted from the correlation. Gross's data for cribs exceeding 20 cm may be regarded as consistent with the others but those less than 20 cm lie above the line. Only for Gross's data can one identify two lines of data. Also plotted in this graph are some data obtained by Byram[6] in whose experiments the

*Whether or not one employed this procedure, some procedure dividing r by an area is at least desirable and justifiable (see Appendix 1).

height of the crib, the stick size and the stick spacing remained constant, but the overall base area of the crib was varied. Byram's crib size varied from about 6 cm to 39 cm and as the cribs become larger his results lie closer to the main body of the data. Also shown are three experiments by Bryan[7] who put three sticks in an equilateral triangle in each layer of his crib, the results of three experiments are all close together and lie only slightly below the main body of data. Byram showed that his data followed a simple law

$$r \propto L^{7/4}$$

and he referred to the similarities between this and the burning of the liquid in laminar flow where there is a quarter power law between both heat and mass transfer coefficients and scale for natural convection. We have plotted

$$\frac{r\,L^{\frac{1}{4}}}{A_V\sqrt{H}} \quad \text{against} \quad \frac{A_S}{A_V}$$

(not reproduced here) and this brings together the results obtained by Gross for the smaller sticks but it tends to separate the data for large cribs. However, Fig.3 shows $\frac{r}{\sqrt{A_V\,A_S\,H}}$ plotted against the size of the crib base, and there is a substantial variation in the value of $\frac{r}{\sqrt{A_V\,A_S\,H}}$ for small values of L. Although one may be tempted from this to argue that there is an effect of L up to 100 cm, and perhaps beyond, no such effect can be found within, say, O'Dogherty's data which suggests that at large values of L the effect disappears and that it would be better to regard $\frac{r}{\sqrt{A_V\,A_S\,H}}$ as falling with increasing scale. That there are design factors which produce some significant effect at these large values of L is clear from the fact that the effects of A_S and A_V cannot strictly be accounted for solely by the simple square root of their ratio.

The equations in Table 4 can be reformulated as in Table 5, and it is seen that for O'Dogherty and Webster's data the values of M and M' are almost equal, the difference is certainly not significant. For Gross's data M and M' are different. A_S and A_V can each be expressed either as proportional to the square of the stick size or to the square of the crib size for given ratios of stick size to stick spacing, etc. The ratio of A_S to A_V is dependent only on such ratios and as such is independent of scale. If only L varies the correlation of Gross's data gives $r \propto L^{1.53}$ (or $b^{1.53}$) which compares with $L^{1.75}$ (Byram) and $b^{1.6}$ (Gross). For O'Dogherty and Webster's data the correlation gives $r \propto L^{1.79}$. However, in the statistical analysis which included A_s; A_v, H, L and b there does not appear to be any statistical justification for replacing the term involving the product $A_v A_s$ by a term involving L or b. In an analysis of $\frac{r}{A_v \sqrt{H}}$ as a function of the above 7 variables, only A_v and A_s were significant for the data as a whole and no pattern of data was common to all three sets of data. In other words the variation of $\frac{r}{\sqrt{A_v A_s H}}$ can be associated with L or b (Fig.3) but in view of the correlation between L, A_s, A_v and b there is no statistical justification for including L or b or f instead of A_s and A_v. If, however, L or b is used one obtains indices similar to those already derived by Gross and Byram.

A suggested empirical formula

We can write

$$\frac{r}{\sqrt{A_v A_s H}} = \frac{k}{(A_v A_s)^{0.052}}$$

where, from table 4,

$$k = \frac{0.0035}{A_s^{0.013} \cdot A_v^{0.118}} \quad \text{for Gross's data}$$

$$k = 0.0019\left(\frac{A_v}{A_s}\right)^{0.010} \quad \text{for O'Dogherty's data}$$

$$k = 0.00145\,\frac{A_s^{\,0.013}}{A_v^{\,0.015}} \quad \text{for Webster's data}$$

$$\text{and } k = 0.0021\,\frac{A_s^{\,0.015}}{A_v^{\,0.053}} \quad \text{for all these data taken together}$$

All but one of these indices of A_v or A_s* are non-significant so we put A_s and A_v at their mean values and obtain four values of k respectively as 0.0018, 0.0015, 0.0020 and 0.00175, the last corresponding to the weighted mean of the three separate values, which, however, do differ significantly between themselves even though the variation is not unduly large.

The standard deviation of k for Gross and Webster's data corresponds to ± 6 per cent and for O'Dogherty's data to ± 1.5 per cent, so that the three populations differ. The σ's for individual values correspond to ± 35 per cent for Gross and Webster's data but only ± 9 per cent for O'Dogherty's. It has already been pointed out that Gross's data might be better represented by two lines than one. The success in correlating O'Dogherty's data so well is partly due to the narrower range of burning rates.

Byram's results show a somewhat smaller variation with size than is accounted

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* The exception is the A_v term in Gross's data

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for by a term such as $\frac{k}{(A_s A_v)^{0.052}}$, the value of k falling from 0.0018 to 0.0015 as the crib size increased from 6 to 39 cm. They clearly do, however, lie close to the other data.

CONCLUSIONS

None of the experiments undertaken so far cover a wide enough range of conditions for the effects of vertical and horizontal vent areas, exposed surface, height of crib, overall dimensions of the crib, stick size, etc. to be sufficiently independent of other variables for its effect to be properly assessed. In all the experiments discussed in this paper there are too many associations between pairs of variables for their effects to be fully separated but the formulae given here are the best simple formulae for which there appears to be reasonable statistical justification.

At the present state of our knowledge there is little point pretending that we know more than we do and obtaining complicated formulae involving several variables for which there is little justification. The equation

$$\frac{r}{\sqrt{A_s A_v H}} = \frac{0.0017}{(A_s A_v)^{0.052}} \qquad \text{in c.g.s. units}$$

appears to be adequate to describe mean burning rates of cribs typical of those used in most experimental purposes in the range 30 - 200 cm size. Some other variable instead of the product $A_s A_v$ might well be more appropriate in the weakly varying term $(A_s A_v)^{0.052}$ but no statistical justification for making any choice has been found so far.

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APPENDIX

The arguments of this paper are statistical though a significance has been given to $A_v\sqrt{H}$ which led to its use as a parameter.

In this appendix we comment on the extent to which the correlation has some physical significance.

Consider a vertical flow of constant velocity, U, at constant temperature through a bed of solids and the conventional mass transfer relation

$$\frac{m''}{\rho U} = f\left(B, \frac{\nu}{D}, Re, \varepsilon\right)$$

where

m'' is the mass transfer per unit wall area

ρ is fluid density

U is the velocity of the flow (based on unit cross-sectional area inclusive of solids)

B is Spalding's mass transfer number

Re is a Reynolds number which is taken as

$$= \frac{6\,U}{\sigma\,\nu}$$

σ is the specific surface of the solids

ν is the fluid kinematic viscosity

ε is the porosity (voidage ratio) of the bed

D is the diffusion coefficient for the fluid, assumed the same for all components

B & $\frac{\nu}{D}$ are properties of the fuel system and of the temperatures. Here they will be regarded as constants, compared with the much larger variation in the geometric quantities. In terms of the variables used in the statistical analysis we have

$$m'' = \frac{\Gamma}{4HL}$$

$$\varepsilon = \sqrt{\frac{A_v}{L^2}}$$

$$\sigma = \frac{A_s}{L^2\,H(1-\varepsilon)}$$

In addition, one has to consider the possibility of the flow being locally determined by the hot surfaces with no bulk movement except that produced by addition of the separate local flows. Then the corresponding mass transfer relation would be

$$\frac{rd}{A_s . \rho . D} = f_2 \left\{ \frac{gd^3}{\nu^2} . \frac{\nu}{D} . B \right\}$$

g is the acceleration due to gravity. d is the stick size. It does not have a constant relation to σ because the product $d\sigma$ depends on the spacing etc but for convenience $d\sigma$ is taken as $\frac{6}{\sigma}$. The difference between, say, $\frac{3}{\sigma}$ and $\frac{6}{\sigma}$ is equivalent only to a systematic change in a numerical constant of about $2^{\frac{1}{4}}$ i.e. 1.2 for the conventional $\frac{1}{4}$ power law.

Evaluating the form of U presents a difficulty. Air enters cribs from the sides and in some designs, notably those of Gross, from the bottom as well. There is therefore no mass continuity from one horizontal section to another, nor can one completely exclude the possibility of pressure variations within some cribs; it is observed that with some cribs the flames lean inwards towards the centre. We can however suggest a functional form for U. If there was only vertical acceleration due to gravity we would have, assuming uniform temperatures

$$U^2 \propto \varepsilon^2 g H \propto \frac{A_v H}{L^2}$$

If there is no acceleration and only vertical flow, we have from the definition of the "friction factor"

$$U^2 = \frac{6 . g . \varepsilon^3}{f_k \sigma (1 - \varepsilon)}$$

where $f_k = f_k \left(\frac{R_e}{1-\varepsilon}\right)$

Hence

$$U = \varepsilon \sqrt{gH} \left\{ \frac{6 \sqrt{A_v} L}{f_k A_s} \right\}^{\frac{1}{2}}$$

If both friction and acceleration have to be considered we would have

$$U \propto \frac{\sqrt{A_v . gH}}{L} \; f_3 \left(\frac{f_k \, A_s}{L\sqrt{A_v}} \, , \, \frac{L}{H} \right)$$

where we have also included $\frac{L}{H}$ to allow for geometric effects.

For packed beds, Ergun[8] gives

$$f_k = 1.75 + \frac{150\,(1 - \varepsilon)}{R_e}$$

and Wraight and Thomas[9] have found for cribs with $\varepsilon = \frac{1}{2}$ that

$$f_k = 0.28 + \frac{75}{R_e}$$

From the above definitions we can summarize the results as in Table 6.

If the mass flow generated from separate sticks is added a mean velocity is obtained. The corresponding Reynolds number is of order of magnitude of

$$\frac{L}{d} \left(\frac{g.d^3}{\nu^2} \right)^{\frac{1}{4}}$$

This is neither negligible compared with any other Reynolds number listed in Table 6, nor much greater so the system is not obviously only locally or only crib determined. The ranges of these Reynolds numbers are also listed in Table 6 (based on $\nu = 0.45\ cm^2/s$).

From the above, summarized in Table 6, we deduce

1) If the flow is locally determined it is by laminar boundary layers, since the Grashof number $\left(\frac{gd^3}{\nu^2} \right)$ does not exceed 10^8.

2) The ranges of the estimated Reynolds number overlap so no one model can be identified as the controlling mechanism.

3) The low Reynolds number neglecting friction (Row 2A in Table 6) implies that the inertia of the air cannot be neglected. The actual Reynolds number allowing for inertia and friction must be lower still.

(4) Of the forms deduced in the last column in Table 6 the nearest to the form deduced statistically are Rows 2A and 2B and 4A. Figures 4, 5 and 6 show $\frac{m''}{\rho U}$ against the appropriate Reynolds number.

The data of Gross clearly cover more than one regime but the data for higher Reynolds numbers have the same trend as in O'Dogherty and Webster's data. There are however significant differences between the three sets of data, Webster and O'Dogherty's data being nearer to $\frac{m''}{\rho U} \propto Re^{-\frac{1}{2}}$ than Gross's.

A very strong effect of $^L/H$ appears in Webster's data perhaps because the greater values of $^L/H$ produce a fast horizontal flow into the crib. O'Dogherty and Webster's data, while producing parallel but not overlapping correlation and the plot of Gross's data, show that all the very small cribs and the two largest lie off the correlation.

In view of the apparent absence of common regimes of behaviour for all the data and the absence of data on the velocities etc, no further analysis will be attempted here.

We can conclude only that there is some evidence to support the idea of correlating the burning of cribs with a mass transfer model.

Table 1

Experimental results

Gross

Rate of burning r g/s	Length of stick L cm	Height of crib H cm	Thickness of stick b cm	Number of layers	Weight of crib W g	Fraction of side open f	Surface area of sticks A_s cm^2	Open area of vertical shafts A_v cm^2
0.128	3.2	3.2	0.32	10	4.55	0.39	112	5.02
0.070	3.2	3.2	0.32	10	7.7	0.30	169	2.56
0.048	3.2	3.2	0.32	10	10.4	0.21	211	0.923
0.443	6.4	6.4	0.64	10	37.2	0.39	450	20.1
0.333	6.4	6.4	0.64	10	62.2	0.30	676	10.2
0.150	6.4	6.4	0.64	10	86.3	0.21	843	3.69
1.24	12.7	12.7	1.27	10	286	0.39	1771	79.0
1.98	12.7	12.7	1.27	10	477	0.30	2655	40.3
0.83	12.7	12.7	1.27	10	670	0.21	3319	14.5
0.98	19.1	5.73	1.91	3	454	0.39	1914	90.3
1.34	19.1	5.73	1.91	3	652	0.31	2477	32.5
1.69	19.1	9.55	1.91	5	752	0.34	3069	90.3
1.56	19.1	9.55	1.91	5	1052	0.26	3893	32.5
1.34	19.1	13.37	1.91	7	638	0.41	2794	177
2.38	19.1	13.37	1.91	7	1067	0.32	4225	90.3
1.70	19.1	13.37	1.91	7	1498	0.23	5307	32.5
1.97	19.1	19.1	1.91	10	906	0.39	3965	177
3.40	19.1	19.1	1.91	10	1535	0.30	5958	90.3
1.90	19.1	19.1	1.91	10	2118	0.21	7430	32.5
3.58	25.4	25.4	2.54	10	2570	0.39	7100	316
5.58	25.4	25.4	2.54	10	4150	0.30	10650	161
4.23	25.4	25.4	2.54	10	5970	0.21	13300	58
10.3	38.1	38.1	3.81	10	13570	0.30	23950	371
9.88	38.1	38.1	3.81	10	18640	0.21	29870	131
57.5	91.5	91.5	9.15	10	262000	0.21	172300	753
55.7	91.5	91.5	9.15	10	315000	0.16	184800	335

Table 1 (Cont'd.)

Experimental results

O'Dogherty

Rate of burning r g/s	Length of stick L cm	Height of crib H cm	Thickness of stick b cm	Number of layers	Weight of crib W g	Fraction of side open f	Surface area of sticks A_s cm^2	Open area of vertical shafts A_v cm^2
18.9	61	16	2.0	8	14800	0.25	46920	906
37.8	61	32	2.0	16	29800	0.25	92040	906
29.5	61	24	2.0	12	15500	0.32	54800	1520
30.2	61	24	2.0	12	15500	0.32	54800	1520
43.8	61	32	2.0	16	15000	0.37	55800	2020
43.1	61	32	2.0	16	15000	0.37	55800	2020
9.9	40.6	16	2.0	8	3470	0.38	11930	903
14.0	40.6	22	2.0	11	4540	0.38	16330	903
10.6	40.6	16	2.0	8	3290	0.38	11930	903
15.4	40.6	22	2.0	11	4370	0.38	16330	903
27.0	40.6	40	2.0	20	6900	0.38	29520	903
20.7	40.6	32	2.0	16	5680	0.38	23660	903
49.9	61	42	2.0	21	15000	0.40	56800	2400
51.4	61	42	2.0	21	15000	0.40	56800	2400
68.0	61	42.5	0.64	67	5450	0.47	60000	3270
104	61	85	0.64	134	10450	0.47	127900	3270
24.2	61	16.5	1.27	13	9090	0.33	55000	1660
21.2	61	16.5	1.27	13	9300	0.33	55000	1660
40.8	61	25.4	1.27	20	8850	0.40	56500	2330
39.3	61	25.4	1.27	20	8620	0.40	56500	2330
66.5	61	43.2	1.27	34	8180	0.44	67000	2950
141	91.5	61	2.54	24	103000	0.26	298000	2340
183	91.5	73.7	2.54	29	136000	0.25	376000	2100
144	91.5	73.7	2.54	29	114000	0.25	376000	2100
141	91.5	78.8	2.54	31	132000	0.25	400000	2100
142	91.5	73.7	2.54	29	129000	0.25	376000	2100
204	91.5	83.8	2.54	33	129000	0.29	374000	2850
163	91.5	81.3	2.54	32	131000	0.29	364000	2850
163	91.5	81.3	2.54	32	124000	0.29	364000	2850
167	91.5	81.3	2.54	32	130000	0.29	364000	2850
228	91.5	106.8	2.54	42	103000	0.36	343000	4380
240	91.5	106.8	2.54	42	107000	0.36	343000	4380
213	91.5	91.5	2.54	36	90000	0.36	294000	4380
242	91.5	91.5	2.54	36	92000	0.36	294000	4380
130	91.5	76.2	2.54	30	52600	0.30	165000	3120
71	91.5	61	2.54	24	29000	0.24	91800	1870
236	91.5	106.8	2.54	42	106000	0.36	343000	4380
239	91.5	106.8	2.54	42	105000	0.36	343000	4380
243	91.5	106.8	2.54	42	104000	0.36	343000	4380

Table 1 (Cont'd.)

Experimental results

O'Dogherty (cont'd)

Rate of burning r g/s	Length of stick L cm	Height of crib H cm	Thickness of stick b cm	Number of layers	Weight of crib W g	Fraction of side open f	Surface area of sticks A_s cm^2	Open area of vertical shafts A_v cm^2
307	91.5	112	1.27	88	65300	0.44	348000	6410
329	91.5	122	1.27	96	68100	0.44	379000	6410
317	91.5	122	1.27	96	68500	0.44	379000	6410
Webster								
3.64	25.4	20.3	2.54	8	2270	0.3	6800	231
3.96	25.4	20.3	2.54	8	2270	0.3	6800	231
2.65	25.4	15.3	2.54	6	1590	0.3	5200	231
7.28	25.4	40.6	2.54	16	4170	0.3	13400	231
5.66	25.4	30.5	2.54	12	3630	0.3	10200	231
15.2	50.8	20.3	2.54	8	6800	0.3	27200	930
10.7	25.4	40.6	1.27	32	4450	0.3	26700	231
21.2	50.8	20.3	1.27	16	7930	0.325	48400	1090
7.05	25.4	40.6	2.54	16	4990	0.25	15800	162
7.96	25.4	30.5	1.27	24	2900	0.3	20100	231
12.1	35.6	20.3	1.27	16	4430	0.322	24100	523
10.35	25.4	50.8	2.54	20	7030	0.3	8500	231
6.4	35.6	20.3	2.54	8	3310	0.322	12200	523
4.03	25.4	17.8	2.54	7	2510	0.25	7100	162
5.66	25.4	27.9	2.54	11	4080	0.25	11000	162
4.13	25.4	22.8	2.54	9	2770	0.25	9000	162
3.02	25.4	17.8	2.54	7	2040	0.25	7100	162
250	203	30.5	2.54	12	137000	0.375	438000	23000
165	203	20.3	2.54	8	89300	0.375	294000	23000
430	203	33.0	2.54	13	153000	0.375	474000	23000
325	203	33.0	2.54	13	147000	0.375	474000	23000
276	203	33.0	2.54	13	147500	0.375	474000	23000
50.5	101.5	58.4	2.54	23	68000	0.375	209000	5780
78	152.3	22.8	2.54	9	68000	0.375	186000	13000
213	152.3	33.0	2.54	13	90700	0.375	265000	13000

Table 2

Correlations Including W

Data	Order	L	H	f	A_v	b	A_s	W	Overall Correlation Coefficient for r	
Gross	1		X	X				X	97.34	For these regressions L = 10b
	2	X			X			X	97.29	
	3		X		X			X	97.28	
	4				X		X	X	97.11	
	5			X	X			X	97.10	
O'Dogherty	1		X		X		X		99.46	
	2		X		X			X	99.07	
	3	X	X		X				98.99	
	4		X	X			X		98.95	
	5		X	X	X				98.77	
Webster	1	X				X		X	98.22	
	2		X			X		X	98.21	
	3				X	X		X	98.16	
	4					X	X	X	98.00	
	5			X		X		X	97.91	
All	1		X		X		X		98.73	
	2		X	X			X		98.65	
	3			X			X	X	98.63	
	3	X			X		X		98.63	
	5			X	X		X		98.59	

Table 3

Correlations Excluding W

Data	Order	L	H	f	A_v	b	A_s	Overall Correlation Coefficient for r	
	1	X		X			X	96.93	
	2		X	X			X	96.92	(b)
Gross	3	X			X		X	96.87	(c)
	4		X		X		X	96.86	(a)
	5			X	X		X	96.85	
	1		X		X		X	99.46	(a)
	2	X	X		X			98.99	
O'Dogherty	3		X	X			X	98.95	(b)
	4		X	X	X			98.77	
	5	X	X	X				98.75	
	1	X	X			X		97.90	
	2	X	X				X	97.68	
Webster	3		X		X		X	97.55	(a)
	4				X	X	X	97.30	
	5	X				X	X	97.29	
	1		X		X		X	98.73	(a)
	2		X	X			X	98.65	(b)
All	3	X			X		X	98.63	(c)
	4			X	X		X	98.59	
	5			X		X	X	98.56	

TABLE 4

Regression Analysis of $y = (\log_{10} \frac{r}{A_v\sqrt{H}})$.

	No. of tests	y min	y max	$\overline{\log_{10}A_s}$	$\overline{\log_{10}A_v}$	b_{Av} / b_{As}	σ	t_{Av} / t_{As}	σ^2	k
GROSS	26	-2.65	-1.54	3.552	1.669	-0.670 / +0.435	0.064 / 0.058	10.4 / 7.5	0.016	0.0035
O' DOGHERTY	42	-2.56	-1.99	5.066	3.362	-0.542 / 0.438	0.036 / 0.019	15 / 23	0.0014	0.0019
WEBSTER	25	-2.94	-2.14	4.552	3.008	-0.567 / 0.461	0.119 / 0.147	4.8 / 3.15	0.015	0.00145
ALL	93	-2.94	-1.54	4.505	2.794	-0.605 / 0.463	0.03 / 0.032	19.8 / 14.5	0.011	0.0021

$$\frac{r}{A_v\sqrt{H}} = k \cdot A_v^{\,b_{Av}} \cdot A_s^{\,b_{As}}$$

TABLE 5

Reformulation of equations in Table 4

$$\frac{r}{\sqrt{A_V A_s H}} \propto \frac{1}{A_V{}^{M}}, \frac{1}{A_s{}^{M}}$$

Gross	$\frac{r}{\sqrt{A_V A_s H}} \propto \frac{1}{A_V{}^{0.17}} \quad \frac{1}{A_s{}^{0.065}}$
O'Dogherty	$\frac{r}{\sqrt{A_V A_s H}} \propto \frac{1}{A_V{}^{0.042}} \quad \frac{1}{A_s{}^{0.062}}$
Webster	$\frac{r}{\sqrt{A_V A_s H}} \propto \frac{1}{A_V{}^{0.067}} \quad \frac{1}{A_s{}^{0.039}}$

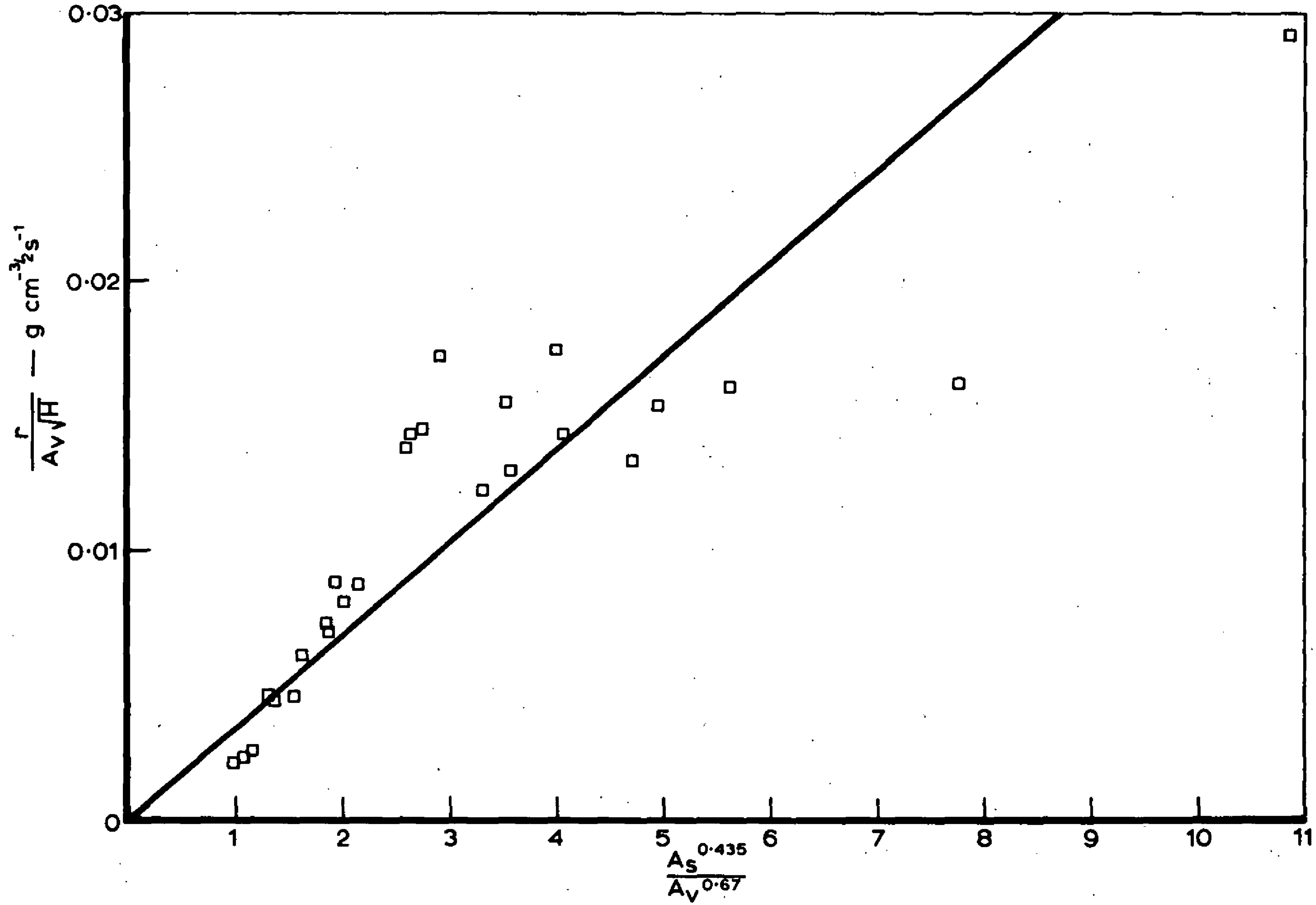


FIG. 1. DATA FROM GROSS

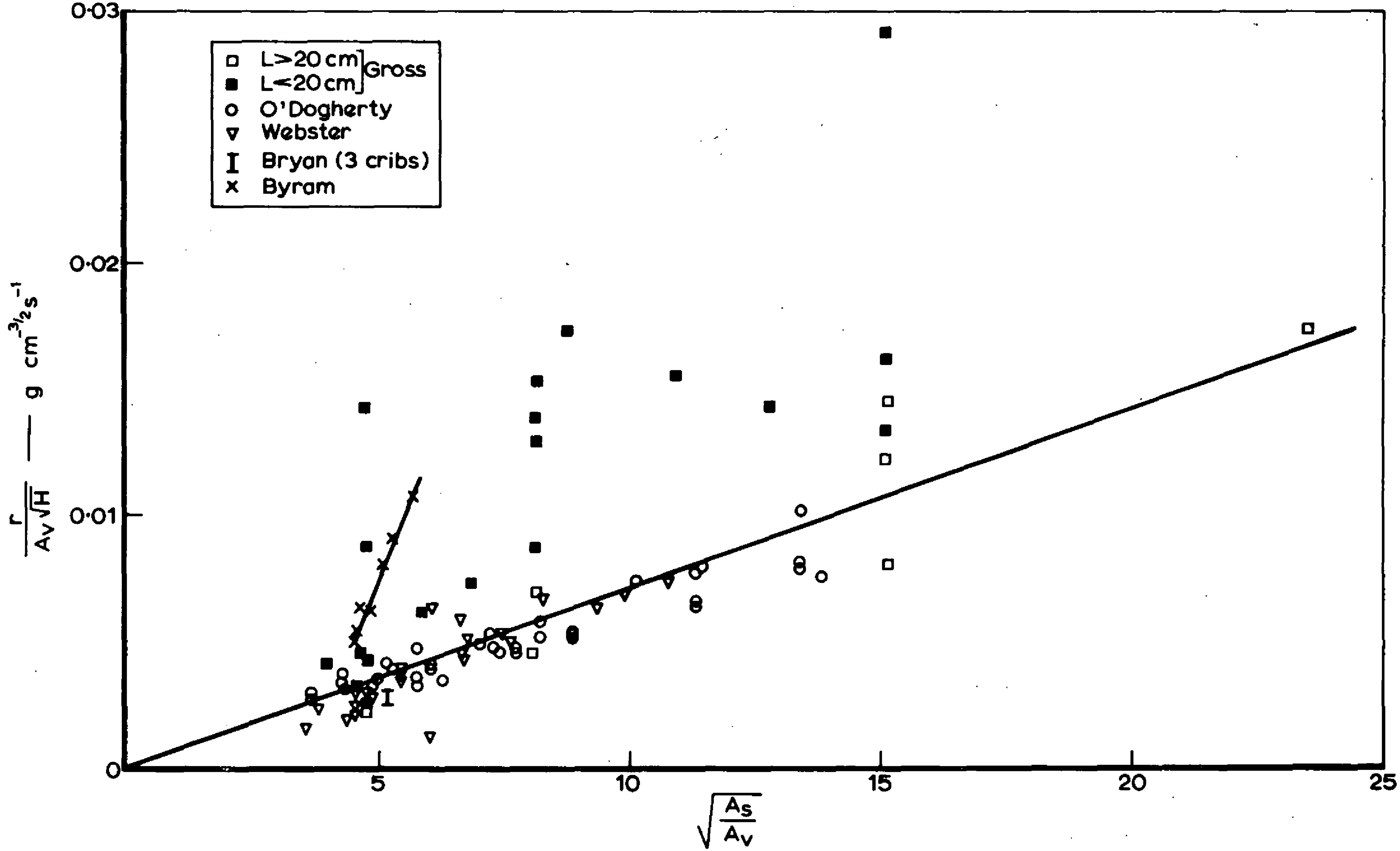


FIG. 2. CORRELATION OF $\frac{r}{A_V\sqrt{H}}$ WITH $\sqrt{\frac{A_S}{A_V}}$

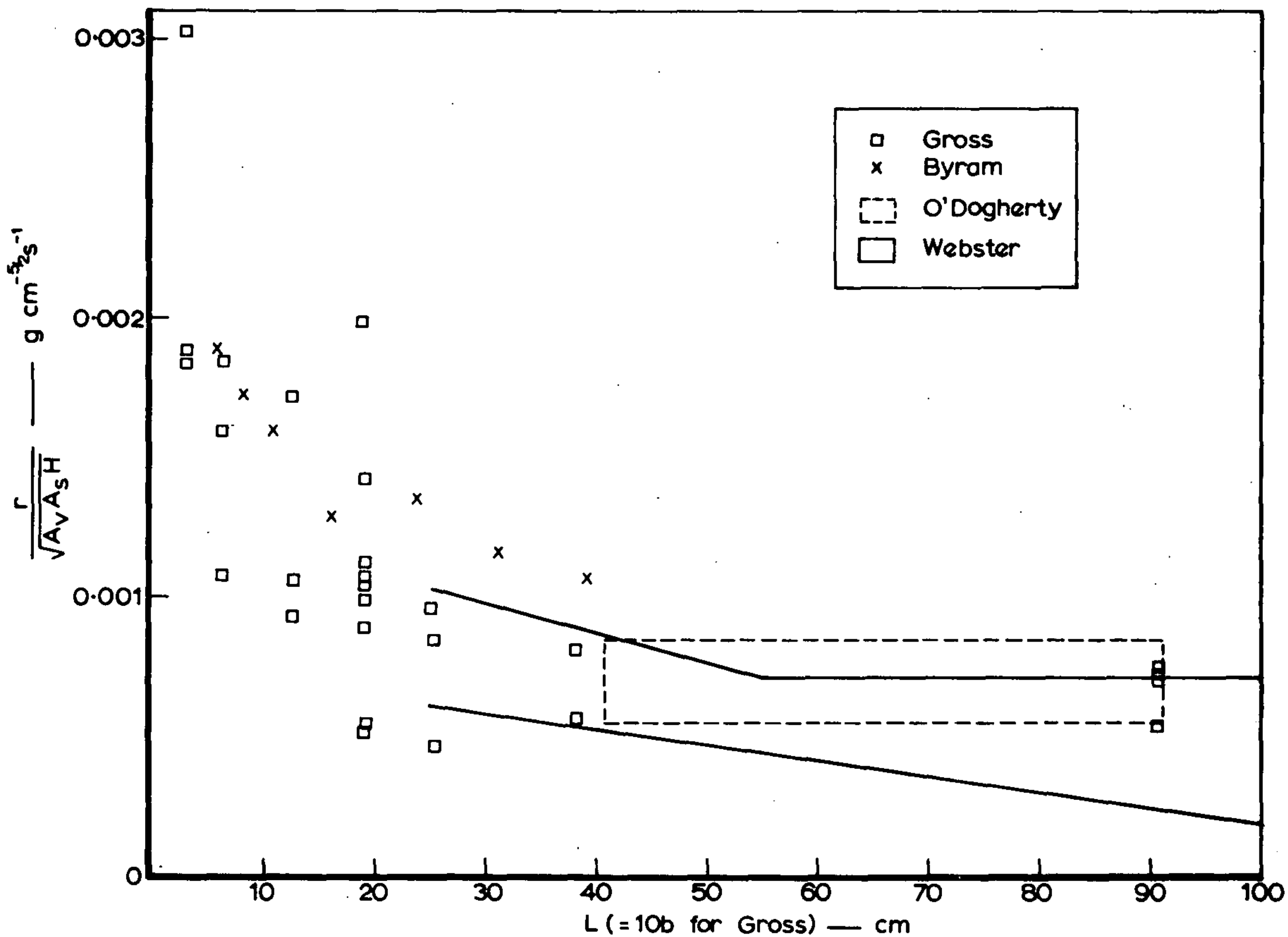
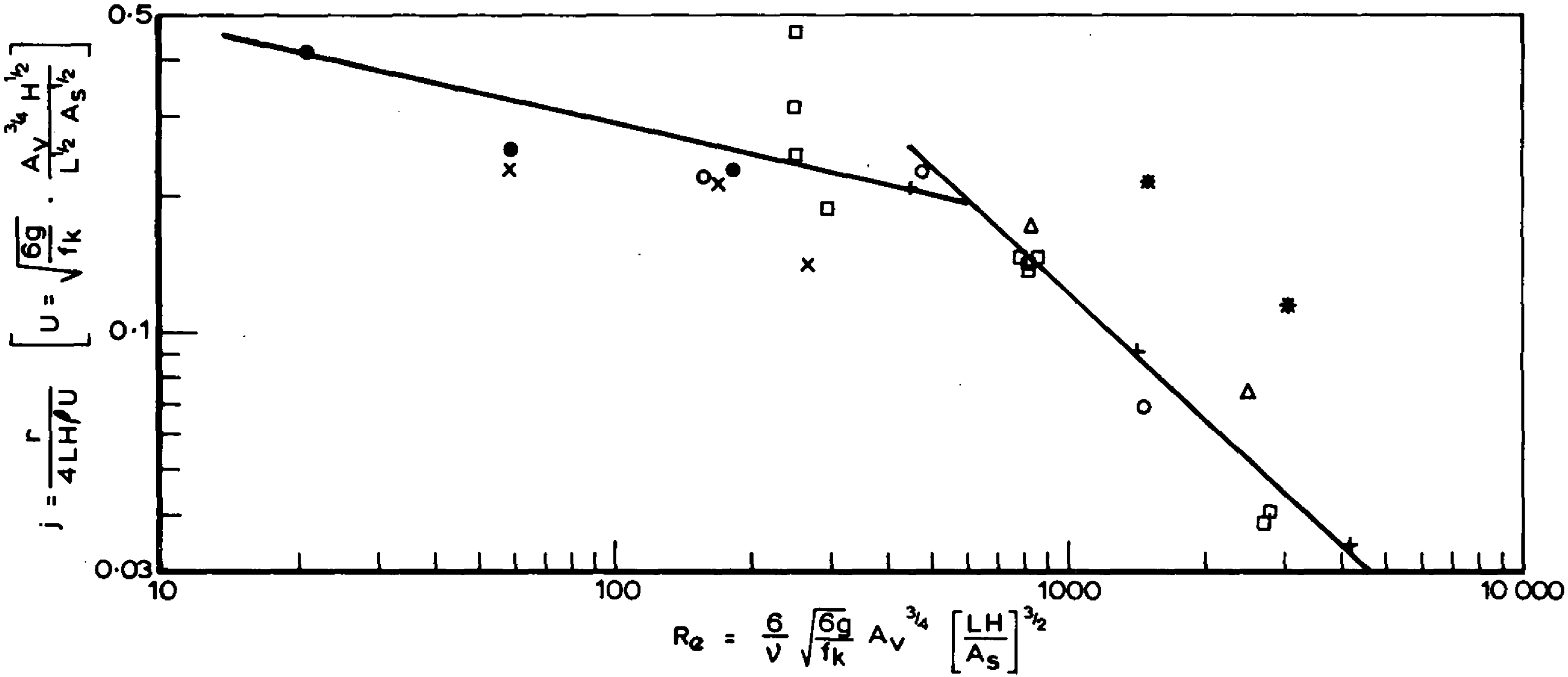


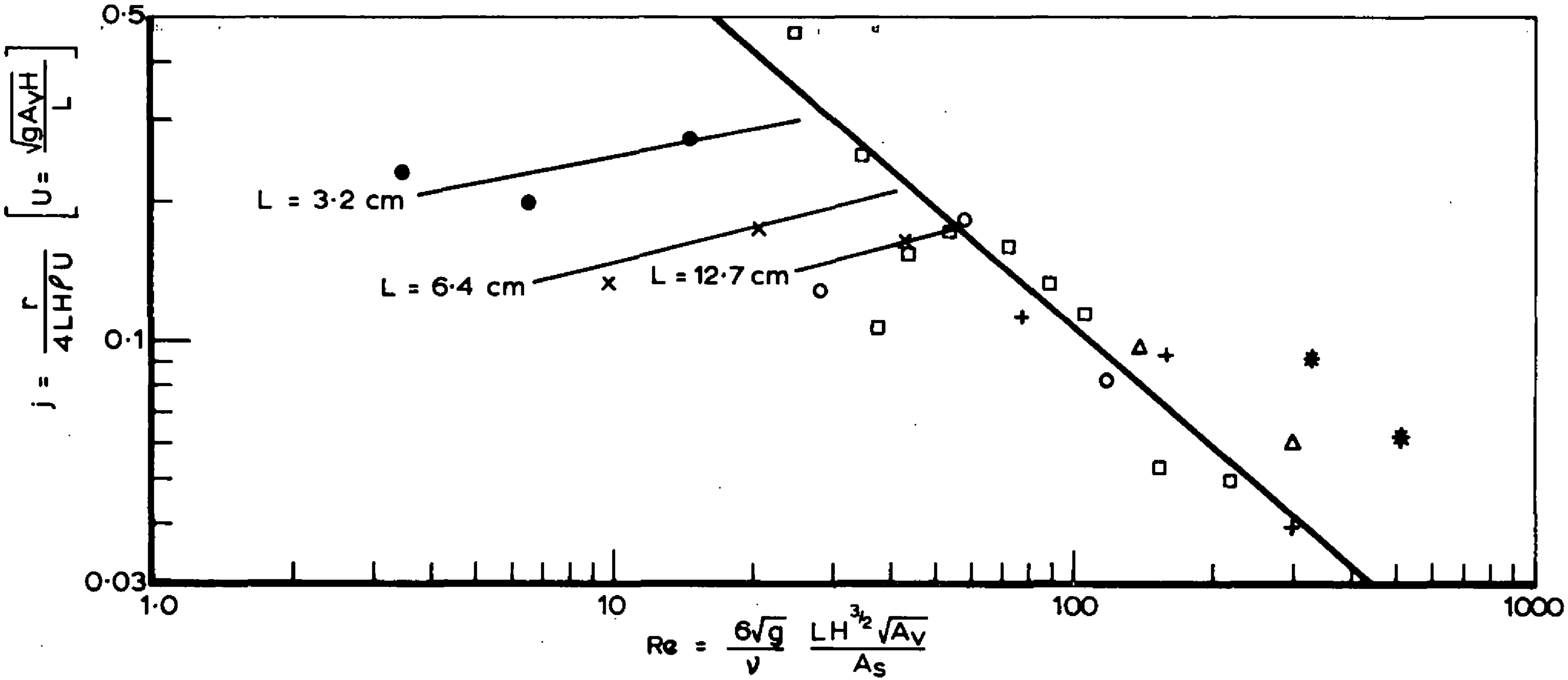
FIG. 3. VARIATION OF $\frac{r}{\sqrt{A_V A_S H}}$



Symbol	Size of cube-cm
●	3·2
×	6·4
o	12·7
□	19
+	25
Δ	38
✱	91·5

f_k = 0·28
ν = 0·45 cm^2/s
ρ = 0·3 kg/m^3

FIG. 4A. GROSS'S DATA – CORRELATION ASSUMING $\frac{f_k A_S}{L\sqrt{A_V}}$ LARGE AND NO ACCELERATION (MODEL 4)



Symbol	Size of cube - cm
●	3·2
×	6·4
○	12·7
□	19
+	25
△	38
✱	91·5

$f_k = 0{\cdot}28$
$\nu = 0{\cdot}45\ cm^2/s$
$\rho = 0{\cdot}3\ kg/m^3$

FIG. 4B. GROSS'S DATA – CORRELATION ASSUMING $\frac{f_k A_S}{L\sqrt{A_V}}$ SMALL AND ONLY ACCELERATION (MODEL 2)

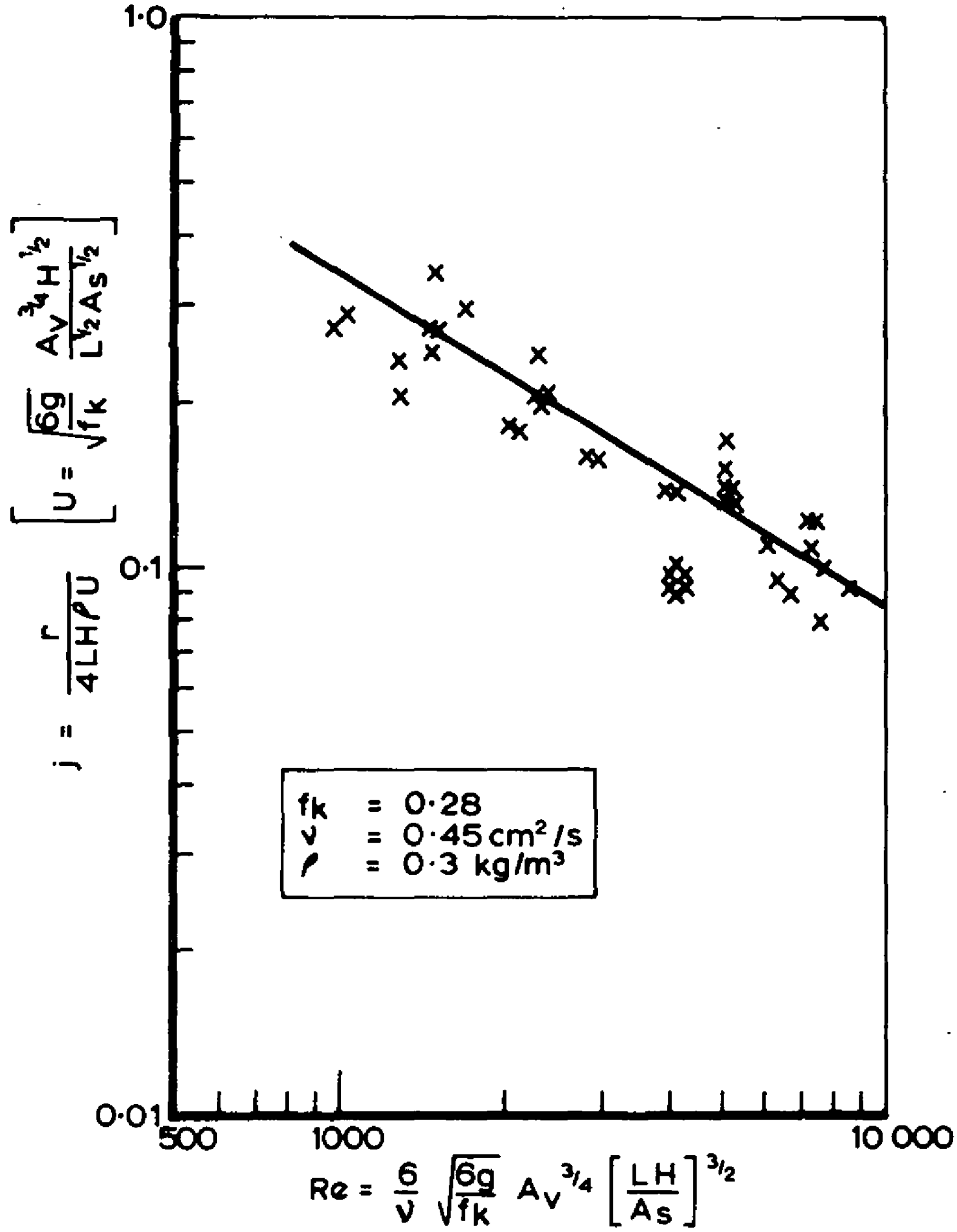


FIG. 5A. O'DOGHERTY'S DATA – CORRELATION ASSUMING $\frac{f_k A_s}{L\sqrt{A_V}}$ LARGE AND NO ACCELERATION (MODEL 4) FRICTION FACTOR f_k = CONSTANT

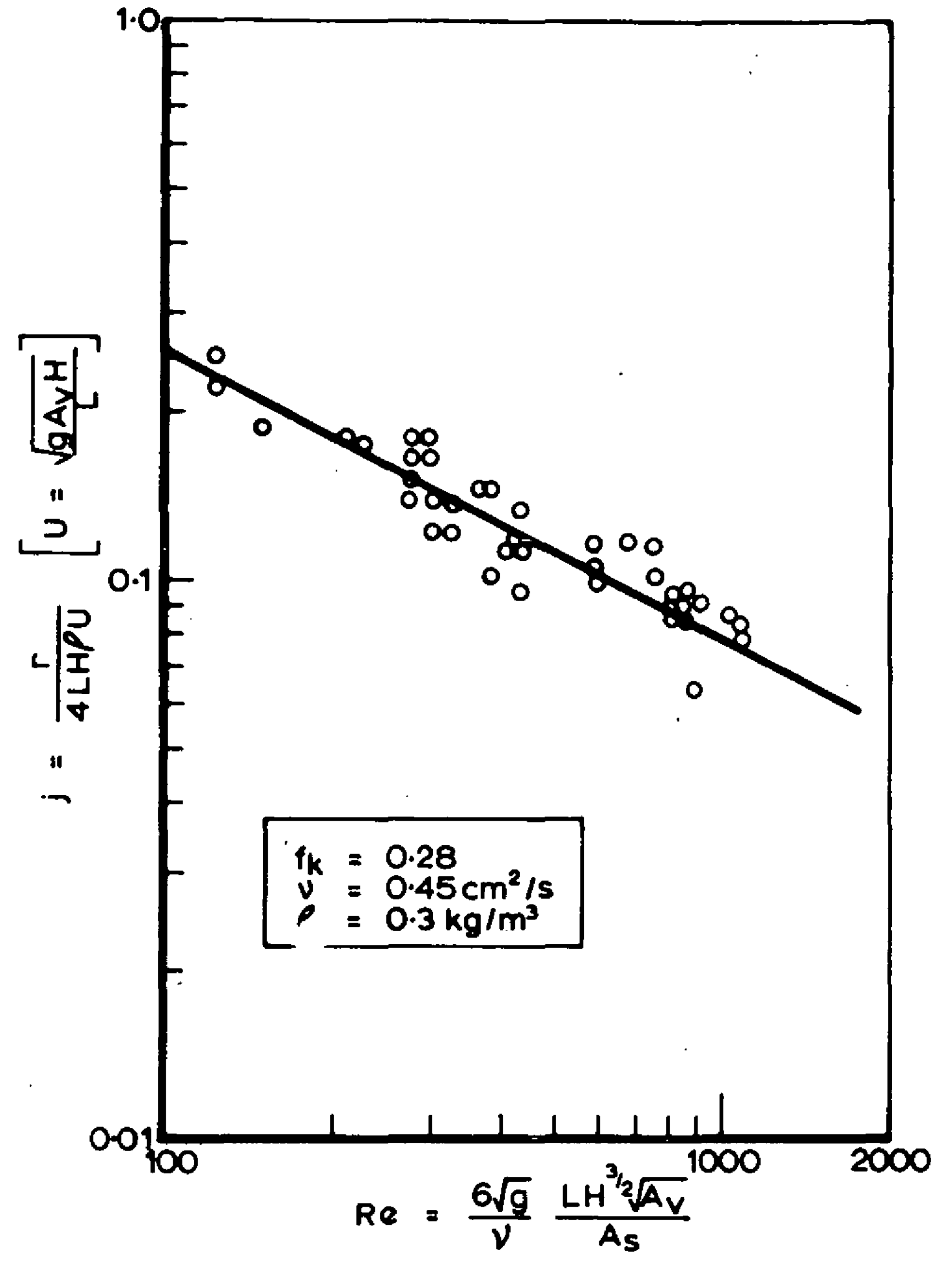


FIG. 5B. O'DOGHERTY'S DATA — CORRELATION ASSUMING $\frac{f_k A_s}{L\sqrt{A_v}}$ SMALL AND ONLY ACCELERATION (MODEL 2) FRICTION NEGLIGIBLE

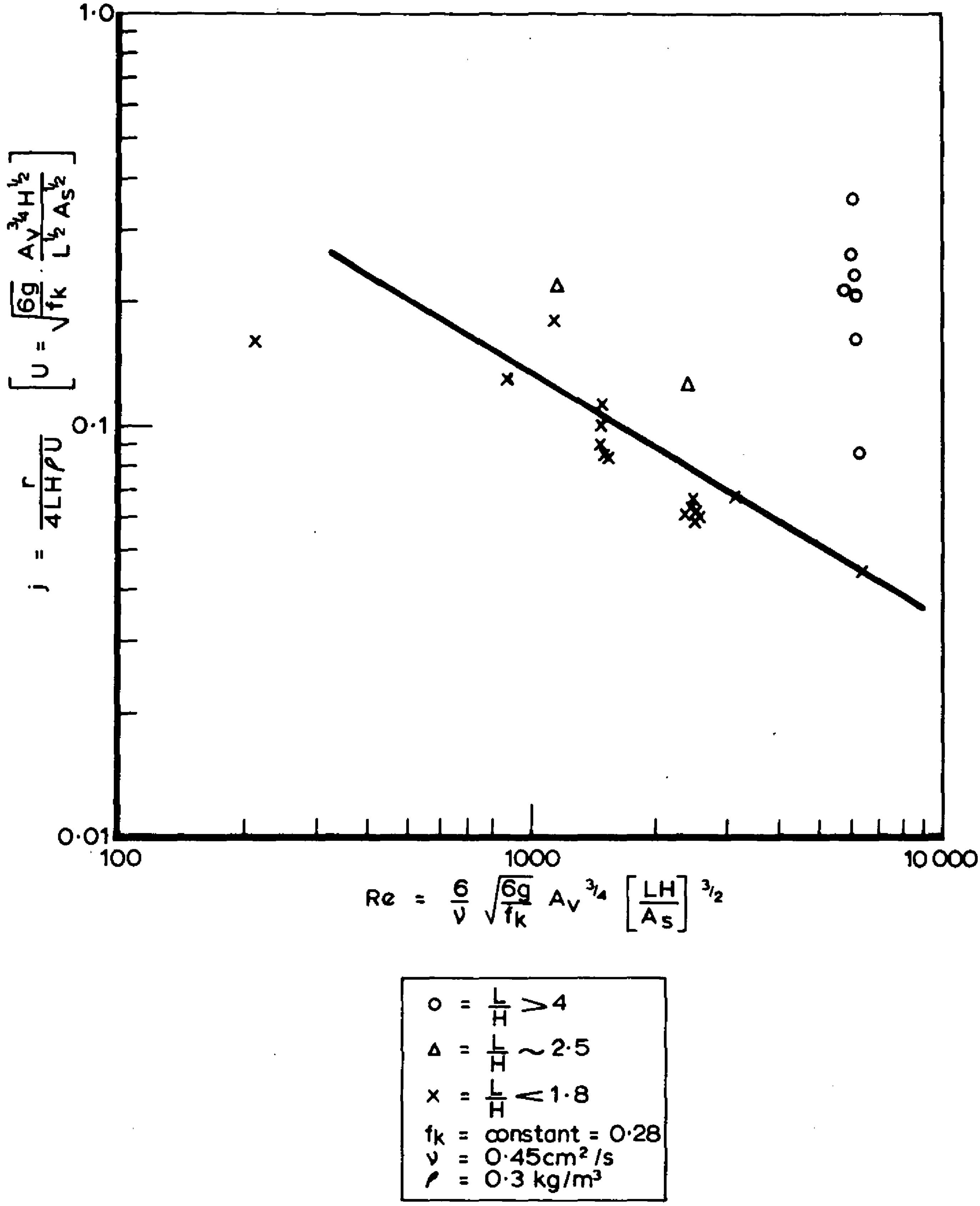


FIG. 6A. WEBSTER'S DATA – CORRELATION ASSUMING $\frac{f_k A_S}{L\sqrt{A_V}}$ LARGE AND NO ACCELERATION (MODEL 4) FRICTION FACTOR f_k = CONSTANT

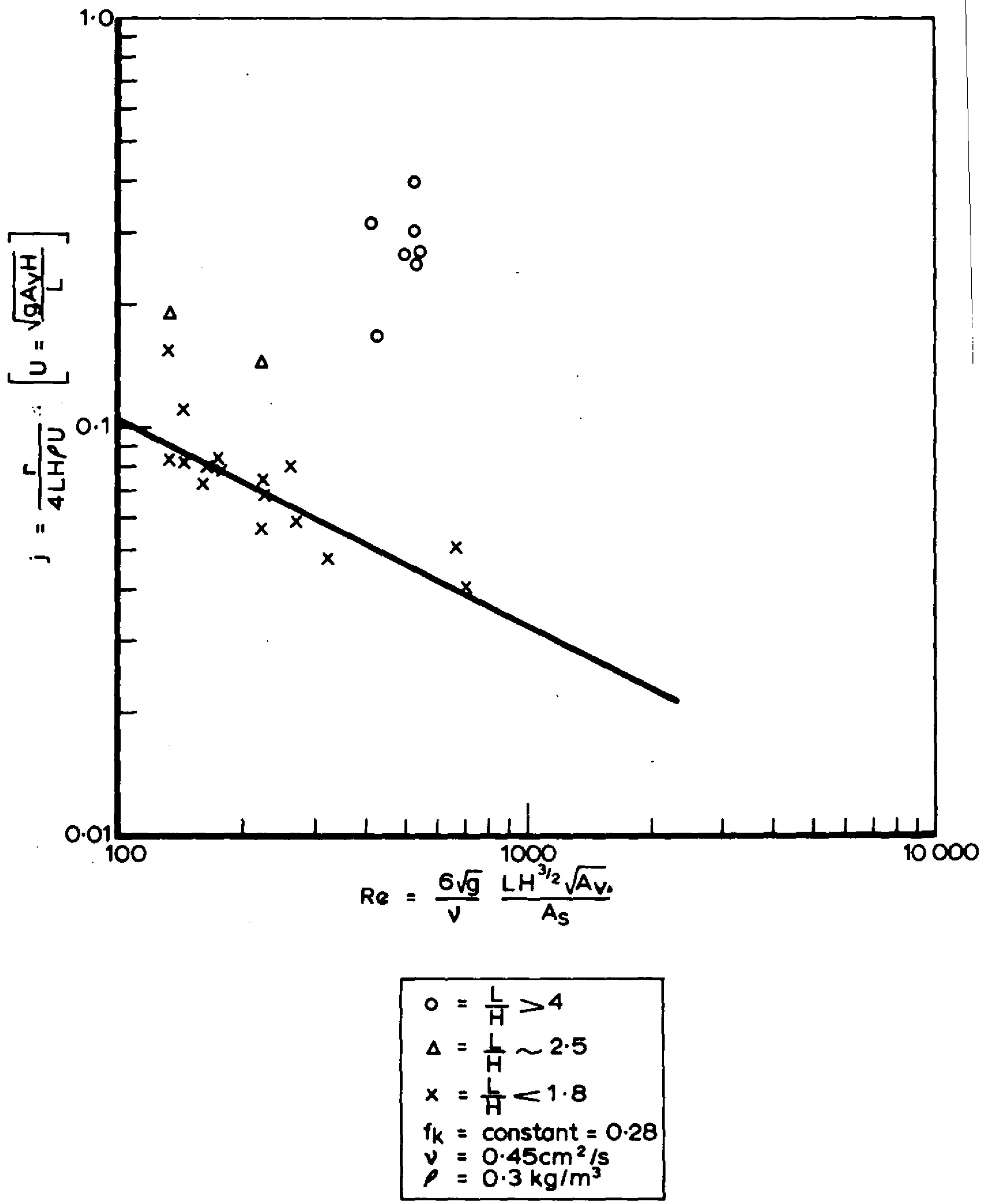


FIG. 6B. WEBSTER'S DATA — CORRELATION ASSUMING $\frac{f_k A_s}{L\sqrt{A_v}}$ SMALL AND ONLY ACCELERATION (MODEL 2) FRICTION NEGLIGIBLE

Table 6

Summary of possible correlations

Control of mass transfer	Correlation	U	Dimensionless burning rate	Variable part of dimensionless burning rate	Range of Re: Gross	Range of Re: O'Dogherty	Range of Re: Webster	Re*	If assumed from correlation	Then r proportional to
1 Bulk flow is addition of locally determined flows	$\frac{r}{A_s}\frac{d}{\rho D} = f\left(\frac{gd^3}{\nu^2}\right)$	—	$\frac{rd}{\rho A_s D}$	$\frac{rL^2 H}{A_s^2}$	13→1900+	36–285+	100–285+	$\frac{6\sqrt{6g}}{\nu}\frac{L^3 H^{3/2}}{A_s^{3/2}}$ **	$\frac{rd}{\rho A_s D} \propto \left(\frac{gd^3}{\nu^2}\right)^{\frac{1}{4}}$	$\frac{A_s^{5/4}}{L^{1/2} H^{1/4}}$
DETERMINED BY CRIB AS A WHOLE										
Accelerating flow (2A	$\frac{m''}{\rho U} = f\left(\frac{U}{\nu\sigma}\right)$	$\frac{\sqrt{g}\, A_v^{1/2} H^{1/2}}{L}$	$\frac{r}{4HL\rho U}$	$\frac{r}{A_v^{\frac{1}{2}} H^{3/2}}$	3.5→540	100→1100	120→700	$\frac{6\sqrt{6g}}{\nu}\frac{LH^{\frac{3}{2}}A_v^{\frac{1}{2}}}{A_s}$ ***	$\frac{m''}{U} \propto R_e^{-1/2}$ Laminar boundary layer	$A_v^{\frac{1}{4}} H^{\frac{3}{4}} A_s^{\frac{1}{2}} L^{-\frac{1}{2}}$
(2B									$\frac{m''}{U} \propto R_e^{-0.2}$ Turbulent boundary layer	$A_v^{0.4} A_s^{0.2} H^{1.2} L^{-0.2}$
Steady 3 laminar flow $f_k = \frac{150}{Re}$	$\frac{m''}{\rho U} = f\left(\frac{U}{\nu\sigma}\right)$	$\frac{36 g A_v^{\frac{3}{2}}}{150\nu}\frac{LH^2}{A_s^2}$	$\frac{r}{4HL\rho U}$	$\frac{r A_s^2}{L^2 H^3 A_v^{3/2}}$	1→3 x 10^4	1900→13x10^4	80→7.4x10^4	$\frac{216g}{150\nu^2}\left(\frac{LH}{A_s}\right)^3 A_v^{\frac{3}{2}}$ ***	$\frac{m''}{U} \propto R_e^{-\frac{1}{2}}$	$A_v^{\frac{3}{4}} H^{\frac{3}{2}} L^{\frac{1}{2}} A_s^{-\frac{3}{4}}$
Steady turbulent flow f_k=const. (4A	$\frac{m''}{\rho U} = f\left(\frac{U}{\nu\sigma}\right)$	$\sqrt{\frac{6g}{f_K}}\frac{A_v^{\frac{3}{4}} H^{\frac{1}{2}}}{L^{\frac{1}{2}} A_s^{\frac{1}{2}}}$	$\frac{r}{4HL\rho U}$	$\frac{rA_s^{\frac{1}{2}}}{L^{\frac{1}{2}} H^{\frac{3}{2}} A_v^{\frac{3}{4}}}$	20→4000	1000→8500	210→6250	$6\sqrt{\frac{6g}{f_K}} A_v^{\frac{3}{4}}\left(\frac{LH}{A_s}\right)^{\frac{3}{2}}$ ***	$\frac{m''}{U} \propto R_e^{-\frac{1}{2}}$ Laminar boundary layer	$A_v^{\frac{3}{8}} A_s^{\frac{1}{4}} H^{\frac{3}{4}} L^{-\frac{1}{4}}$
(4B									$\frac{m''}{U} \propto R_e^{-0.2}$ Turbulent boundary layer	$A_v^{0.6} L^{0.2} H^{1.2} A_s^{-0.2}$

* neglecting variation in $1 - \varepsilon$

** Re taken as $\left(\frac{gD^3}{\nu^2}\right)^{1/2}$

*** Re taken as $6U/\sigma\nu$

+the corresponding ranges of $\frac{L}{d}\left(\frac{gd^3}{\nu^2}\right)^{1/4}$ are 35 - 430, 280 - 720, and 100 - 1350.