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ON THE RATE OF BURNING OF CRIBS

by

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SUMMARY

This paper discusses the rate of burning of wood cribs and the comparison between the data of O'Dogherty and Young and Webster, and a theoretical model having much in common with Block's. It is suggested that the source of a discrepancy between the data and Block's original theory is the over-simplification of an averaging procedure for the mass transfer process and the use of the Reynolds analogy. Difficulties remain with describing the pyrolysis process and the mixing of the fuel and air in the crib shafts which preclude too exacting a comparison between present theories and currently available data.

KEY WORDS: crib, burning rate, wood

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NOTATION

a_v	cross-section of single duct or shaft $(= s^2)$
a_s	surface area in single duct or shaft $(= 4\ s\ h_c)$
b	stick thickness
c	specific heat
d_p	diameter of spheres of equal specific surface to crib
f_D	friction factor for duct
f_P	friction factor for crib
g	acceleration due to gravity
h_c	height of crib
j_m	mass transfer number
l	length of duct $(= h_c)$
m_{ox}	concentration of oxygen
n	m number of sticks in horizontal layer
Δp	pressure difference
r	stoichiometric ratio of oxygen to fuel
s	horizontal spacing between sticks
t	an index
z	height
A_v	total cross-section of all shafts in crib $= (n - 1)^2\ a_v$
A_s	total fuel surface area
B	Spalding transfer number
D	hydraulic mean diameter
G	a function defined by Block
ΔH	heat released by combustion of unit mass of fuel
L	length of stick

M	mass flow
M''	mass flux for unit time
N	number of vertical layers
P	perimeter of duct or shaft
R	rate of weight loss
R_e	Reynolds number
T	temperature
U	velocity
α) β)	constants
ϵ	heat required to produce gaseous fuel at T_s
ξ	fractional void volume
μ	viscosity
ν	kinematic viscosity
ρ	density
σ	specific surface
ψ	$\left(= \frac{f_D a_s}{2 a_v}\right.$ defined by Block)

Suffixes

o	ambient value
s	surface value
1	initial value
2	final value
v	value for cross-section of vertical passage, shaft or duct

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INTRODUCTION

The problem of theoretically estimating the rate of burning of the wood cribs used in standard fires has increasingly attracted attention since Emmons[1] drew attention to Folke's[2] work and posed questions as to the mechanisms of burning.

The justification for this interest is the convenience of using cribs in experimental fires and one needs to examine whether they burn in a way different from conventional real fires; crib fires have rarely, if ever, been the subject of an insurance claim! Apart from their use as free burning fires, they have been widely used in experimental compartment fires.

Thomas[3] has shown that spread within cribs follows the same mechanism as does spread in cities and forests (in the absence of high winds) but any corresponding similarity between crib fires and furniture or piles of stored goods, for example, has yet to be fully demonstrated.

A major advance in understanding crib fires has been made by Block[4] following Gross's[5] earlier study which demonstrated the existence of two regimes of behaviour. The essence of Block's theory is the argument that leads to justifying the independence of the various vertical passages or shafts in the crib, to which a more or less conventional mass transfer approach is then applied. Block has included the acceleration terms in evaluating the vertical flow under drag and buoyancy. His theory allows one to calculate the gas phase temperature within the crib and the proportion of unburnt fuel in the stream emerging from the top of the cribs. We have plotted Fig. 1 from his theoretical results, using his physical property values. Figure 2 shows the data of O'Dogherty and Young[6] and Webster[7] superimposed on Block's correlation. Later in the paper we shall show that a modification leads to results also illustrated in these figures, more in accordance with the data under discussion.

ASSUMPTIONS AND APPROXIMATIONS OF BLOCK'S MODEL

There are certain assumptions and approximations inherent in Block's model, apart from and in consequence of the idealisation of a crib into parallel ducts. Some of these will be retained in the modification to be introduced below. The most important assumptions and approximations are:

(1) The mass burning rate bears a constant ratio to the local heat flux. Wood is assumed to be inert below a surface temperature T_s of 370°C and pyrolises so as to maintain its surface at 370°C irrespective of the rate of pyrolysis and the gas temperature.

(2) The temperature is assumed uniform along the duct. The energy equation does not require this assumption but the simplification of a uniform mass transfer rate coupled with its expression in terms of a heat transfer dependence on temperature does. Strictly, mass transfer cannot commence until the local gas temperature has risen to above T_s.

(3) The concept of duct surface area is introduced as an approximation to fuel surface area and defined by the minimum hydraulic diameter and the height of the crib shafts. This introduces some ambiguity in defining the rate of burning per unit area.

(4) The Reynolds analogy is assumed to apply to cribs.

(5) Block's treatment of the 'open' regime neglects, as he himself acknowledges, the reduced radiation loss from sticks in cribs.

The following are additional comments on the above.

Pyrolysis of wood

The calculation of temperature and unburnt fuel fraction are dependent on quantitative and qualitative assumptions about pyrolysis. There is still argument[8,9] about this process in wood and uncertainty about numerical values. Block's parameter ϵ, the enthalpy of gases emerging from the solid, has been reported in the literature with values from 1000 cal/gm and over to near zero values and is defined in such a way as to depend on T_s.

It is not correct to assume that the surface of pyrolising wood must remain at 370°C. It rises to over 500°C according to calculations by Simms[10] even before spontaneous ignition. There may be good heat transfer between gases and solid so that the gases emerge at the high surface temperature.

In the important extension of crib studies to enclosures it is necessary to consider the effect of changes of ambient oxygen concentration and temperature. Such variation would provide a sensitive test of the applicability of this mass transfer model.

<u>Definitions of areas</u>

The definition of M'' the mass transfer rate can be based on the actual wood surface A_s or on a nominal area treating the shafts as having a peripheral surface like a duct, viz. $(n - 1)^2 a_s$ where n is the number of sticks per layer. Block writes

$$a_s = 4 s h_c = 4 s N b \qquad \ldots\ldots (1)$$

where s is the distance between horizontal sticks of thickness b, N is the number of layers and h_c the crib height. One could, of course, also define a_s by $4(s + b)h_c$, provided a friction factor "f" is defined in a manner consistent with this. However, it is not possible to define a priori an "a_s" directly related to A_s. Using Gross's definition of A_s and A_v, the total cross-section of open area in the vertical paths

$$\frac{A_s a_v}{A_v a_s} = \frac{s^2\left[2nb\left(2NL + b\left(N - n(N-1)\right)\right)\right]}{4 s N b (L - nb)^2}$$

where a_v $(= {A_v}/(n - 1)^2)$ is the effective cross-section for one shaft defined by Block as . L is the stick length.

Hence

$$\frac{A_s a_v}{A_v a_s} = \frac{\left(1 - \frac{nb}{2L}\left(1 - \frac{1}{N} - \frac{1}{n}\right)\right)}{\left(1 - \frac{1}{n}\right)\left(1 - \frac{nb}{L}\right)} \qquad \ldots\ldots (2)$$

In the limit for large cribs

$$\frac{A_s a_v}{A_v a_s} = \frac{1 + \xi}{2\xi} \qquad \ldots\ldots (3)$$

where ξ is the fractional volume voids.

It should be noted that for low values of ξ, both the numerator and the denominator in equation (2) are very dependent on the formulation of the terms involving n and N.

In view of these uncertainties when comparing cribs of very different structure (O'Dogherty and Young's[6] cribs range from some having N as low as 8 to one with N equal to 134), and in view of the necessary approximations in the theory, it seems sufficient to use Block's theory essentially as a framework for correlating data, using either a_s/a_v or A_s/A_v .

The Reynolds analogy

The Reynolds analogy can be directly applied in certain flows but in packed beds, for example, its direct use presents difficulties since the analogy applies to frictional drag but not form drag. If cribs are not completely the idealised ducts envisaged in theory and some of the pressure drop is the result of form drag - due to the considerable roughness of the "shafts" then when f_D is defined conventionally in terms of the pressure drop

$$j_m < \frac{f_D}{2}$$

The Open Regime

As a_v/a_s increases the resistance to flow falls, and the degree of mixing between the boundary layers surrounding each stick and the main duct flow is expected to decline. Each stick then tends to become independent of the others except for the conservation of radiation.

We shall need to use the open regime in certain applications of crib theory and we note that Block himself points out[4] that treating a crib as a collection of independent isolated sticks is open to objection because the formulae widely used to correlate such behaviour e.g.

$$\dot{M}'' \propto b^{-t} \qquad \ldots\ldots (4)$$

where the index t is about 1.5, are empirical and mostly based on data for single sticks*, and in cribs the radiation is conserved. This is historically the reason <u>why</u> cribs are used in experiments. They allow one to burn thicker sticks than will sustain burning in isolation.

From these arguments one would expect the radiation balance in "open" cribs to depend on 'n' which mainly controls the number of radiation "mean free paths". For free burning cribs a higher 'n' means lower heat loss and M'' should increase as n increases. Block, however, did not find such an effect in the range he studied.

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* Block's own comparison of his correlation with other fuel beds is for the "open" regime - and not for that regime for which the theory applies.

For cribs inside compartments the walls and ceilings of the compartment may become hotter than the inside of the cribs if a large part of the combustion takes place outside the crib. Then a higher 'n' may mean a lower M'' ... not obviously distinguishable from a decrease in M'' resulting from a reduction in air flow from an increase in 'n'. Any departure from M'' being independent of porosity in the open regime prejudices the combination of the two regimes into a single correlation, and defining a porosity parameter by normalising the burning rate to that of open cribs is then possibly misleading. For this reason it is ill-advised to use either Gross's or Block's porosity parameter for compartment fires.

The range of n and N in Gross and Block's experiments may need extending to effect a realistic study of "open" cribs to resolve this particular problem.

The mixing of air and fuel

In addition to the above comments on explicit assumptions and approximations, there is another concerning a less obvious one which needs to be better recognised even though one must continue to use the simplification involved. From Block's theory one can evaluate the mass fraction of fuel within one of the vertical ducts, and based on Block's calculations this would seem to be over 40 per cent for most of the range shown in Fig. 1. Now mixing between air and fuel is assumed to be perfect but if this were in fact so, the mixture is too rich to burn. In fact flames will exist because the mixture is not perfect and this (in principle) affects the assumption regarding the flow and the use of friction factor based on flow without combustion. All this suggests that agreement between this or a modified model cannot justify too great an extension to other uses.

SMITH AND THOMAS'S CORRELATION

Smith and Thomas[11] have shown that the data of O'Dogherty and Young[6] and Webster et al[7] and those of Gross[5] for cribs exceeding 20 cm x 20 cm square base follow approximately

$$R \approx 7 \times 10^{-2} (A_v . A_s . h_c)^{1/2} \quad \mathrm{kg/m^2 s} \quad \ldots\ldots (5)$$

where R is a mean rate of weight loss equal here to $A_s M''$.

Kanury's[12] apparent correlation of O'Dogherty and Young's data as if they were open cribs does not explain the statistically significant effect of A_v as well as of A_s and the absence of b in equation (5). It should be noted that a_v, a_s and h_c are not statistically independent but A_s, A_v and h_c are (though highly correlated in many experiments).

Alternatively, the data can be represented[13] by

$$\frac{M''}{\rho_0 (g h_c)^{1/2}} = 0.02_2 \left(\frac{a_v}{a_s}\right)^{0.6} \qquad \ldots\ldots (6)$$

The data are superimposed on Block's calculated line in Fig. 2 and there is clearly a difference between that calculation and the trend of the data.

We have used both Block's value for f_D of 0.13 and a lower one of 0.08 more consistent with the data of Wraight and Thomas[14].

Equation (5) is in accordance with a simple empirical observation[15] that if the spacing between sticks and stick size remain constant, R is proportional to superficial crib volume; for then

$$A_V = L^2 \xi^2$$

$$A_S = L^2 h_c (1-\xi)\sigma$$

where σ is specific surface of the sticks

$$\therefore \quad R \propto (A_v A_s . h_c)^{1/2} \propto L^2 h_c \xi \sqrt{\sigma(1-\xi)}$$

The same result holds good for cribs in the open regime since the total surface is proportional to crib volume for a given ξ and stick size.

Modification of Block's theory

We shall revise Block's approach treating j_m as an unknown number not necessarily equal to $f_D/2$.

The equation employed by Block for the conservation of enthalpy leads to a relation which can be shown to be identical to the following which is here given in Spalding's notation and is conventional.

$$\frac{R}{M_2} = \frac{M_2 - M_1}{M_2} = \frac{B_1 - B_2}{1 + B_1} \qquad \text{..... (7)}$$

where

$$B_1 = \frac{M_{ox}\frac{\Delta H}{r} + c(T_o - T_s)}{\epsilon}$$

and

$$B_2 = \frac{c(T_2 - T_s)}{\epsilon}$$

(the concentration of oxygen is assumed to be zero at exit from the crib).

B_1 is the B defined by Block without a suffix, the 1 represents here initial conditions. B_2 is Block's θ and is the final value of B, and M_2 and M_1 are final and initial mass flows. The conventional local mass transfer relation for Prantdl and Schmidt numbers of unity is

$$M'' = \dot{j}_m \frac{M}{A_v} \ln(1+B) \qquad \text{..... (8)}$$

where B and M are local values and by definition

$$\frac{dM}{dz} = P \cdot M'' \qquad \text{..... (9)}$$

and z is a distance along a flow path.

Assuming j_m is independent of M gives the well known mass transfer relation

$$\dot{j}_m A_s/A_v = \ln \frac{\ln 1+B_1}{\ln 1+B_2} \qquad \text{..... (10)}$$

After eliminating B_2 between equation (7) and (10) we obtain

$$\frac{R}{M_2} = 1 - (1+B_2)^{-(1 - e^{-j_m A_s/A_v})} \qquad \text{..... (11)}$$

The term $e^{-j_m A_s/A_v}$ is similar in form to the term $e^{-\psi}$ in Block's expression for mass flow and arises for analogous reasons. We shall follow Block in neglecting temperature variation in the buoyancy when calculating mass flow and so use his equation for M_2 viz

$$M_2 = A_v \rho^{1/2}(\rho_0 - \rho)^{1/2}(g h_c)^{1/2} G(\psi) \qquad \ldots\ldots (12)$$

where $G(\psi)$ is as given by Block and in our notation is

$$G(\psi) = \frac{1}{\psi}\left\{\frac{1 - e^{-\psi}}{1 - \frac{\rho}{\rho_0}\left(\frac{M_1}{M_2}\right)^2 e^{-\psi}}\right\}^{1/2}$$

It then follows that

$$M'' = \left[\left(1 - \left(\frac{1}{1+B_1}\right)^{1 - e^{-\dot{j}_m A_s/A_v}}\right)\right] \frac{f_0}{2} \rho^{1/2}(\rho_0 - \rho)^{1/2}(g h_c)^{1/2} \frac{G(\psi)}{\psi} \qquad \ldots (13)$$

If $j_m = f_0/2$ this does not exactly reduce to Block's result because here we have allowed for temperature variation in the mass transfer equations (treating j_m as constant) whereas Block used a mean velocity.

The comparison is shown in Fig.1. However, if $\psi \gg 1$ when $j_m = \frac{f_0}{2}$

$$\frac{R}{M_2} \rightarrow \frac{B_1}{1 + B_1}$$

as does the corresponding expression by Block. But if $j_m A_s/A_v$ is small the situation is different and equation (11) becomes

$$\frac{R}{M_2} \approx 1 - e^{-\dot{j}_m \frac{A_s}{A_v} \ln(1+B_1)} \qquad \ldots\ldots (14)$$

$$\rightarrow \dot{j}_m \frac{A_s}{A_v} \ln(1+B_1)$$

This, of course, is equivalent to assuming that M_2 and B are constant, i.e. most of the upward flow in the crib is air whereas if $j_m = f_0/2$ and $\psi \gg 1$ most of it is fuel and it would be too rich a mixture to burn. The consequence of equation (13) is that if $j_m A_s/A_v \ll 1$ the presence of the ratio A_s/A_v in the exponent of $1 + B$ makes $M''/\rho^{1/2}(\rho_0 - \rho)^{1/2}$ depend more nearly on $(A_v/A_s)^{\frac{1}{2}}$ instead of $(A_v/A_s)^{3/2}$.

The use of the energy equations (7) and (11) in principle allows one to calculate temperature but this has little effect on the dependence of M'' on A_V/A_S because $\rho^{1/2}(\rho_D - \rho)^{1/2}$ varies only from 0.5 when T is 300°C to 0.435 when $T = 900^{\circ}$C.

Whilst the calculation of T itself depends more on the assumption regarding T_s, $j_m\, A_s/A_V$ is not always small enough for the above approximation to be without significant error and in fact according to this theory $R/(A_V\, A_s\, h_c)^{1/2}$ is not exactly constant.

Inserting Block's numerical values, a mean value of 0.47 for $\rho^{1/2}(\rho_0 - \rho)^{1/2}/\rho_0$ and the mean experimental value of $R/(A_V\, A_S\, h_c)^{1/2}$ of 7×10^{-2} kg/m^2 s gives a mean j_m near to 0.02. A constant j_m would lead to a small decrease in $R/(A_V\, A_S\, h_c)^{1/2}$ as A_s/A_V increased, as equation (6) implies. In Block's model the effect is too large. Figure 2 shows the results of detail of equation (13) using equation (7) to obtain T_2. Two pairs of values for f_D and j_m are shown and it is clear that the results are more sensitive to j_m than to f_D. Possible "best" values are in the range $f \simeq 0.13$, $j_m \simeq 0.02$ or $f_D \approx 0.08$ and $j_m \approx 0.015$. The discrepancy is at the low end of the scale of A_s/A_V and ψ where measured values of M'' are higher than calculated and the calculated temperatures appear unrealistically high; T exceeds 2000 K for $a_s/a_V \simeq 20$. Changing f_D makes little difference to T but lower j_m means higher T values.

Decoupling f_D and j_m has allowed us to reduce j_m, with the possibility of obtaining better agreement with data. However, the calculated temperatures still tend to possibly unrealistic values given the values assessed for B_1. If in equations (7) and (11) we have $2 j_m \psi / f_D \ll 1$

then $$T_2 - T_s \simeq \left(m_{ox}\frac{\Delta H}{rc} + T_0 - T_s\right)\left(1 - \frac{2 j_m \psi}{f_D}(1+B_1)\right) \quad \ldots\ldots (15)$$

If ϵ were <u>less</u> than the 425 cal/gm assumed by Block, B_1 would be greater and the calculated temperature would be less. Also, Block's property values give $m_{ox}\frac{\Delta H}{r}$ as about 0.27 x 4400 i.e. 1200 cal/gm about 50 per cent higher than values given by Roberts.[16]

The values of j_m are reasonable for a duct and are about $\frac{1}{4} - \frac{1}{2}$ of the values of f_b. The calculated value of j_m would be slightly higher if the value of T_s were higher and the value of B were accordingly lower. However, to obtain a low enough B to have a significant increase in j_m would require a much larger value of ϵ.

CONCLUSIONS

The form of the correlation of data by Smith and Thomas appears to be consistent with a modification of Block's model for a low porosity crib which decouples mass transfer from "friction" within the crib, but there are difficulties in making detailed comparisons between data and theory owing to ambiguities in defining geometrical terms and in values to be attributed to ϵ.

The assumption of a constant surface temperature for pyrolising wood needs refinement as does the applicability of the Reynolds analogy of the cribs.

The question of mixing may be important. If one assumes perfect mixing, the range of conditions in which the mixture is not too rich to burn nor too lean to produce extensive flaming above the crib is narrower - possibly much narrower - than occurs in practice. The possibility that the practical usefulness of cribs depends on two features excluded from theory (this and the effects of re-radiation in open cribs) means that too much must not be expected of the quantitative aspects of theory so far developed. However, that said, it is suggested that the arguments of this paper go some way to reconciling the statistically based correlations of Smith and Thomas with Block's physical model of crib behaviour.

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APPENDIX

THE FRICTION FACTOR FOR CRIBS

Wraight and Thomas[14] correlated their pressure drop data for cribs in terms of a friction factor defined for the crib as a whole like a packed bed. Following Ergun[17] they obtained

$$f_P = \frac{\Delta p}{\rho U^2} \cdot \frac{\xi^3}{1-\xi} \frac{d_p}{l} \qquad \ldots\ldots (1.1)$$

$$= 0{\cdot}28 + \frac{200(1-\xi)}{Re} \qquad \ldots\ldots (1.2)$$

where R_e is defined by $U\,d_p/\nu$

U is the flow velocity in the unobstructed bed

ξ is the void fraction and was $\frac{1}{2}$ for all their data

ν is the kinematic viscosity (0.18×10^{-4} m^2/s)

d_p is the diameter of spheres of equal specific surface and hence taken here as 2b

l is the length of the bed

Their data were expressed by

$$\frac{\Delta p\, b^2}{\rho \nu l} = \nu(100 \pm 25) + 0{\cdot}57ub \qquad \ldots\ldots (1.3)$$

For a duct

$$f_D = \frac{2\Delta p}{\rho U'^2} \frac{D}{l} \qquad \ldots\ldots (1.4)$$

where D is the hydraulic mean diameter of the duct

and where U' is the mean velocity in the duct, taken first as U/ξ.

We shall assume

$$f_D = \frac{\alpha}{R_e'} + \beta \qquad \ldots\ldots (1.5)$$

where R_e' is defined by $U'D/\nu$

For the experiments with cribs of ξ equal to $\frac{1}{2}$ and $d_p = 2b$

$$D = \frac{s}{4} = \frac{b}{4}$$

Hence from equations (1.4) and (1.3)

$$f_D = \frac{2\Delta p}{\rho (U'/_{1/2})^2} \frac{b/4}{\ell} = 0.07 + 6.25/Re'$$

The first term is the more important: Block obtained 0.13 for f_D.

If the friction factor f_D is defined by the velocity at the narrowest section, as could be necessary to be consistent with Block's definition the cross-section of shaft and mass flow U' is U/ξ^2 and the value of f_D becomes even less. There appears to be a real difference between the friction factor for the two sets of data.

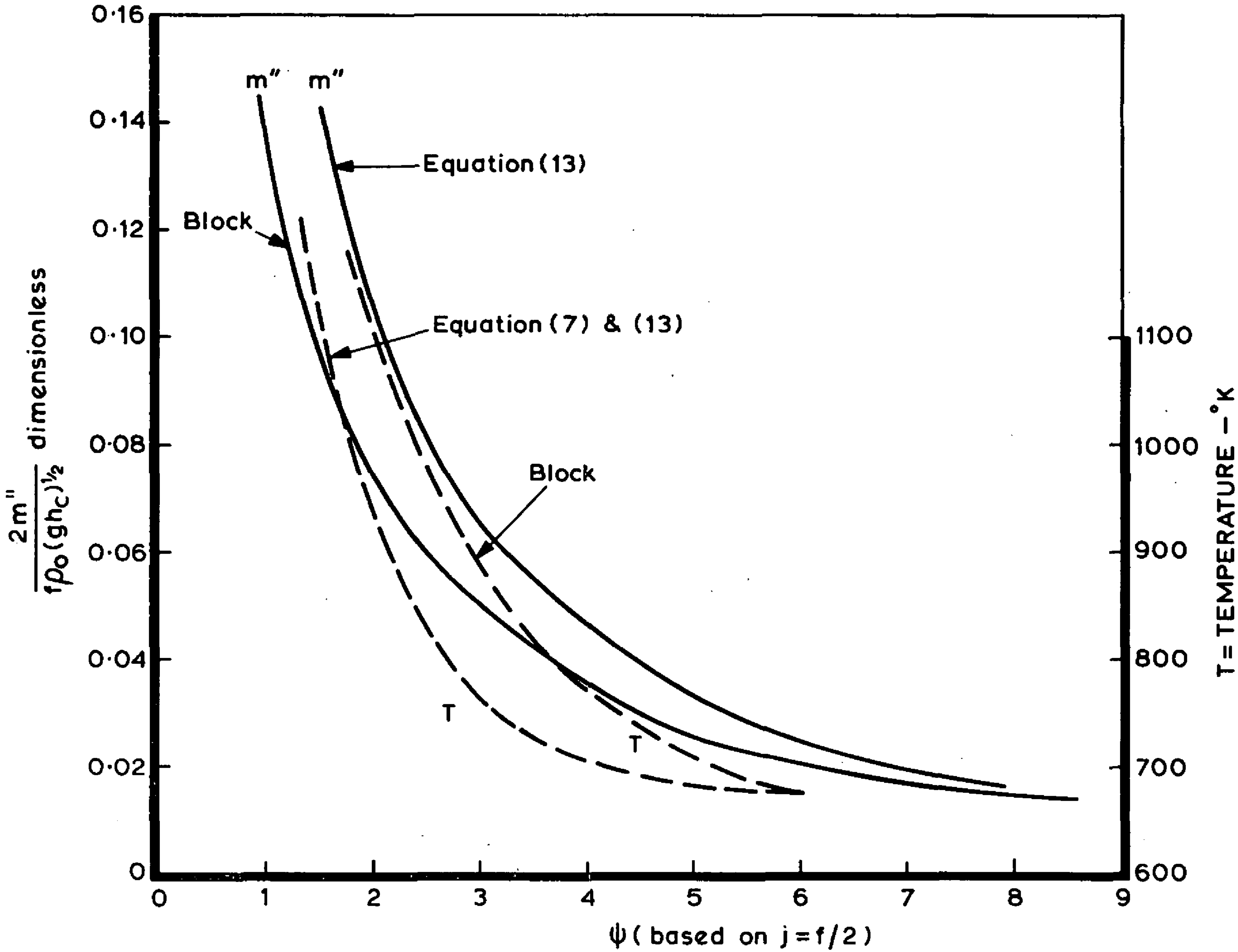

FIG. 1 THEORETICAL RELATIONS $m''(\psi)$ AND $T(\psi)$ USING BLOCK'S VALUES FOR PHYSICAL PROPERTIES

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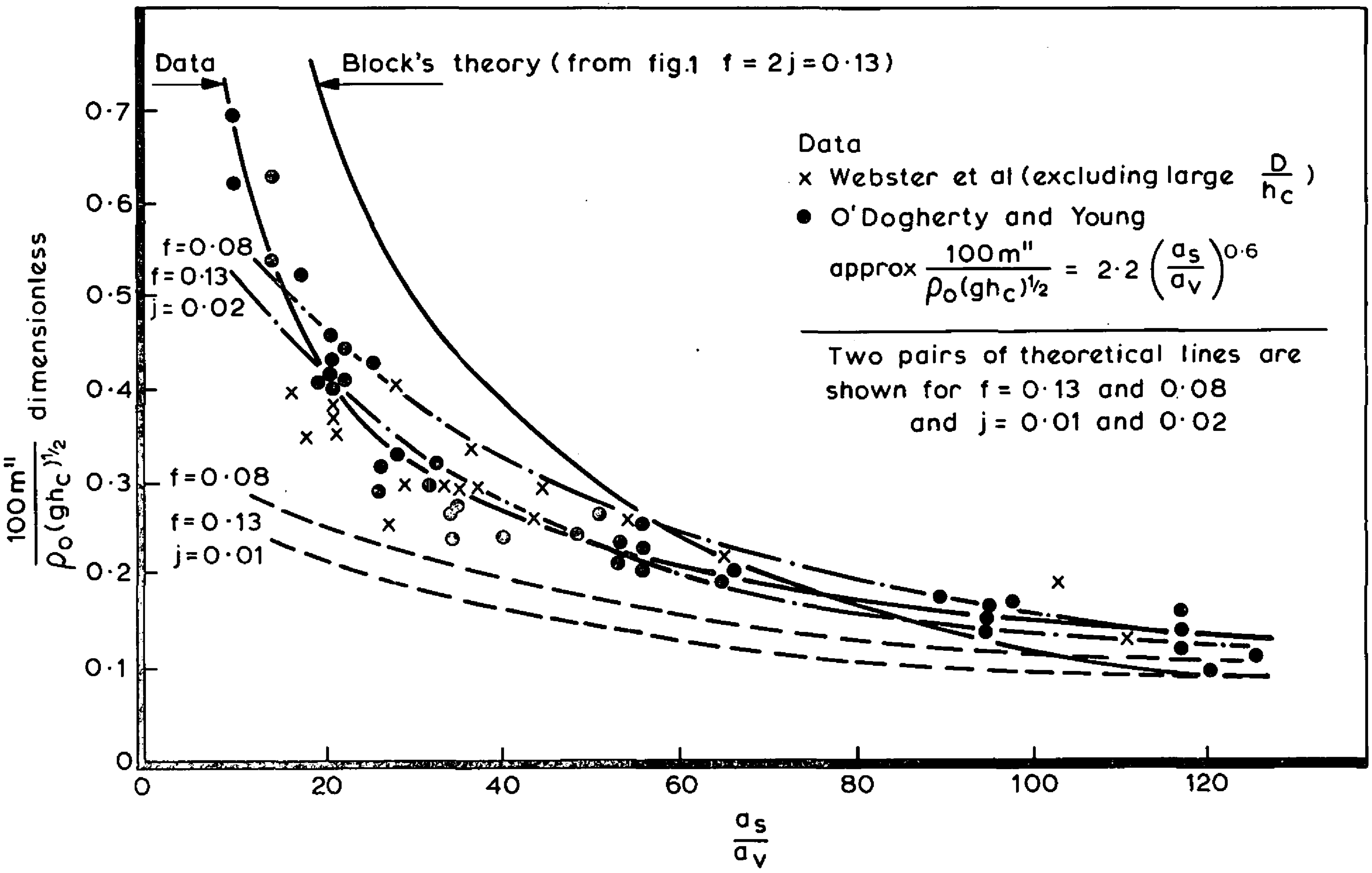

FIG. 2 THEORETICAL VALVES OF m'' AND EXPERIMENTAL DATA