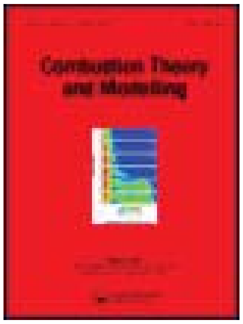

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Insights into and the evolution of a novel predictive model for free burning wooden cribs

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The extensive work on wood crib fires, both experimental and model development over the last six decades is examined in some detail. The wide range of parameters of crib tests and the theories have been reviewed in the literature and a satisfactory correlation has still to emerge from these studies. From early times, the burn flux (g/m^{2}s) has been considered the most appropriate parameter to characterise the burn behaviour of the cribs. These data on a re-examination revealed a surprisingly simple behaviour of a linear variation of the mass loss rate (g/s) with the mass of the crib, particularly for smaller size sticks with the crib placed on the ground. Some insight into this behaviour is brought out and the basic idea has been pursued to reveal an alternate and a more accurate correlation for the burn rate with crib mass and the crib size as principal parameters with the crib height-to-spacing ratio providing a minor correction. The resulting correlation has been compared with over a hundred and fifty experimental data along with a modified Thomas correlation and shown to perform much better for smaller-size sticks.

Keywords: crib fires; burn rate; modelling crib fires

List of symbols

A_s	Crib surface area (cm^2)
A_v	Crib vent area (cm^2)
b	Stick thickness (cm)
B	Transfer number
C	Dimensional Constant (g/cm$^{1.5}$s)
C_o, C_1 and C_f	Constants used in the correlation
d	Diameter (cm)
f_w	Moisture Fraction
Gr	Grashof number
h	crib height $= n_l b$ (cm)
h_v	Vertical separation between ground and bottom of the crib (cm)
L	Length of the stick (cm)
s	Stick spacing (cm)
t_b	Burn time (s)
m_c	Crib mass (g)
$\dot{m}_c$	Mass burn rate (g/s)

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$\dot{m}_{ld}$	Mass burn rate of liquid droplet (g/s)
$\dot{m}_{dm}$	Mass burn rate of solid biomass sphere (g/s)
n_l	Number of layers
n_{sl}	Number of sticks per layer
n_s	Number of sticks
R	$\dot{m}_c/m_c$
Re_c	Reynolds number
ρ_{fu}	Density of the fuel (kg/m^3)

1. Introduction

The burning rate of wood cribs has been considered important not only for standard fire testing to qualify fire extinguishing media as per standards, but also to create an understanding of the behaviour of wildland fires. Literature indicates that the first set of cribs was tested by Fons et al. [1] who measured the rate of propagation of fire through a crib and the gas phase temperatures. Propagation rates of a specific crib were measured as about 0.5 mm/min and the gas temperatures were about 650°C at the top of the crib and increased to a peak of 900°C in about a distance equal to the bed height.

Gross [2, 3] conducted experimental studies on a range of cribs with thicknesses from 0.16 to 9.15 cm with lengths ten times the size with various combinations of the number of sticks per layer, n_{sl}. In this study, he invokes an earlier research of Folk and Byron (see Refs. [2, 3]) which showed the dependence of burn rate of the crib

$$R = \dot{m}_c/m_c \sim b^{-1.6} \tag{1}$$

to construct further arguments and setting out the data in terms of $Rb^{1.6}$ depending on what they term as porosity defined by

$$\phi = \sqrt{h}A_v/b^{0.6}A_s \tag{2}$$

where $\sqrt{h}$ arises from gas velocity due to free convection as $\sqrt{gh}$ with g representing acceleration due to gravity, h is the crib height and the term $b^{0.6}$ in the denominator arises from the fuel regression rate of the individual sticks, the exponent 0.6 directly related to behaviour of R with b as in Equation (1). The term porosity really is representative of the air-to-fuel ratio and larger values imply adequate availability of air for diffusive combustion and small values lead to fuel-rich mode. The plot of the results of R with ϕ with the data they presented shows a near linear variation till a value of $\phi = 0.3$ and a constant maximum of about 8 regarded as that which is attained for adequate availability of air. They show data for several biomass and there are significant differences for specific biomass, Balsa and Mahogany and this is argued to be due to thermal diffusivity differences. They seem to have ignored the fact that R has also a fuel density dependence, and in a classical biomass sphere combustion (Mukunda et al. [4]), R that scales as the inverse of burn time, t_b varies as $\rho_{fu}b^2$ with ρ_{fu} representing the solid fuel density. In the present case, b has the same role as the diameter of the sphere and so, the density effect can account largely for what they have observed.

O'Dogherty and Young [5] conducted similar investigations over a wider range of parameters and inferred that the spacing between the stick, s is another important parameter controlling the crib burn rate. The wider range of the spacing showed clear additional dependence on s. The data plotted by them shows clearly that the correlation proposed by Gross [3] is inadequate to cover the range of data. Byram et al. [6] conducted experiments in steady propagating mode and obtained the propagation rates that are essentially burn rates of the crib. The cribs were mounted on an asbestos cloth which was placed on a pan so that the effective spacing of the crib from the 'ground' is zero. The experiments in still air were correlated to yield a correlation in terms of mass flux with sick size. The dimensionless quantity stated in terms of present notation can be written as

$$Re_c \sim \dot{m}_c/(b\mu_\infty) \sim Gr^{0.25} \tag{3}$$

where Re_c is a Reynolds number based on fuel mass flux, Gr is the Grashof number whose dependence can be set out as

$$Gr \sim gb^3/(\mu/\rho)^2_\infty \tag{4}$$

where μ refers to viscosity and the subscript ∞ refers to the condition at which it is evaluated. This result can be expressed as

$$\dot{m}_c \sim b^{1.75} \quad \text{and so,} \tag{5}$$

$$t_b \sim b^{1.25} \tag{6}$$

The exponent 1.25 is quite different from 1.6 obtained by Gross [3]. The presence of cross members of the crib and spacing between the sticks influence this exponent. In a study of burning of cylindrical sticks, Murthy and Blackshear [7] presented data on the normalised mass loss with time and indicated a t/d^n with n varying between 1.6 and 1.7. Even here, the length-to-diameter ratio varies and so, the influence of the length can be taken as being embedded in the expected result.

Grummer and Strasser [8] conducted studies on fires with the aim of determining the ambient velocities created by fire. One set of tests with *vertical sticks* with select spacing has burn rates similar to the cribs tested by Gross. Measured air stream speeds due to free convection are in the range of 5–10 cm/s. Anderson [9] performed experiments on cribs following the broad ideas of Gross but using excelsior wood material for ignition. The data of the combustion process was experimentally extracted to less than 50% in many cases. The number of data points of significance for use in comparison against predictions seems very limited and so, these are not considered further. Smith and Thomas [10] attempted to put the data from Gross [3], O'Doherty and Young [5] into a curve fit. While discussing the alternatives, they considered the mass of the crib as a possible alternative, but argued against its use in the correlation as according to them, they indicated that '… it does not seem to be meaningful term to include'. Further, they stated 'For any one species of wood, weight is uniquely determined by the other parameters, and we decided to exclude it from the analysis for these reasons'. These are being brought out here explicitly as the present study shows a deep relationship between the mass burn rate and the mass of the crib and the reasons for it.

Block [11] constructed a fluid dynamicsbased thermal model for the burn behaviour of cribs. The essence of the theory has been that the various vertical passages can be treated as independent combustion elements that could be dealt with by conventional mass transfer behaviour. The burn rate per unit exposed surface area ($\dot{m}/A_s$) is considered the parameter to be determined and is taken uniform all through the crib. The assumption of uniformity is not considered satisfactory for dense cribs beset with complex interactions by Block himself. The final result has two major controlling features. A parameter that is controlled by free convection velocity and another denoted by $G(\psi)$ where ψ is set out as

$$\psi = 2f\frac{h}{s} \tag{7}$$

where f is the friction factor. While several fluid dynamic arguments are advanced with regard to the dependence of the friction factor, what is ultimately chosen is a constant value of 0.13. One could speculate that if the model for f as a function of a range of crib packing densities had been set out, the resulting correlation would indeed be different. The results of the model were compared with some limited data from his own experiments (the full details are not set out in his paper). This model was reviewed by Thomas [12] pointing out several deficiencies in the modelling framework. He also set out modifications to overcome some of them. Yet, he declared that '... means that too much must not be expected of the quantitative aspects of theory so far developed '. Even so, it is important to recognise that the most crucial influences have got identified through a theory.

Burrows [13] has performed experiments with eucalyptus wood and leaves. The dependence of the mass burn rate with the size is related to diameter since the length was fixed. The experiments may be considered indicative of the general behaviour of $\dot{m} \sim d^n$ where $\dot{m}$ is the mass loss rate and the index n on diameter d is between 1.25 and 1.875. Drawing more precise conclusions is hampered primarily by the lack of simplicity in the fuel arrangement.

Xu et al. [14] conducted experiments on small cribs ($b = 0.2$–0.4 cm) in a cone calorimeter to enable determine the heat release rate and in this process determined the mass burn rate as well.

Heskestad [15] has discussed the crib fires with regard to enclosure fires and has identified a definition of porosity currently identified as Heskestad porosity.

McAllister and Finney [16–18] have performed an extensive series of experiments over a range of parameters, analysed the past data and theories and presented a valuable picture of the burn rate behaviour of cribs. Recognising the role of the vertical spacing between the ground and the bottom of the crib (h_v), they conducted experiments by varying this distance. They have also presented the analysis of the correlations by the earlier authors, and the comparison of the predictions from correlations with their new data and indicate that the correlations proposed by Gross [3], Block [11] and Heskstad [15] are not satisfactory most certainly for thin sticks. They have pointed out that both Gross [3] and O'Dogherty and Young [5] have not provided information on the spacing between the ground and the bottom of the crib (h_v). They have modified the correlation of Thomas [12] by including the effect due to h_v and compared their results as well as of some of the others and suggest that the modified correlation is the best fit for a range of their data except for small size sticks.

$$\frac{100\,\dot{m}_c}{\rho_0 A_s\sqrt{gh}} = \frac{3.27s}{h}\left[1 - \left\{0.277\ln\left(\frac{l}{b}\right) - 0.565\right\}\mathrm{e}^{-h_v}\right] \tag{8}$$

In Equation (8), the left-hand side can be interpreted as the ratio of actual fuel mass flux, $\dot{m}_c/A_s$, with a free convective flux, $\rho_0\sqrt{gh}$. The right-hand side shows a strong dependence on the crib spacing to crib height. The factor 3.27 results from (0.85/0.26) related to the constants set out in their paper. It can be recast as

$$\dot{m}_c = 0.0327\rho_0\sqrt{\frac{g}{h}}sA_s\left[1 - \left\{0.277\ln\left(\frac{l}{b}\right) - 0.565\right\}\mathrm{e}^{-h_v}\right] \tag{9}$$

Where A_s can be calculated from the geometry and the expressions are set out as

$$A_s = [4Lbn_ln_{sl}]\left[1 + \frac{b}{2L}\left\{1 - \frac{n_{sl}(n_l - 1)}{n_l}\right\}\right] \tag{10}$$

$$L = bn_{sl} + s(n_{sl} - 1) \quad \text{and so,} \tag{11}$$

$$A_s = [2b^2 n_{sl}]\left[n_l n_{sl} + n_l + n_{sl} + 2\frac{s}{b}n_l(n_{sl} - 1)\right] \tag{12}$$

2. Crib porosities

Most earlier work has tried to correlate the burn rate to crib porosities. The three porosities are those due to Gross [3], Block [11], and Heskestad [15]. These are defined below.

$$\phi_{\text{Gross}} = n_l^{0.5} b^{1.1} \frac{Av}{As} \tag{13}$$

$$P_{\text{Block}} = 0.5f\,[\rho(\rho_0 - \rho)g]^{0.5} h^{0.5} b^{0.5} \frac{G(\lambda - 1)}{C\psi\lambda} \tag{14}$$

$$\phi_{\text{Heskestad}} = s^{0.5} b^{0.5} \frac{Av}{As} \tag{15}$$

where P_{Block} is the parameter used by Block to correlate the burn rate, C is a dimensional constant ($\mathrm{g/cm^{1.5}\,s}$) dependent on the biomass used in the crib and ψ has been deduced as $\psi = 2f\,(h/s)$. Block separated the crib structure into densely and loosely packed regimes depending on the parameter P_{Block}. One can notice that the parameters b, s, n_l, enter into the equations in different ways. It is not clear which of these is superior. While one would think that porosity as is understood normally should be dimensionless, both Gross and Heskestad porosity parameters are dimensional. Even though Heskestad porosity is widely used, the fact that there is not even an underlying argument to render it dimensionless with a physically relevant constant renders it difficult for use in rigorous model development.

In order to examine the quality of predictions with these as parameters, all the data available in literature (discussed in more detail later) is set out against the parameters in Figures 1 and 2. Figure 1 shows the plots of the dimensionless burn rate with the dimensionless crib-related parameter by Block as well as with Heskestad porosity. The dimensionless burn flux was first introduced by the Block as $\dot{m}''b^{0.5}/C$, where $\dot{m}''$ is the mass flux, b is the stick thickness and C is a dimensional constant as discussed above. The experimental data of Block seems to follow the prediction shown in dotted lines with a distinct separation between densely and loosely packed cribs. However, when all the data are examined together, the experiments of densely packed crib have such a broad spread that, clearly Block parameter is inadequate to present any meaningful behaviour. The situation is not any different with Heskestad's porosity.

To further pursue the relationships, the data are set out as mass burn rate as it is the final parameter of significance, with the parameters noted above. As is evident from Figure 2, the comparisons over the full range of burn rates up to 350 g/s as well as for smaller cribs up to 20 g/s (the expanded part on the right side of the figures) seem poor and the only inference is that the use of the porosities will not aid in creating better prediction procedures. One inference of significance can be that the data by Gross at high burn rates seems far above the rest at comparable parameters of Block and Heskestad raising possible

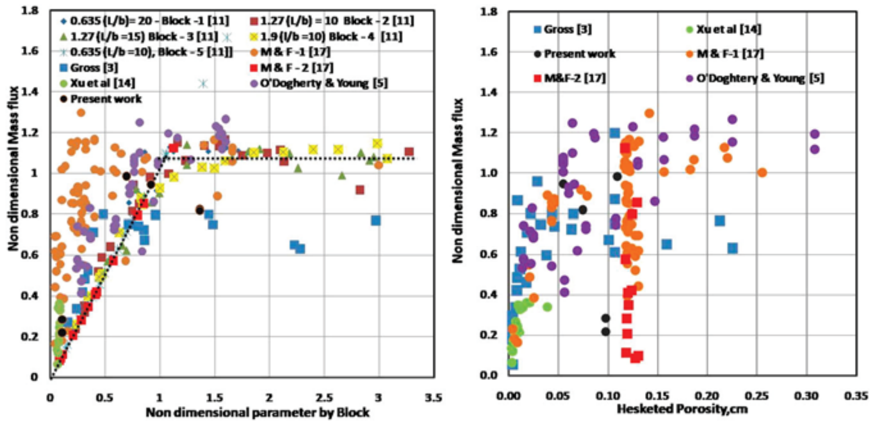

Figure 1. Comparison of the flux with the parameters P_{Block} and ϕ_{Heskstad} for all the data.

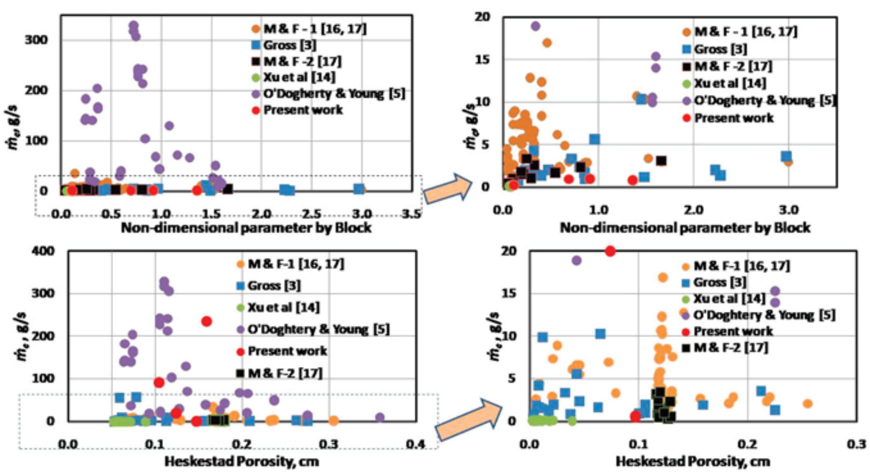

Figure 2. Comparison of $\dot{m}_c$ with the Block's parameters and Heskestad's porosity for all the data.

questions about the accuracy of their data. It would be appropriate to state that the broad conclusions on the value of these porosities as parameters for correlation were also arrived at by McAllister and Finney [17].

3. The present approach

While the aim of any modelling procedure is to provide a correlation for the burn rate

$$\dot{m}_c = \dot{m}_c(b, s, n_l, n_{lc}, \text{ specific fuel}) \tag{16}$$

The data from various sources – references [3, 5, 6, 14, 16, 17] was put together. Since it has been known that the burn rate is sensitive to b, the experiments were classified into 8 different groups to enable an understanding of the behaviour. The broad summary of data are set out in Table 1. From S1 to S8, the mass of the cribs increases with b as also n_{sl} and n_l.

Table 1. Basic data for cribs.

Class	b cm	s cm	n_{sl}	n_l	L cm	m_0 g	N.E	Ref
S1	0.16 – 0.2	1.5 – 1.7	3 – 16	8 – 70	15 – 25	14 – 36	14	[16]
S2	0.3 – 0.4	0.4 – 10	2 – 8	3 – 80	5 – 31	6 – 200	26	[14, 16]
S3	0.6 – 1.0	0.5 – 11	3 – 14	4 – 134	6 – 61	30 – 10,000	49	[3, 16]
S4	1.27	0.6 – 10	2 – 16	3 – 96	10 – 91	500 – 68,000	27	[3, 16]
S5	1.9 – 2.0	0.9 – 10	3 – 18	3 – 21	19 – 61	400 – 30,000	24	[3, 5]
S6	2.54 – 9.15	1.2 – 9	5 – 17	10 – 40	25 – 92	3500 – 262,299	23	[3, 5]
S7	0.16 – 0.64	1.9 – 4.2	3 – 16	6 – 15	15 – 40	6 – 1530	23	[6, 16]
S8	3.81	5.4 – 5.8	3 – 9	10 – 27	50 – 110	23,000 – 237,500	9	Present

Note: N.E = Number of experiments.

Figure 3. Experimental arrangement used in the dry chemical powder qualification tests and crib during its peak burn rate.

In Table 1, the size range of each of the groups is shown in the second column. Class S7 is similar to S1, S2 and part of S3, but these experiments were conducted by the investigators [6, 17] by placing them on the ground ($h_v = 0$). A few experiments have been conducted by O'Dogherty and Young [5] with b of 9.15 cm.

Class S8 constitutes the experiments conducted at the laboratory of the authors of this work as a part of qualification tests for dry chemical powder-based extinguishers. Figure 3 shows the experimental arrangement which consists of a crib placed at a height of 0.4 m from the ground, a pan with the required amount of n-heptane fuel to ignite the crib and the balance on which the crib is placed to obtain the mass vs time data during the burn. Figure 4 shows plots of mass vs time of several crib configurations tested with the data on b-n_{sl}-n_l shown. The peak burn rate is obtained during the flaming combustion as shown in the plot.

Table 2 shows the configuration of the cribs used and the peak burn rates obtained as described above. The data of all other authors used in this work have obtained the peak burning rate in the same regime except O'Dogherty and Young [5] which will be discussed further. The number of experiments performed in each class is shown and the total number of experiments is 193.

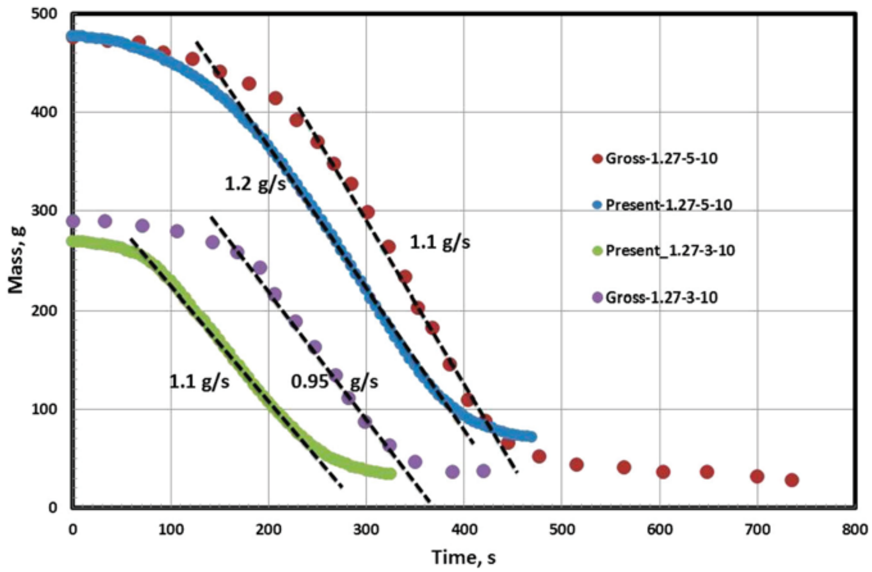

Figure 4. The plot of mass vs time for several crib configurations with legend showing $b - n_{sl} - n_l$.

Table 2. Data of the experiments carried out in this study.

Biomass	b cm	s cm	n_{sl}	n_l	L cm	m_0 g	$\dot{m}_c$ g/s
Pine	3.8	5.85	12	27	110.0	237,500	234.8
Pine	3.8	5.73	9	20	80.0	97,500	91.6
Pine	3.8	5.73	9	20	80.0	96,500	91.6
Pine	3.8	5.44	6	12	50.0	23,980	21.2
Pine	3.8	5.44	6	12	50.0	23,820	20.0
Pine	1.27	4.45	3	10	12.7	269	1.1
Pine	1.27	1.59	5	10	12.7	477	1.2
Cocos nucifera	0.2	1.65	9	10	15.0	45	0.53

The range of parameters turns out to be as follows: Stick thickness, b varies from 0.16 to 3.8 cm (some data even up to 9.15 cm), spacing, s, from 0.3 to 11 cm, the number of sticks in a layer, n_{sl} from 2 to 20, the number of layers, n_l from 3 to 80 and the total number of sticks, n_s, up to 820, with stick lengths from 5 to 90 cm giving a mass range from 6 to 2.2×10^5 g. The burn rate data and the burn behaviour in 193 different experiments performed in several different laboratories constitute a wide range challenging to the modelling procedure. To obtain an idea of the range of $\dot{m}$ for the range of data, a plot of $\dot{m}$ with m from the experiments was set out as in Figure 5. The variation of burn rate is 10^4 over a mass range of 10^6. There is a variation in the relative burn rates depending on the crib size, b and perhaps other parameters. The mass burn rate varies nearly linearly with the crib mass over a wide range of scales. There are systematic deviations which must be examined and accounted for using geometric parameters in a general form to ensure greater applicability of the expression. In this process, it was thought appropriate to address the

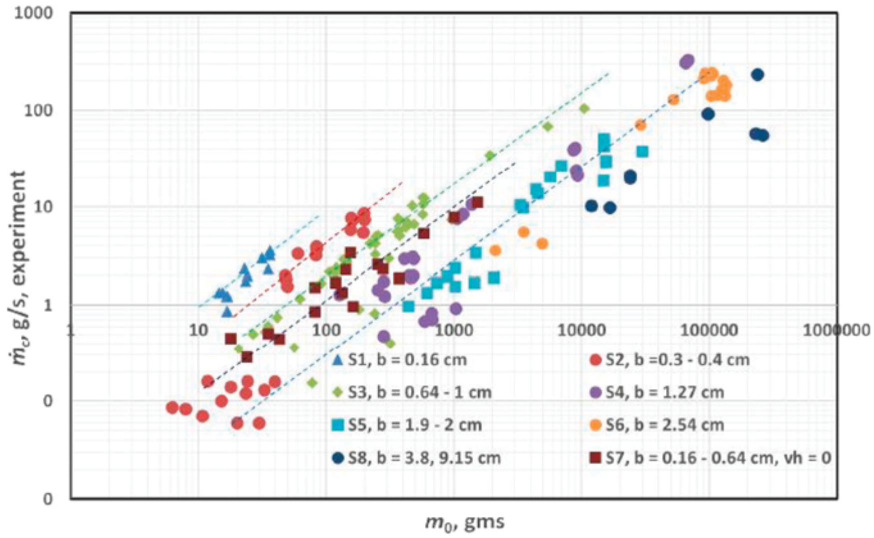

Figure 5. The plot of $\dot{m}_c$ with m_0 for all the crib data.

smaller-size material resting on the ground because of its possible applicability to wildland fires.

Gross [3], O'Dogherty and Young [5] as well as Byram et al. [6] have directly related the results to $R = \dot{m}_c/m_c$, the thermodynamic analysis by Block [11] and Thomas [12] has rightly chosen $\dot{m}_c/A_s$ as the parameter since this appears naturally in the heat balance relation at the surface of a burning wood crib as the gas phase flux being proportional to mass flux from the surface times the heat of phase change.

A study of liquid spheres and wood spheres has been pursued in the combustion literature (see, for instance, Agoston et al. [19] and Mukunda et al. [4]). This shows that rigorous analysis leads to a result

$$\dot{m}_{ld} = 2\pi d_s ln(1 + B) \tag{17}$$

$$\dot{m}_{bm} = d_s f(B, f_w, \rho_{bm}) \tag{18}$$

where $\dot{m}_{ld}$ and $\dot{m}_{bm}$ are the mass burn rates of liquid droplet and solid biomass sphere, d_s, the diameter and B, the transfer number, f_w, the moisture fraction in biomass, and ρ_{bm}, the biomass density that can affect the burn rate because of shrinkage. This brings up a question as to what would happen to $\dot{m}'' = \dot{m}_c/A_s$. Because $\dot{m}$ is proportional to the characteristic dimension, d_s, one would get $\dot{m}''$ varies as $1/d_s$. While this may well be true, it is not obvious whether the spacing between the sticks will not play a more crucial role in defining the relationship. This appears to be important because crib burn time data show a $t_b \sim b^{1.25-1.75}$ dependence as brought out earlier.

Towards this objective, it was thought that the data on the cribs resting on ground ($h_v = 0$) should be examined first. The data on these are set out in Table 3. As evident from the table, the range of number of sticks per layer, the number of layers and even the length of the sticks have a reasonably wide range of variation. The plot in Figure 6 presents the results from the three different investigators. As can be inferred from the figure, the linear variation between $\dot{m}_c$ with m_0 is indeed significant even though the range of parameters is wide.

Table 3. Burn rate data for cribs resting on ground, $h_v = 0, f_w = 2.5$ to 10%.

Biomass	b cm	s cm	n_{sl}	n_l	L cm	m_0 g	$\dot{m}_c$ g/s	t_b s	Ref
Pond-Pine	0.16	1.73	9	10	15.2	17.9	0.46	39	[17]
Pond-Pine	0.16	1.52	16	8	25.4	35.0	0.50	70	[17]
Pond-Pine	0.16	1.52	13	8	20.3	23.9	0.28	85	[17]
Rad-Pine	0.20	0.49	8	9	5.0	8.6	0.20	43	[14]
Rad-Pine	0.20	0.49	8	12	5.0	11.4	0.17	67	[14]
Rad-Pine	0.20	0.49	8	15	5.0	15.1	0.24	63	[14]
Rad-Pine	0.20	0.49	8	5	5.0	3.3	0.07	47	[14]
Rad-Pine	0.20	0.49	8	5	5.0	3.3	0.07	47	[14]
Pond-Pine	0.32	2.66	6	12	15.2	48.0	1.04	46	[17]
Pond-Pine	0.32	2.54	8	12	20.3	81.7	1.52	54	[17]
Pond-Pine	0.32	3.26	8	18	25.4	154.5	3.38	46	[17]
Pond-Pine	0.32	2.00	14	9	30.5	163.3	0.96	170	[17]
White-Fir	0.64	1.93	4	12	8.4	82.1	0.85	96	[6]
White-Fir	0.64	1.93	5	12	10.9	134.1	1.33	101	[6]
White-Fir	0.64	1.93	7	12	16.1	276.3	2.30	119	[6]
White-Fir	0.64	1.93	10	12	23.8	584.3	5.31	110	[6]
White-Fir	0.64	1.92	13	12	31.4	1003.0	7.86	127	[6]
White-Fir	0.64	1.92	16	12	39.0	1534.1	11.10	138	[6]
White-Fir	0.64	1.94	3	12	5.8	42.7	0.45	95	[6]
Pond-Pine	0.64	2.07	12	6	30.5	371.8	1.87	198	[17]
Pond-Pine	0.64	2.53	8	8	22.9	254.0	2.57	99	[17]
Pond-Pine	0.64	3.01	5	9	15.2	119.6	1.69	71	[17]
Pond-Pine	0.64	4.23	4	14	15.2	141.7	2.29	62	[17]

We need to interpret this simple result. The quantity $m_0/\dot{m}_c$ is essentially the burn time. The data show that the burn time varies from about 40 to 200 s over various parameters of crib geometry largely controlled by b as well as s, n_{sl} and n_l. For spheres burning in ambient air, it varies as $t_b \sim d_0^2$. It is unclear how it would vary since there are many dimensions in the case of crib. In an attempt to explore the possibility of relating to a single dimension, based on the consideration that m_0 has an important role in this range of data, an effective diameter was sought by relating it to m_0 through $d_0 = [(m_0/\rho_{fu})\,(6/\pi)]^{(1/3)}$ and examining the relationship of the burn time with this diameter. Figure 7 shows the plot of the data from Table 3 and also from the data drawn from [20].

Keeping in mind that we are seeking the variation of the behaviour, the variation of the burn time for cribs involves an arbitrary scaling factor (of 1/6) to bring the range of the sizes into the same range as of spheres. And so, $d_0 = [(m_0/\rho_{fu})\,(6/\pi)]^{(1/3)}/6$. It is only the slope that is independent of this scale. For spheres, the index is 2 and the variation of the burn time can be described as $t_b = 30\,(d_0/10)^2$. For the crib, the burn time variation has an index of 0.46. This shows that other parameters have an influence on the inference of an effective length scale (or diameter).

Irrespective of this result, the fact that burn time is largely independent of crib structure either crib size or spacing implies that diffusion of the oxidant into the structure is fast to all the interior segments without any preference. The free convection due to the fire leads to air entrainment at velocities of 5–10 cm/s (Grummer and Strasser [8]) and even at these speeds the time required for air to reach the centre of the crib is only about a second for the experiments set out in Table 3. This aspect does not by itself preclude the dependence

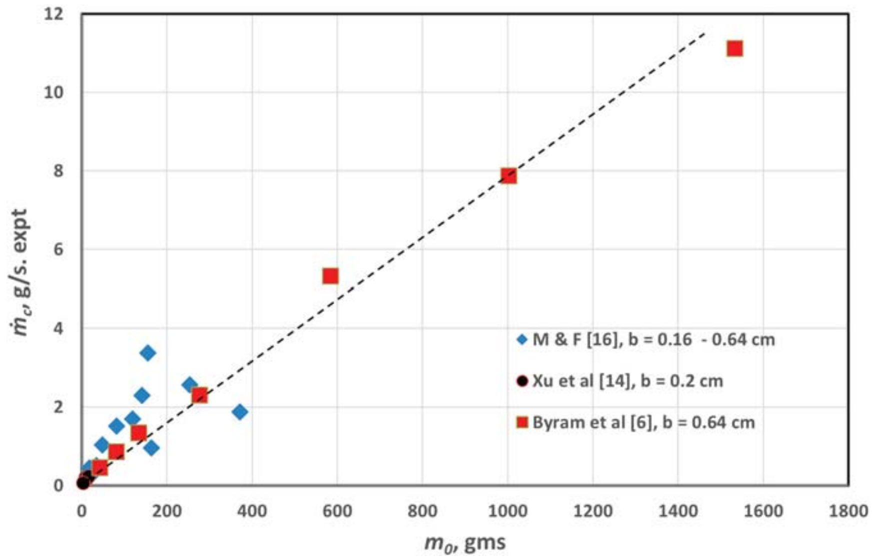

Figure 6. The plot of $\dot{m}$ with m_0 for $h_v = 0$.

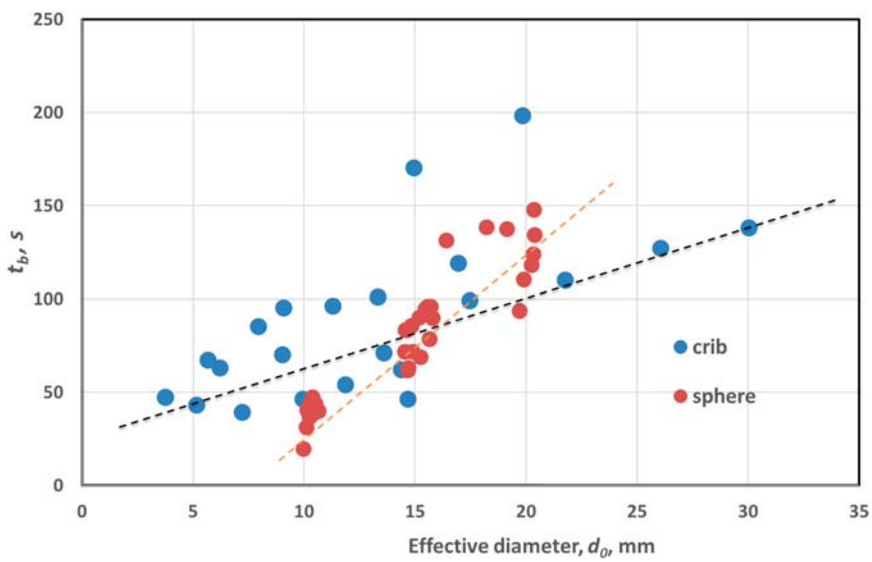

Figure 7. The plot of the burn time t_b with an effective diameter of the crib and the actual diameter of a sphere, d_0 with the data for the latter drawn from [20].

on size. A closer examination shows a slightly different trend for some data at a vary small m_0. In any case, the conclusion is that *the dominant burn behaviour is captured by the overall mass of the crib* with other effects controlled by b to be included.

In order to examine how the data behaves for specific cases (S2 to S8), the raw data was put together as in Figure 8. As can be noted, even though the data exhibit a linear dependence of $\dot{m}_c$ with m_0, there are considerable deviations. Also, the slopes decrease with increasing b. For $b = 0.3$–0.4 cm, the slope is 0.04 for a number of data and also

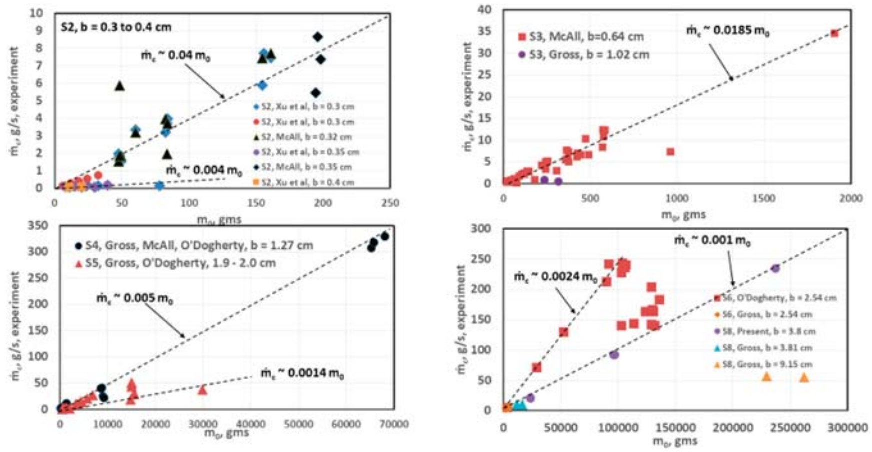

Figure 8. The plot of $\dot{m}$ with m_0 for data on S2 to S8.

0.004 for some data (largely from Ref. [14]), 0.0185 for $b = 0.64$–1.02 cm, 0.005 for $b = 1.27$ cm, 0.0014 for b 1.9–2 cm, and 0.0024 and 0.001 for $b = 3.81$ cm. These show that b has a strong influence on the slopes, even though the linear behaviour of m_c with m_o seems present.

Before we explore the influence of b, it is necessary to account for the effect of spacing between the ground and the bottom of the crib. This has been explored by McAllister and Finney [17] and Figure 9 is a replot of their data with an explanation of their data. Even though these plots are a variation of the mass flux, the relative variation can be made use of in attempting to account for the influence of both the spacing s and h_v on the burn behaviour. While McAllister and Finney used a factor $[1 - \exp(-h_v)]$ to account for the influence of the separation distance, it appears that one needs to account for the effect of s as well. Further, the dependence on b cannot be excluded. After a consideration of the data the following correction factor, C_0 was arrived at.

$$C_0 = \left[1 - \mathrm{e}^{-(h_v + b/s)}\right] \tag{19}$$

The data on $b = 0.16$ cm with different separation distances of the crib from the ground obtained by McAllister and Finney [17] has been set out in Figure 10. In this plot, the data on the experimental $\dot{m}_c$ corrected for the effects of h_v and b/s has also been set. The scatter in the raw data of $\dot{m}_c$ with m_0 is brought down in the corrected plot of $\dot{m}_c/C_0$ with m_0. The effective behaviour is captured with $\dot{m}_c = 0.096 m_0/C_0$.

The correction due to h_v and b/s is introduced into all other data as well. Each of the cases was found to be a function of b and $n_l b/s$ where $n_l b$ is the height of the crib. The dependence was found to be strong with b and was extracted (along with that of vertical height) as

$$C_1 = 0.011 C_0 b^{-1.35} \left[1 - \mathrm{e}^{-b/0.109}\right] \tag{20}$$

Where the second part $[1 - \exp(-b/0.109)]$ was a minor correction to the larger dependence $b^{-1.35}$. After this was introduced and the results of the correlation were examined, it was uncovered that a specific set of experimental data that had deviations had a higher value of h/s. The deviations were particularly significant with the data of O'Dogherty and

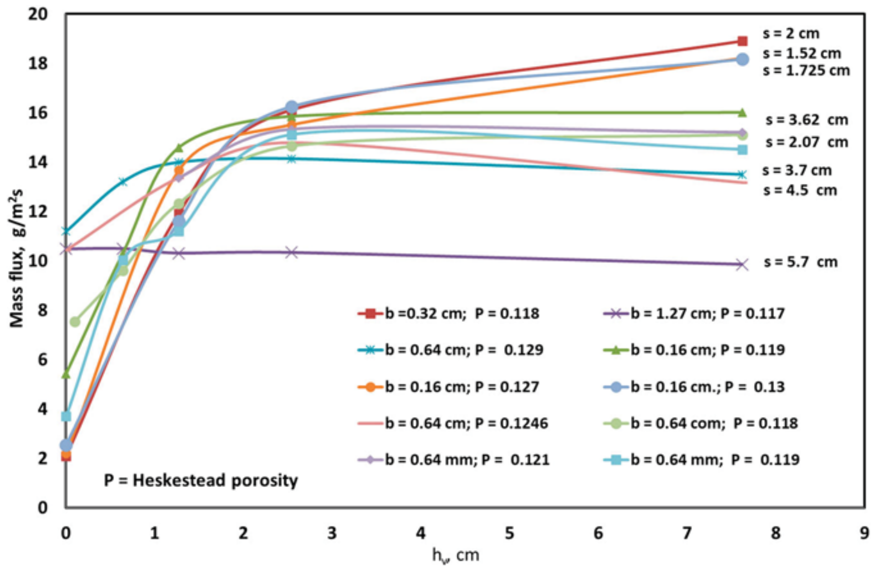

Figure 9. The plot of Mass flux with h_v, drawn from McAllister and Finney [17].

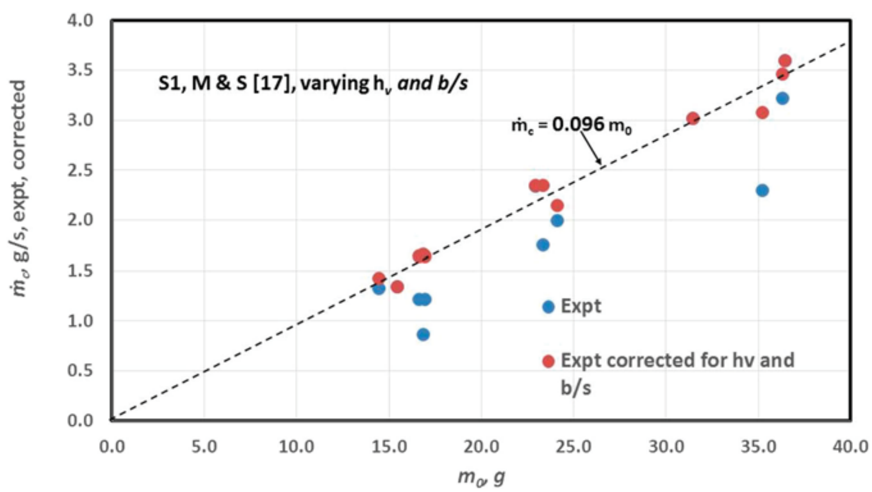

Figure 10. The plot of $\dot{m}$ with m_0 for varying h_v up to 7.62 cm.

Young [5], with one set of theirs having a much larger *h*/*s* compared to his other experiments. Further, the data by Gross [3] showed that the density of the fuel has a significant effect as briefly discussed in the introduction and will be further discussed in Section 4.2. These have led to correction due to *h*/*s* led to

$$C_f = 0.011\left[1 - \mathrm{e}^{-(h_v + b/s)}\right] b^{-1.35}\left[1 - \mathrm{e}^{-b/0.109}\right] \exp\left[-0.015\frac{\rho_{fu}}{425}\left\{\frac{h}{s}\right\}^{1.2}\right]\left[\frac{\rho_{fu}}{425}\right]^{-1} \tag{21}$$

The density-related corrections are set in a normalised mode since a large number of data on pine had values around 425 kg/m^3. The use of density effect with regard to the effect of *h*/*s* has limited data support since it has been based on the data by Gross with a wide range of densities. But the effect is so clear as discussed in Section 4.2 that its inclusion is considered valuable. Further, in the above expression, h_v and b have dimensions to be used presently in terms of cm. All dimensions can be understood to be rendered dimensionless by using a characteristic length for free convective dominated flows given by $[\nu_g^2/g]^{1/3}$ where ν_g is the gas phase kinematic viscosity (m^2/s) and g is the acceleration due to gravity (m/s^2) (see for more discussion, ShivaKumar et al. [21]). The actual value of this number is about 20–21 cm. Thus there is no loss of generality in obtaining the above expression in dimensional terms.

This then led to the expression that could be used uniformly for S1 to S8 (all excepting the case of $h_v = 0$. The expression for $\dot{m}_c$ is written as

$$\dot{m}_c = C_f\, m_0 \tag{22}$$

4. Comparison of predictions

There are two correlations that can predict the burn rate of cribs – that due to Thomas modified further by McAllister and Finney [17] as set out in Equation (9) and the present one – Equation (22). It must be remembered that these are inspired by different approaches to the evolution of the correlation. In the case of the modified Thomas equation, the dimensionless burn flux scales inversely with *h*/*s*. In the present correlation, the geometric parameters are understood to be incorporated in the mass of the crib and the strong variation with crib size is brought in along with a direct weak dependence on *h*/*s*. It is not immediately obvious whether the present correlation will indeed work better. Since Gross [3] and O'Dogherty and Young [5] have not provided complete information on the experimental arrangement (as also brought out by McAllister and Finney [17]), it was decided to test the present correlation against the modified Thomas correlation using the data of Refs. [14, 17] first and subsequently consider those of [3, 5].

4.1. *Comparison with results of McAllister and Finney [16, 17]*

Figure 11 shows the comparison of burn rates for case S1 (for $b = 0.16$ cm) and S2 (for $b = 0.3$–0.4 cm). One can clearly notice that the present correlation is superior to the modified Thomas correlation. Figure 12 presents the comparisons of burn rates for cases S3 ($b = 0.64$ cm) and S4 ($b = 1.27$ cm). Here both the correlations seem to perform as well on the average. There are differences, part of which may be due to experiment-related features. Thus, the present correlation performs better than of modified Thomas correlation with regard to smaller-size cribs and both perform similarly for larger-size sticks for the experiments of Ref. [16].

4.2. *Comparison with results of Gross [3]*

Gross [3] conducted experiments with cribs of $b = 1.02$, 1.27, 1.9, 2.54, 3.81 and 9.15 cm. The experimental data are set out in Table 4. While the density of Douglas fir (DF) is around 430–450 kg/m^3, others like Balsa and Ash (rows 6–8 in the table) have very different values and with identical geometric features, the mass and mass burn rates vary substantially. Rows 9–11 carry the data for the same variety of species with identical parameters across, but differing from the previous set in the value of *h*/*s* that is 20 for

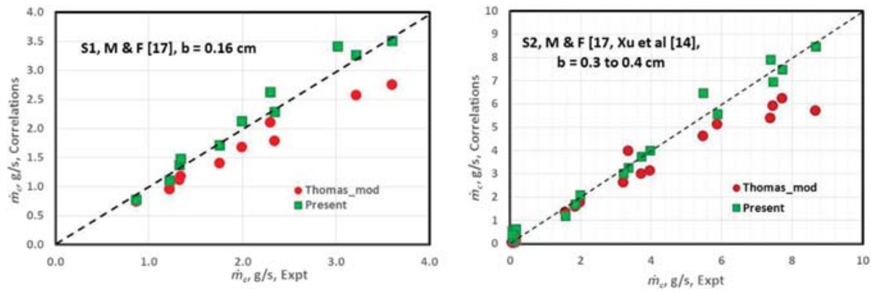

Figure 11. A comparison of the present predictions and of Thomas with experimental data for cases S1 and S2.

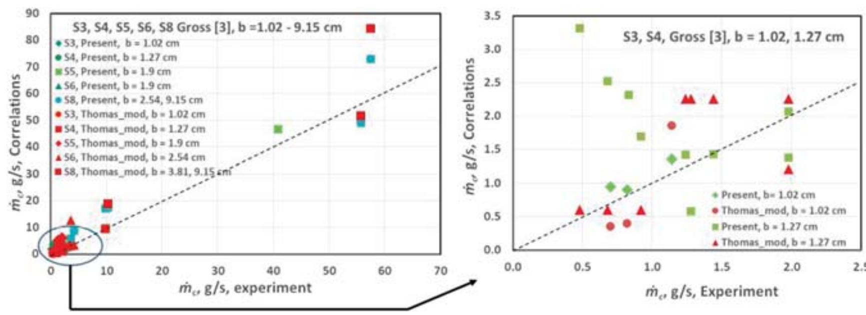

Figure 12. A comparison of the present predictions and of Thomas with experimental data for cases S3 and S4.

rows 6–8 and 2.9 for rows 9–11 indicating the role of *h*/*s* in affecting the burn rate. This was the reason for its inclusion in the exponential term in Equation (21). The results of the present correlations and those from the modification of Thomas are compared with experimental data in Figure 12. The left side of the figure shows the data for all the sizes, 1.02–9.15 cm tested by them and the right side shows the smaller range data corresponding to the sets S3 and S4. While the left side figure shows the overall consistency of the predictions with the data, the smaller size systems show considerable variability. This is true of both the correlations. Perhaps the quality of data obtained from the sensors and instrumentation used in their experiments in 1962 might be a possible explanation.

4.3. *Comparison with results of O'Dogherty and Young [5]*

The work of O'Dogherty and Young followed the work of Gross. However, several crucial experimental details are not reported. The fact that the cribs were mounted with a specific h_v cannot be inferred from their work. Though the work of Refs. [3, 5] occurred before the realisation of the importance of h_v that came about due to the work of McAllister and Finney [16–18], the explanation of the experiment could be used to infer the parameters and this cannot be done for the work of ref [5]. As such, predictions of their data followed with the assumption that $h_v = b$ as was taken for the experiments of Gross and the results of the correlations are set out in Figure 13.

While the broad conclusion that both the correlations seem to be performing well on the average, the differences inspired a more careful examination of the data of Ref. [5]. Some of the plots showed a sharply changing $\dot{m}_c$ vs. time. Figure 14 presents a few of

Table 4. The data for cribs provided by Gross [3], $f_w = 9\%$, $\dot{m}_{c,c}$ = burn rate with the present correlation.

No.	Biomass	ρ kg/m^3	b cm	s cm	n_{sl}	n_l	h/s	L cm	m_0 g	$\dot{m}_c$ g/s
1	DF	450	1.02	1.28	5	10	8.0	10.2	238.8	0.82
2	DF	428	1.02	2.04	4	10	5.0	10.2	181.7	0.90
3	DF	428	1.02	0.51	7	10	20.0	10.2	317.9	0.40
4	DF	465	1.27	1.59	5	10	8.0	12.7	476.2	1.98
5	DF	465	1.27	4.45	3	10	2.9	12.7	286.0	1.24
6	Balsa	196	1.27	0.64	7	10	20.0	12.7	281.0	0.48
7	Mahogany	409	1.27	0.64	7	10	20.0	12.7	586.0	0.68
8	Ash	718	1.27	0.64	7	10	20.0	12.7	1030.0	0.92
9	Balsa	207	1.27	4.45	3	10	2.9	12.7	127.0	1.28
10	Mahogany	410	1.27	4.45	3	10	2.9	12.7	252.0	1.44
11	Ash	719	1.27	4.45	3	10	2.9	12.7	442.0	1.98
12	DF	467	1.27	0.64	7	10	20.0	12.7	286.0	1.24
13	DF	428	1.90	0.95	7	7	14.0	19.0	286.0	1.24
14	DF	428	1.90	0.95	7	10	20.0	19.0	286.0	1.24
15	DF	428	1.90	2.38	5	3	2.4	19.0	286.0	1.24

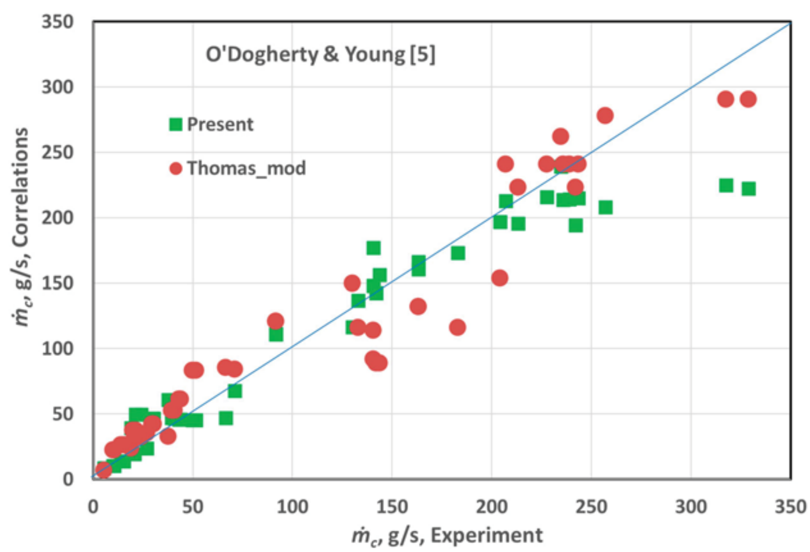

Figure 13. A comparison of the present predictions and of Thomas with experimental data of O'Dogherty and Young [5].

the data. The left side of the figure shows the plot of burn rate vs time drawn from the work of Ref. [5]. The data obtained from a few experiments performed at our laboratory on cribs of set ST8 are set along with those of Ref. [5] on the right side figure. One can see clearly that in the case of present data, there is a significant portion where the burn rate is constant and this is taken as the measure of the burn rate. The increase at earlier times is due to transients related to the ignition process. This process appears to be very long in the case of several experiments of Ref. [5]. It is also clear from the description that they used only about 2–3% of the crib mass as the liquid fuel (an alcohol) for ignition. This

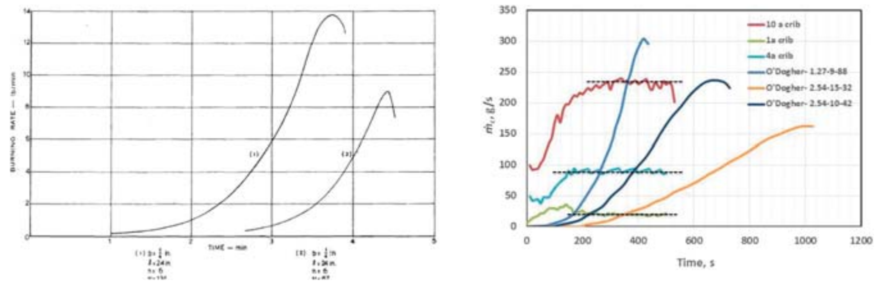

Figure 14. A comparison of the burn rate data with the left side drawn from the work of O'Dogherty and Young [5], and the right side of some experiments performed at our laboratory and also from Ref. [5].

must have resulted in a slow flame spread, a longer ignition process and would have taken more time to attain the peak burn rate. Since it is difficult to evaluate the precise influence of the unevenness of the ignition dynamics on the mass burn behaviour, it is inferred that the comparisons set out in Figure 13 are reasonable.

5. Distributed diffusion limited combustion

In traditional combustion–high-temperature conversion of biomass, one encounters a diffusive combustion mode that is controlled by the diffusion rate of the oxidant to the surface and this leads to $t_b \sim d^2$ behaviour discussed earlier. If the conversion process of a porous char that results after the volatile combustion is completed, the high-temperature gasification reactions with CO_2 and H_2O result in $t_b \sim d^n$ dependence with $n = 0$ to 1. The exponent 0 is obtained when the reaction rate is very slow compared to diffusion. In the present case, as has been seen in Figure 6, a large number of members inside a porous body receive the oxidant very fast and the individual members burn in a diffusive mode because their burn rate is faster than the diffusion rate onto the surface. Therefore, the burn behaviour of a conglomerate of the individual elements of the crib gets averaged out over the mass of the crib. This is the reason for the simple dependence of the burn rate with crib mass. As an extended examination of the simplicity of $\dot{m}_c$ vs. m_0 relationship, the data was arranged in increasing order of density calculated as $\rho_{\text{crib}} = m_0/(L^2 h)$. Data up to about 60 kg/m^3 seem to behave providing a linear relationship between $\dot{m}_c$ and m_0 as shown in Figure 15. The predictions up to 10 kg seem to be excellent for the present correlation and

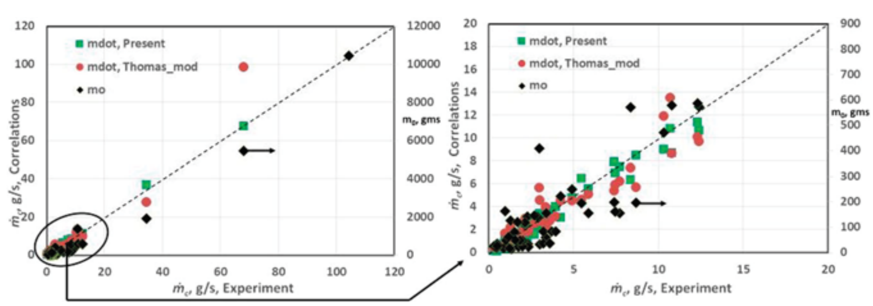

Figure 15. The burn rate with crib mass for less than 10 kg and the corresponding predictions of the burn rate with experimental data.

reasonable for the modified Thomas correlation. This finding may have been on the waiting for a long because Thomas noted the possibility, but actually discarded it because of the lack of possible physics in this approach.

Therefore, the predictions of the present approach as well as the Thomas correlation modified by McAllister and Finney [17], denoted as 'Thomas mod' are set out in Figure 16.

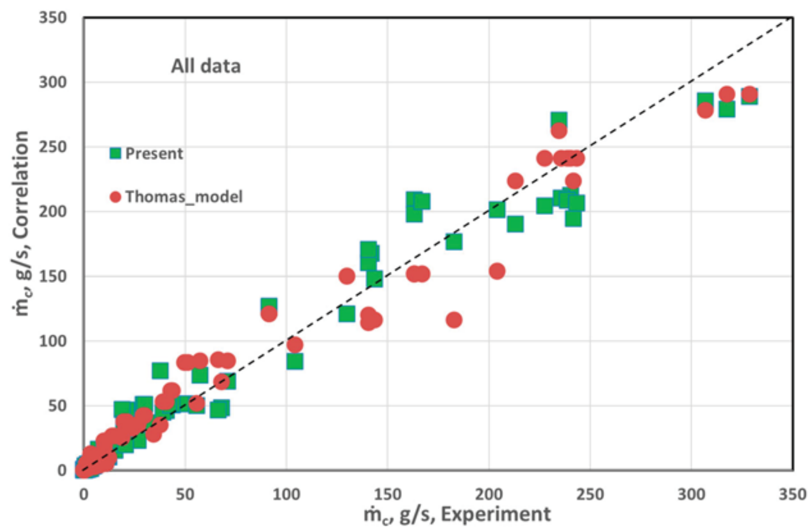

Figure 16. A comparison of the present predictions and of Thomas with experimental data.

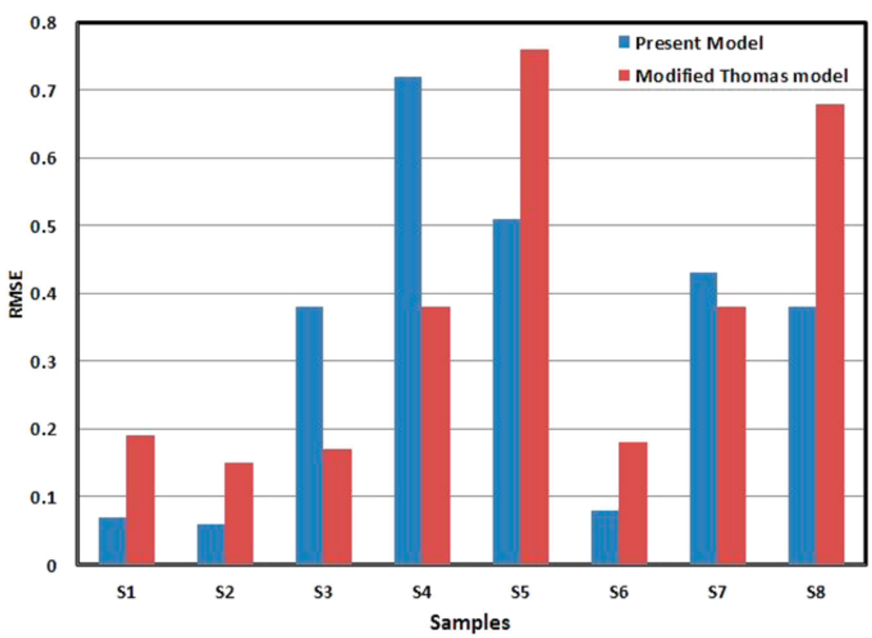

Figure 17. RMSE for present and Thomas modified model.

From this plot, it appears that both the correlations seem to perform similarly on the average. But the predictions from the present model are more accurate in most of the cases compared to the Thomas Model which is evident from the comparison of root mean square error plot as shown in Figure 17 for the different classes of data S1 to S8 (as described in Table 1). The larger errors seen for S3 and S4 categories are related to the accuracies of data discussed earlier.

6. Concluding remarks

The present paper has considered the data on crib fires set out in the literature and examined the possibility of improving the correlations. In the effort, it was uncovered that the mass burn rate scales linearly with the mass of the crib even though other dependences influence the choice of the coefficients. Like in earlier studies, the dependence on the crib size has been found very important. The role of crib spacing (s) is indeed important and enters into the earlier correlation in a strong way, but enters the present correlation in a relatively weak manner. The most important finding that the burn rate correlates with the mass of the crib is indeed interesting and not intuitive in its behaviour.

The present correlation inspired by the strong mass dependence of the burn rate appears to perform better most certainly in small sizes and about just as well at very large sizes.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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