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Summary

The role of various material fire properties in the model of fire growth developed by Magnusson and Karlsson [1] is examined in the context of the dimensionless variables containing them. It is shown that their successful representation of their calculations by power laws (one for fires which do not flashover and one for those which do) permits one to devise weighting factors for the rate of heat release as a function of time for the particular scenario examined.

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List of symbols

A = Area of opening
A_t = Wall surface area
c = Heat capacity
D = Thickness of solid
g = Gravitational acceleration
h = Heat transfer coefficient
H = Height of opening
$k\rho c$ = Thermal inertia
k = Thermal conductivity
q'' = Radiative heat transfer per area
q''_{ig} = Minimum radiant heat flux per area for sustained piloted ignition
Q'' = Energy release rate per fuel area
Q_o = Maximum energy release rate per fluel area in bench–scale test
S = Length
T = Temperature
T_{ig} = Ignition temperature
T_s = Surface temperature
V = Flame spread velocity
α = Indices
β = Indices
γ = Indices
Δ = Indices
δ = Flame heat transfer length
$\Delta\theta$ = Temperature rise
λ = Decay coefficient
ρ = Density
ψ = Flame spread coefficient from bench–scale test

subscripts:
f = flame
g = gas
ig = ignition
s = surface or solid
m = maximum

1. Introduction

Dimensional analysis has a well established place in heat and mass transfer engineering and although modern analytic and computational techniques permit more detailed calculations than in the past, the correlation of data by dimensional analysis, accompanied by statistical analysis, remains a valuable tool and has been successfully used in fire studies in describing flame size, upper layer gas temperatures, the throw of water sprays, etc.

The techniques of dimensional analysis are well documented and there are lists of dimensionless variables appropriate to the fire problem [2], [3]. The problem is not which ones to include but which to omit.

Here we shall consider the problem of the time scale of fire growth in a simple rectilinear compartment with one opening and seek to develope an approach in terms of dimensionless variables based on the only factor varied in the experiments viz the thermal properties of the materials. We are excluding geometrical factors at this stage.

2. Representation of calculation model

We shall approach the problem as if it were an experimental one with data to correlate. However good agreement between experiments and calculation [1] has already been found so we are in fact discussing the lesser problem of representing a set of equations by a statistically derived power law. The reasons for undertaking this are:

1. to see if a simple power law formula can be derived for what is otherwise an exercise on a computer and
2. to seek a basis for identifying some variables excluded from the calculation because they were kept constant.

Our first step is to consider the form of the various equations used in the model by Magnusson and Karlsson [1] which includes submodels of ignition, opposed flow flame spread and heat release. The upper layer gas temperature rise was calculated by the regression obtained by McCaffrey, Quintiere and Harkleroad [4]. Various view factors and constants were employed and initial calculations were for one geometry and one scale.

For simplicity the heat transfer coefficients (from which temperature rises of surfaces exposed to the convection and radiation from the upper layer gas were calculated) were given constant values independent of temperature.

One could set down all the equations used including the initial and boundary conditions and formally derive the full set of dimensionless variables. Here we identify the processes and conditions described by these equations e.g. one ignition equation representing all others of the same basic type and separate independant from dependant variables recognizing those which are purely internal variables. For example the flux on a surface over which flame is spreading is not considered since it is itself dependant on other variables.

2.1 Ignition

Scale will be represented by S. The other dimensions should appear as fractions or multiples of S but these ratios are omitted because they were held constant. A fixed source was assumed and ignition at any stage of development was represented by formulae such as

$$T - T_o = \frac{2\ \dot{q}''_{ig}\sqrt{t}}{\sqrt{\pi}\sqrt{k\rho c}} \qquad (1)$$

Here we regard $\dot{q}''_{ig}$ as characteristic of the heat flux used for ignition. All heat fluxes derived from internal heat exchange and from the hot gas in the ceiling are part of dependent variables other than that involved in opposed flow flame spread, but will be connected to temperature by means of independant heat transfer coefficients.

2.2 Surface temperature rise and heat transfer coefficients

A temperature rise $T_s - T_o$ on a surface depends on view factors, values of the temperature rise on other surfaces, terms like equation (1) and values of heat transfer coefficients. For a thick solid these have the form given by

$$\frac{1}{h} = \frac{1}{h_g} + \frac{1}{h_s}$$

h_g is treated as constant in time but so long as $\sqrt{\alpha_s t} << D$

$$h_s = \frac{k_s}{\sqrt{\alpha_s t}} = \sqrt{\frac{k_s \rho_s c_s}{t}} \qquad (2)$$

where D is the thickness of the solid. If $\sqrt{\alpha_s t} >> D$, h_s is also constant in time.

Here we only use the transient form of equation (2) for h_s. h_g will depend on surface emmissivity, temperatures of surface and surroundings, local gas velocity etc but here it is taken as constant and normalized by $\frac{h_g(T_{ig}-T_o)}{q''_{ig}}$ the numerator being of the order of the minimum flux causing ignition.

h_s appears as $\sqrt{\frac{k\rho c}{t}} \cdot \frac{(T_{ig}-T_o)}{q''_{ig}}$ which shows the need for defining a time scale.

The time to reach any particular condition which is defined by a given value of one of the internal varables eg. $\frac{\theta}{T_o}$ or $T_s = T_g$, is repesented by t_1 and appears both as $\frac{t_1 \dot{q}''^2_{ig}}{k\rho c(\Delta\theta_{ig})^2}$ and λt_1 (see 2.4) where $\Delta\theta_{ig}$ has some appropriate constant value. One or other can be chosen but their ratio is dimensionless and must appear amongst the dependant variables. Hence heat transfer within the solid is represented by $\frac{(T_{ig}-T_o)}{q''_{ig}}\sqrt{\lambda k_s \rho_s c_s}$ but this (apart from the ratio of $(T_{ig} - T_o)/\Delta\theta_{ig}$) is the same as that previously obtained – the ratio of the time scales so it adds none to the set of dimensionless varables.

2.3 Flame spread

The linear spread of flame down walls – i.e. the extension of the burning surface is described by

$$V = \frac{dx}{dt} = \frac{4}{\pi} \frac{\dot{q}''^2_f \delta}{k_s \rho_s c_s (T_{ig}-T_s)^2} \qquad (3)$$

This is essentially the same as equation (1) where t has been replaced by δ/V and where $\dot{q}''^2_f$ δ is a property of the material for a given oxygen concentration. The model did not consider changes in any gas concentration. T_{ig} is a material property in this context, T_s is an internal variable, V is an internal variable but one can find a characteristic velocity by which to scale "V", viz. a length "S" and either one of two time scales so we use $S\lambda$. If one sought to treat δ as a distance defined by external variables one would need to introduce chemical kinetics and those dimensionless variables implicit in the gas phase aspects if flame spreads. However here it is treated as associated with another internal variable as a material property $\dot{q}''^2_f\delta$.

2.4 Heat generation

It is assumed that after ignition the heat released from unit area of flammable material varies as

$$Q''_m\, e^{-\lambda t} \tag{4}$$

2.5 Temperature Rise

Temperature rises due to a flux on an internal surface are governed by equations similar to equation (1) except that $\dot{q}''_{ig}$ is supplemented by a flux which is an internal variable dependent on the upper layer gas temperature, heat transfer coefficients and view factors.

The upper layer gas temperature T_g is governed by

$$\frac{T_g - T_o}{T_o} = \frac{\Delta\theta}{T_o} = 1.6 \left[\frac{Q}{A\sqrt{gH}\ \rho_g c_g T_o}\right]^{2/3} \left[\frac{h_k A_T}{A\sqrt{gH}\, c_g \rho_g}\right]^{-1/3} \tag{5}$$

Q is of the form $Q''S^2 + Q_o$ where Q_o is a constant for a given ignition source. We assume that the temperature changes instantaneously with a change in Q. This effect could be included and would be implicit if the model included gas flow dynamics and plume theory which

it does not .We shall not include as dimensionless groups, terms which do not change e.g. Prandtl number. The ratio $q''_{ig}S^2/Q_o$ is omitted because it is here a constant, but is clearly a way of scaling Q_o.

Karlsson has used his model to evaluate the time for the heat release to reach a particular quantity. The absolute ignition temperature T_{ig} is omitted (except as $T_{ig}-T_o = \Delta\theta_{ig}$) because the chemistry of ignition is omitted. T_o appears only in association with heat release Q.

3. Dimensionless equation

Accordingly we propose

$$t_1 = \frac{k_s\rho_s c_s(\Delta\theta_{ig})^2}{\dot{q}''^2_{ig}} F\left[\frac{\dot{q}''^2_{ig}}{k_s\rho_s c_s(\Delta\theta_{ig})^2\lambda}, \frac{\dot{q}''^2_f\,\delta}{k_s\rho_s c_s\,(\Delta\theta_{ig})^2 S\lambda}, \frac{\dot{Q}_m S^2}{A\sqrt{gH}\rho_g c_g T_o}, \frac{hS^2}{\rho_g c_g A\sqrt{gH}}\right] \qquad (6)$$

where ratios of dimensions are omitted, all compartment external dimensions being represented by S. In equation (6) any variable can be replaced by any multicaplicative combination of itself and any other variable e.g. either of the first two can be replaced by $q''^2_f\delta/q''^2_{ig}S$.

A is not separable from $\sqrt{gH}$ in the original physical basis of the theory and they are not therefore separate terms in a dimensional analysis of this form of theory. One could include the window height to width ratio and also $\sqrt{gH}/S\lambda$ if one relaxed the constraint of taking T_g to respond instantaneously to a change in Q in equation (5). Note too that if the transient form equation (2) is used for h the role of $hS^2/\rho_g c_g A\sqrt{gH}$ can be replaced by the first term in F and either

$$\frac{S^2 q''_{ig}}{\rho_g c_g A\sqrt{gH}(\Delta\theta_{ig})}$$

or

$$\frac{Q''_m}{q''_{ig}} \cdot \frac{\Delta Q_{ig}}{T_o}$$

4. Analysis

In the absence of multiple solutions or discontinuities in the original theoretical equation, we might expect power laws to express the calculations at least over a limited range of variables. We rearrange equation (6) as follows

$$t = \frac{1}{\lambda} F\left[\frac{\psi}{s\lambda}, \frac{\lambda k_s \rho_s c_s (\Delta\theta_{ig})^2}{\dot{q}''^2_{ig}}, \frac{Q''_m S^2}{\rho_g c_g T_o A\sqrt{gH}}, \frac{S^2 \dot{q}''_{ig}}{\rho_g c_g (\Delta\theta_{ig}) A\sqrt{gH}} \right] \tag{7}$$

ψ is $q^2_f \delta / k\rho c(\Delta\theta_{ig})^2$ and is tabulated as a material property. The range of $\Delta\theta_i$ is small and the values somewhat uncertain in relation to their range. Many dimensionless variables such as geometric ratios, $\frac{\sqrt{gH}}{S\lambda} Q_o / q''_m s^2$ are omitted. Only those containing terms varied during he experiments to which the calculations apply have been retained. The last group in equation (7) is in effect constant here. The variable parts of the other quantities inside the brackets are the material properties only and are respectively

$\frac{\varphi}{\lambda} \cdot \lambda k_s \rho_s c_s$ and Q''_m so we explore

$$t \sim \lambda^{\alpha} \cdot \left[\frac{\varphi}{\lambda}\right]^{\beta} \cdot (\lambda \cdot k\rho c)^{\gamma} \cdot Q''^{\Delta}_m \tag{8}$$

In this form we should of necessity find $1+\alpha$ not significantly different from zero.

This is a test we have of whether the results can be expressed in dimensionless form. However we know a priori that theoretical values are so expressed so the test is much more a test of the consistancy of the indices in the power laws. For experimental values the problem is different. We shall need to decide whether $\mathrm{Ln}(t_{exp}) - \mathrm{Ln}(t_{calc})$ is associated with any of the variables or is, as it should be, randomly distributed.

The "best" equation can be written as[1]

$$t_{100} = e^{11.98}\,\lambda^{-0.98} \cdot \left[\frac{\psi}{\lambda}\right]^{-0.26} \cdot (\lambda \cdot k\rho c)^{0.83} \cdot Q_m''^{-0.44} \tag{9}$$

or with λ constrained

$$t_{100} = e^{11.98}\,\lambda^{-1} \cdot \left[\frac{\psi}{\lambda}\right]^{-0.26} \cdot (\lambda \cdot k\rho c)^{0.83} \cdot Q_m''^{-0.44} \tag{10}$$

$$\text{i.e. } t \sim (K\rho c)^{0.83}\,\psi^{-0.26}\left[\frac{Q_m''}{\lambda^{0.21}}\right]^{-0.44} \tag{11}$$

Fig. 1 shows the time to 100 kw as calculated by the Magnusson and Karlsson model, plotted against the results from equation 9. It is clear from the figure that the regression equation does not compare well with the model for times greater than 800 seconds, but is otherwise a very satisfactory description of the theoretical model.

A separate regression was run for data with times greater than 800 seconds, the results are shown in Fig. 2, the "best" equation can in this case be written as

$$t_{100} = e^{15.95}\left[\frac{\psi}{\lambda}\right]^{-0.41}(\lambda k\rho c)^{0.93}\,Q_m''^{-0.82} \tag{12}$$

and with λ constrained

$$t_{100} = e^{16.19}\,\lambda^{-1}\left[\frac{\psi}{\lambda}\right]^{-0.42}(\lambda k\rho c)^{0.97}\,Q_m''^{-0.84} \tag{13}$$

The coefficient of determination $r^2 = 0.83$.

Calculations for all of the materials involved with t_{100} exceeding 800 seconds ψ has a very low value and $k\rho c$ has a very high value but the two types of behaviour are mainly associated with a difference in the dependance of growth time on rate of heat release viz the indices of Q_m'' are different.

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[1]More recent work has changed the indices slightly but not the conclusions drawn form them.

5. The weighting of heat release

It is a commonplace that in building fires heat liberated early is more hazardous than heat liberated later, and many of the older reaction to fire tests recognize this by weighting any transient measure such as temperature rise of the combustion products by an inverse function of time. All too often the choice of weighting factor is governed by commercial expediency or by matching to historic levels of acceptability. So far as the authors are aware this is the first time any theoretical connection of any kind is offered for the weighting functions.

We note from the equation (11) the combination between Q''_m and λ is $\frac{Q''_m}{\lambda^{0.21}}$, such as would be obtained from integrating a weighted heat release

$$\int_o^\infty \frac{Q''_m e^{-\gamma t}}{t^{0.79}} dt$$

For the fires which do not flashover ($t_{100} > 800$ secs) the coupling of λ and Q''_m is as $Q''_m/\lambda^{0.47}$ which implies a weighting close to $t^{-1/2}$.

6. Conclusion

The model developed by Magnusson and Karlsson gives results over a substantial practical range of conditions for times to near flashover expressed as power laws of conventional dimensionless variables, based on data from ISO draft standard tests.

In particular the association between Q'' and λ offers a rule for use in practical testing of materials with a view to classification.

Problems of the limiting condition for flashover still need study because approximations based on power laws must be expected to break down when any term or its reciprocal approaches zero.

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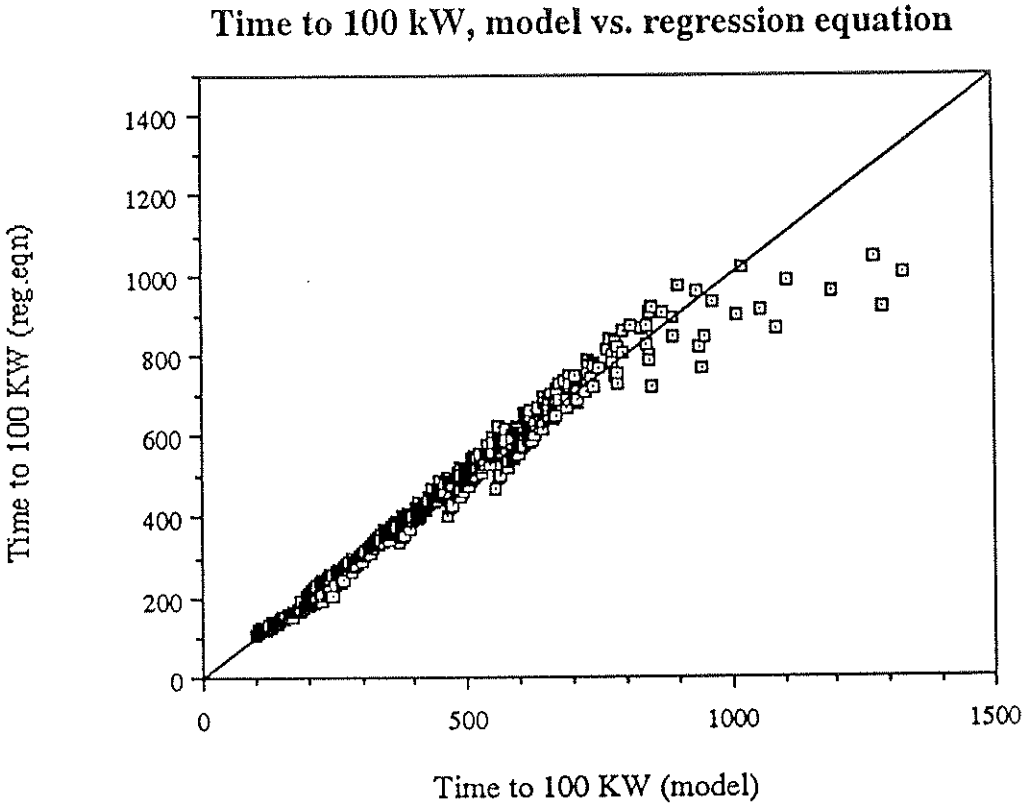
Time to 100 kW, model vs. regression equation
Time to 100 KW (reg.eqn)
1400
1200
1000
800
600
400
200
0
0
500
1000
1500
Time to 100 KW (model)

Fig. 1

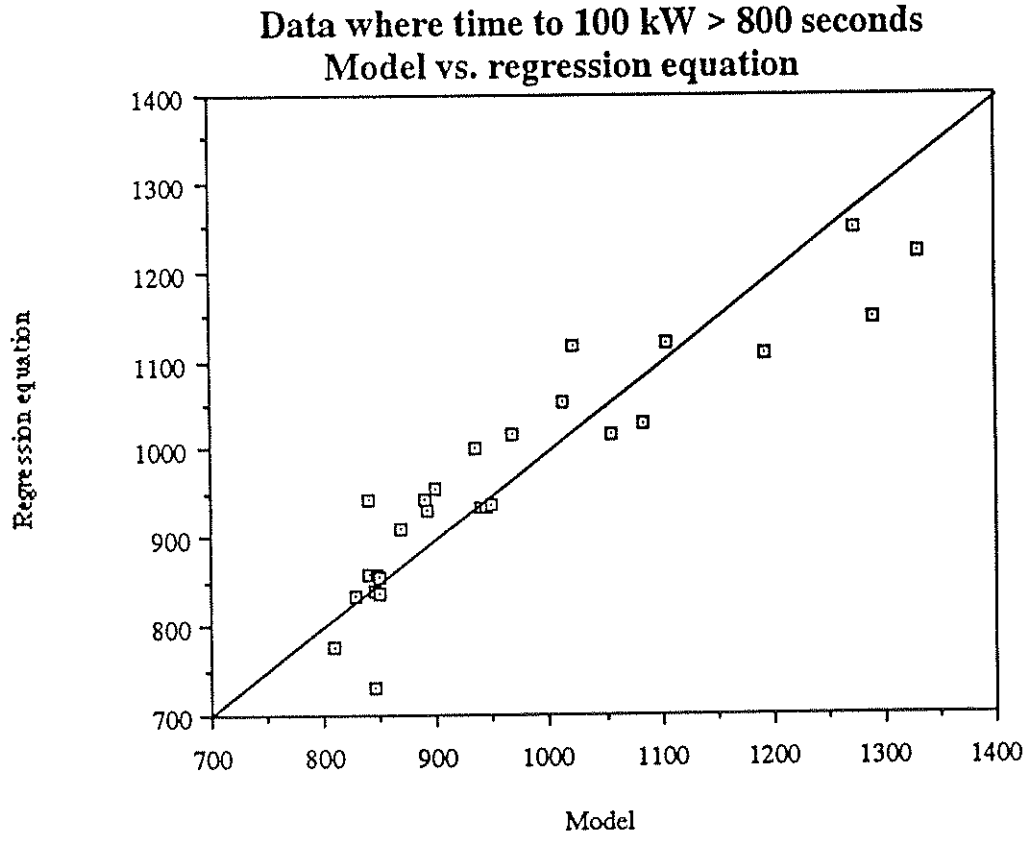
Data where time to 100 kW > 800 seconds
Model vs. regression equation
Regression equation
1400
1300
1200
1100
1000
900
800
700
700
800
900
1000
1100
1200
1300
1400
Model

Fig. 2