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EXPERIMENTAL AND THEORETICAL INVESTIGATIONS ON COMPARTMENT FIRES

Sigma-Tryck

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Lund Institute of Technology, Sweden, 1974

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The paper embraces the following publications:

/1/ The Effect of the Porosity and Air Flow Factor on the Rate of Burning for Fire in Enclosed Space (Porositets- och luftflödesfaktorns inverkan på förbränningshastigheten vid brand i slutet rum). Swedish Council for Building Research. Report R22:1971, Stockholm, 1971

/2/ Time Curve of Heat Release for Compartment Fires with Fuel of Wooden Cribs. Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology. Bulletin 36, Lund, 1974.

Introduction

In a differentiated and functionally based fire technological design of bearing constructions, the following steps are included which also constitute the corresponding research field, Pettersson (1965):

a) combustion-technological characterization of the fire load of a fire cell,

b) study of energy development, neccessary air supply and gas production during a fire process and evaluation of the smoke gas temperature as a function of time, obtained in the fire cell for a complete fire process,

c) evaluation of the thermal properties of the relevant construction material within the whole temperature range of a fire both for heating and cooling phase,

d) evaluation of the corresponding temperature-time field for the structure exposed to fire and

e) evaluation of the behaviour and bearing capacity of a fire exposed structure based on the temperature-time curve field determined according to d), knowing the corresponding changes in strength- and deformation properties of the material.

In both publications which pertain to the design step or the research field b), the influence of variations in the size of the fire load, porosity factor and stick thickness with fuel in the form of wood crib plus the influence of variations in ventilation of the fire cell and thermal properties of the enclosing structures of the fire cell, on some fire process characterizing magnitudes is illustrated. Furthermore, the possibility of relating a fire load of regular wood crib to a realistic fire load in the form of furniture, textile goods and other equipments is briefly discussed.

Scope of the investigation

A theoretical determination of the gas temperature-time curve of a fire process, performed by the heat- and mass balance equations of the fire cell presumes knowledge on the time variation of the energy developed from the fuel during the whole fire process. For wood fuel fires it is, however, extremely difficult to indicate this energy development per unit time in a satisfactory manner, since for this type of fuel the combustion simultaneously takes place both in the solid components and in the gases formed during pyrolysis in such a way that its influence on the combustion rate is not clarified at present. Further refinements of the recently published laboratory methods for a determination of the energy released per unit time for small specimens of, for instance, coverings, under well defined conditions of thermal exposure, can be presumed to be a likely future possibility for a direct experimental solution of the problem, Smith (1972 and 1973), Parker-Long (1972). Therefore, in order to study this energy development for fires, with wood cribs as the fuel, combined theoretical and experimental combustion studies have been performed, with the primary objective of determining the influence on the fundamental characteristics of the fire process for a wood crib in a closed fire cell having one window opening with variations in

the quantity of the combustible material,

the porosity factor of the fuel,

the thickness of the individual stick,

the ventilation properties of the fire cell and

the thermal properties of the enclosing structures of the fire cell.

A large number of tests from the experimental investigation have been analysed by the heat- and mass balance equations of the fire cell, for a systematical determination of the time curve for the energy released per unit time in a complete fire process. For every test the energy-time curve which rendered a satisfactory agreement between the gas temperature-time curve as measured through tests and calculated through a theoretical model, was iteratively determined. It proved to be possible for the results obtained in this manner, to be summarized by groups of relations which, with different degrees of precision, describe the energy-time curve of a complete fire process with fire load of wood crib.

These relations, in turn, facilitate theoretical calculations of the gas temperature-time curve of the fire process, for each individual case, with varying properties of the fire cell and the fuel.

Based on the concept of energy released per unit time, primarily its maximum value, a differentiated classification of compartment fires is further performed with division into ventilation- and fuel bed controlled fire process in the rigorous sense and crib controlled fire process. In addition, a method based on equivalent porosity factor and equivalent stick thickness is outlined, relating the fire load in the form of a regular wood crib to a realistic fire load in the form of furniture, textile goods and other equipments.

The experimental part of the investigation

The experimental investigation has been performed in three cubical, closed fire compartments at the model scale with one window opening and with the internal lateral dimensions measuring 500, 750 and 1000 mm. The main part of the tests were performed in the model fire compartment with the internal lateral dimension of 750 mm, and all the theoretically analysed fire processes described in publication /2/ correspond to the tests at this scale. The window opening of the fire cell was chosen in a square form and the dimensions given to this opening were such that the five different values, namely, $A\sqrt{H}/A_t =$ $= 0.020$, 0.032, 0.040, 0.070 and 0.114 $m^{1/2}$ were obtained for the opening factor, which together cover a broad and realistic range of variation. In the above relation, A_t (m^2) denotes the inner surface area of the walls, floor and ceiling which bound the fire cell from its surroundings, A (m^2) is the total opening area of the fire cell (windows, doors etc) and H (m) is a weighted mean value of the heights of the openings.

The studied values for the fire load, q, which were normally composed of redwood sticks having square cross sectional areas with the thickness b = 25 mm, were, q = 17.5, 35.0, 52.5, 70.0 and 87.5 MJ/square meter of the enclosing surface. In order to study the influence of the thickness of the individual stick, besides the lateral dimension b = 25 mm even sticks with dimensions b = 10, 12.5, 40 and 50 mm were taken into consideration in a special test series.

In order to characterize the piling density of the fuel, the porosity factor ϕ ($cm^{1.1}$) is used, defined by Gross (1972) through the relation

$$\phi = N^{0.5} \cdot b^{1.1} \frac{A_v}{A_s} \tag{1}$$

with

$$A_s = 2nb\{2NL + b\,[N - n(N-1)]\} \tag{2}$$

$$A_v = (L-n \cdot b)^2 \tag{3}$$

In the formulas, b denotes the thickness (square cross section) and L (cm) the length of each wooden stick, n the number of sticks per layer, N the number of layers, A_s the area of all the sticks, initially exposed to the air, and A_v the free horizontal area for vertical air flow through the pile. The variation range for the porosity factor, ϕ, of the fire load in the investigation is $0.02 \lesssim \phi \lesssim 1.32$ $cm^{1.1}$.

In order to investigate the influence of variations in the thermal properties of the enclosing structures on the fire process, the alternatives as regarded from outside inwards, 1.5 mm steel sheet, 1.5 mm steel sheet + 10 mm asbestos disk (density 1020 kg/m^3) and 1.5 mm steel sheet + 125 mm light weight concrete (density 500 kg/m^3), were studied.

In the investigation, the combustion rate was determined according to the experimentally developed practice, that is, by the weight loss of the fuel per unit time, the gas temperature-time curve of the fire process and radiation conditions.

In publication /1/ a background of the test lay-out and a detailed description of the test arrangements and the test characteristics, is presented. In addition, results from tests dealing with a study of the influence of varying opening - and porosity factor on the fire process with a constant fire load of $q = 35$ MJ/square meter of the enclosing surface and the stick thickness of $b = 25$ mm, are summarized and discussed for a fire cell having the enclosing structures of 1.5 mm steel sheet + 10 mm asbestos disk. For the other tests analysed in publication /2/ and not described in publication /1/, the unchanged testing technic is applicable. A complete and detailed description of all the model fire tests performed - about 300 in number - will be given in some other connection.

Theoretical analysis by the heat- and mass balance equations of the fire process

A theoretical calculation of the gas temperature-time curve of a fire process by heat- and mass balance equations, is based on the identity between the energy released per unit time during the combustion on one side and the energy per unit time removed through openings and enclosing structures of the fire cell on the other, that is

$$I_C = I_L + I_W + I_R + I_B \qquad (4)$$

in which

I_C = the released energy per unit time during combustion (MJ/h)

I_L = the energy removed per unit time through exchange of hot gases with cold air (MJ/h)

I_W = the energy per unit time supplied to such enclosing structures as walls, floor and ceiling and to possible enclosed structures (MJ/h)

I_R = the energy radiated per unit time through the openings of the fire cell (MJ/h)

I_B = the energy stored per unit time in the gas volume of the fire cell (MJ/h)

As mentioned in the beginning, for wood fuel a theoretical description of the fundamental magnitude energy released per unit time, I_C, during the combustion gets extremely complicated, since for this type of fuel the combustion simultaneously takes place both in the solid components and in the gases formed during pyrolysis in such a manner that its influence on the combustion rate is not clarified at present.

In order to find an acceptable approximate solution of the problem for ordinary practical applications, the following technic has been applied, Magnusson-Thelandersson (1970, 1971). Based on the results obtained from the tests, a reasonable polygon-shaped energy-time curve with the basic appearance as in FIG 1 has been assumed for each individual analysed test, whereafter the gas temperature-time curve of the fire process has been calculated. The necessary condition for this assumption has been that the total energy released during the fire process should be equal to the energy available in the beginning of the fire. The calculated gas temperature-time curve has been compared with that measured in the test whereupon the energy distribution assumed for the fire process has been successively modified, until agreement was reached between the calculated and the experimentally obtained gas temperature-time curves.

In publication /2/, this technic has been systematically applied for a large number of combinations of the studied test characteristics. Thereby the following combinations have been discussed:

in Section 4: Five different porosity factors in the interval $0.1 < \phi < 1.1 \text{ cm}^{1.1}$ for all the studied opening factors. The fire load was constant, q = 35 MJ/square meter of the enclosing surface and the stick thickness b = 25 mm. The enclosing structures, as regarded from outside inwards, were composed of 1.5 mm steel sheet + 10 mm asbestos disk, in Section 5: Four different values of the fire load, q, in the interval $17.5 \leq q \leq 87.5$ MJ/square meter of the enclosing surface for all the studied opening factors. The porosity factor was $\phi \approx 0.5$ cm$^{1.1}$ and a constant stick thickness b = 25 mm was used. The enclosing structures as regarded from outside inwards were composed of 1.5 mm steel sheet + 10 mm asbestos disk. For the medium sized opening factor $A\sqrt{H}/A_t = 0.040$ m$^{1/2}$, the analysis is supplemented by further values of the porosity factor, ϕ, and the fire load, q,

in Section 6: Varying stick thickness, b, in the interval $10 \leq b \leq 50$ mm for both of the opening factors $A\sqrt{H}/A_t = 0.040$ and 0.114 m$^{1/2}$ for several values of the porosity factor in the interval $0.1 < \phi < 1.3$ cm$^{1.1}$. The fire load was constant, q = 52.5 MJ/square meter of the enclosing structures. The enclosing structures, as regarded from outside inwards, were composed of 1.5 mm steel sheet + 10 mm asbestos disk.

in Section 7: Three different types of enclosing structures, as in the above, for the fire cell, for all the studied values of the opening factor. The fire load was constant q = 35.0 MJ/square meter of the enclosing surface and the porosity factor $\phi \approx 0.5$ cm$^{1.1}$. For the medium sized opening factor $A\sqrt{H}/A_t = 0.040$ m$^{1/2}$ the analysis was supplemented by tests embracing further values of the porosity factor, ϕ.

Results

Based on the experimental results and the theoretically determined energy-time curves, some different fire process characterizing magnitudes are analysed. Some of the magnitudes corresponding to the energy-time curve are illustrated in FIG 1, namely

I_{Cmax}, which indicates the maximum value of the energy released per unit time

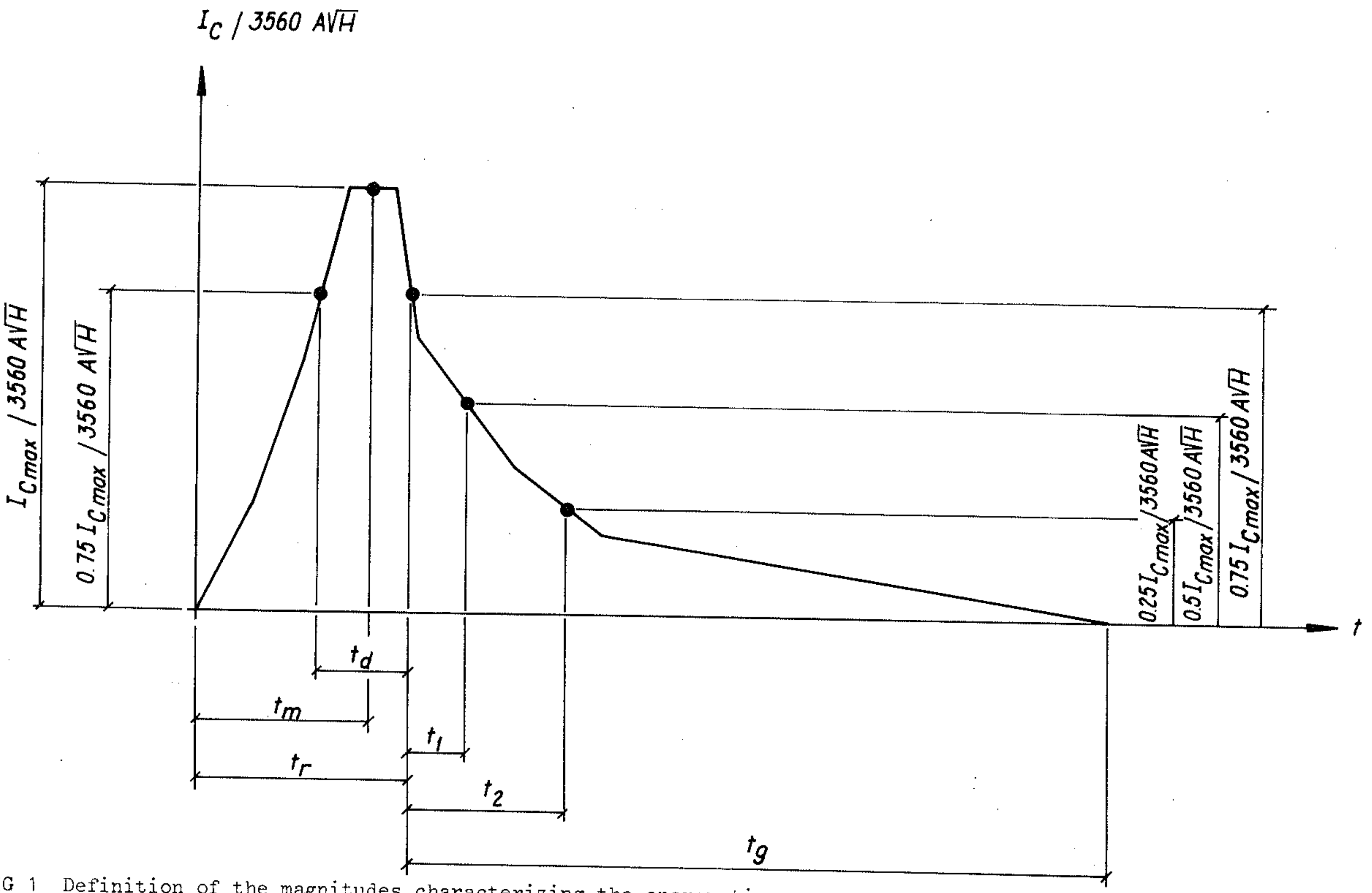

FIG 1 Definition of the magnitudes characterizing the energy-time curve

t_d (h), which expresses the time interval determined by the value 0.75 I_{Cmax} on the ascending and descending part of the energy-time curve and which approximately defines the active phase of the fire,

t_r (h), which describes the time interval between ignition and the time corresponding to 0.75 I_{Cmax} on the descending part of the energy-time curve and which besides t_d, also embraces the ignition- and flaming phases,

t_1 (h), which indicates the time interval between the times corresponding to 0.75 I_{Cmax} and 0.5 I_{Cmax}, on the descending part of the energy-time curve,

t_2 (h),which describes the time interval between the times corresponding to 0.75 I_{Cmax} and 0.25 I_{Cmax} on the descending part of the energy-time curve, and

t_g (h), which is an approximate expression for the total duration of the cooling phase.

As an example on the summarized results, the theoretically determined relation between $I_{Cmax}/A\sqrt{H}$ and $M/A\sqrt{H}$, based on the experimental values is given in FIG 2a for wood crib tests characterized by a porosity factor of $\phi \gtrsim 0.5$ cm$^{1.1}$ and a stick thickness of b = 25 mm, and the corresponding relation for porosity factors $\phi = 0.1$ and 0.3 cm$^{1.1}$ with the stick thickness b = 25 mm plus stick thickness b = 40 and 50 mm with the porosity factor $\phi \approx 0.5$ cm$^{1.1}$ is shown in FIG 2b. In the above relation M is the total fuel quantity of the fire cell in MJ. The polygon shaped curve inserted in the figures - and given by Eqs (47)-(49) in publication /2/ - indicates an upper limit for the maximum energy development per unit time, holding true for an easily combustible wood crib characterized by $\phi \gtrsim 0.5$ cm$^{1.1}$ and $b \leq 30$. With respect to the type of the fire process, the three successive straight lines describe three different ranges, namely, a fuel bed controlled fire process in the rigorous sense within the range $M/A\sqrt{H} < 500$ MJ/m$^{5/2}$, a ventilation controlled fire process in the rigorous sense within the range $M/A\sqrt{H} > 1000$ MJ/m$^{5/2}$ and a transitional zone between both of the mentioned chief types.

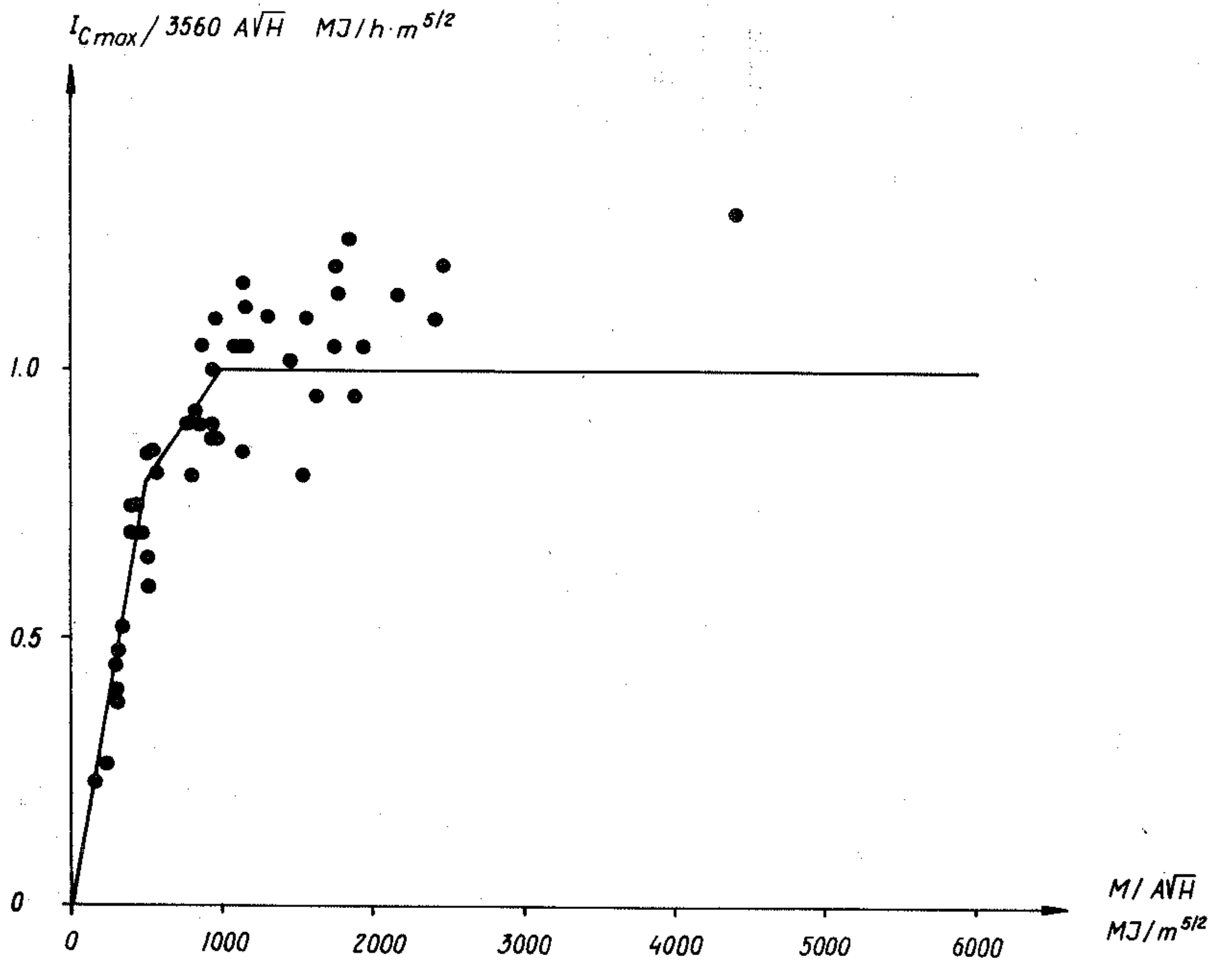

FIG 2a The relation, calculated from the results of the performed model tests, between $I_{Cmax}/3560\ A\sqrt{H}$ and $M/A\sqrt{H}$, where M is the total energy content of the fuel. The inserted straight lines are described by Equations (5)-(7). The fire load is in the form of a regular wood crib. In the summary, only the tests for which the relations $\phi \geq 0.5$ cm$^{1.1}$ and the stick thickness b = 25 mm are true, have been considered.

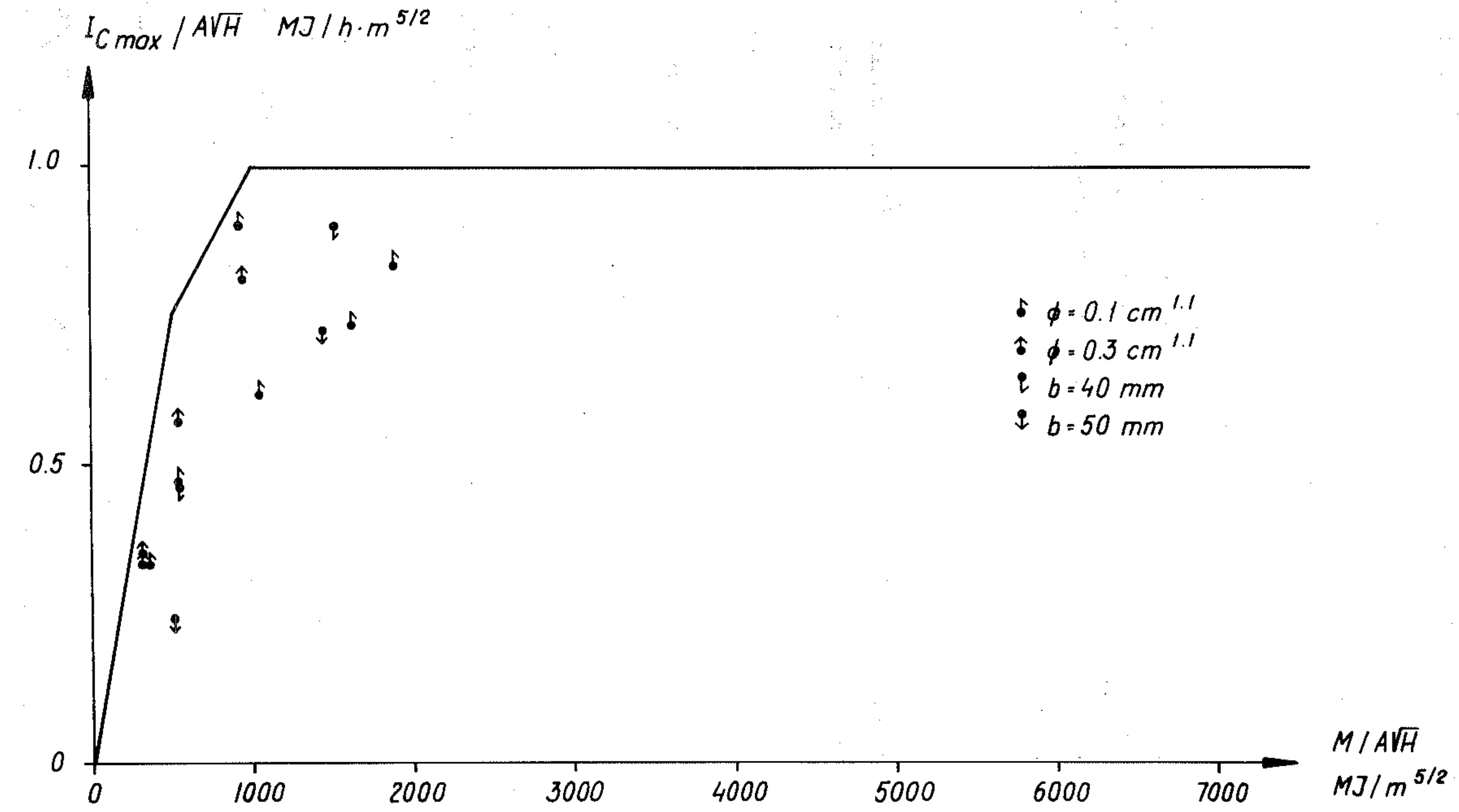

FIG 2b The relation obtained between $I_{Cmax}/3560\ A\sqrt{H}$ and $M/A\sqrt{H}$, determined from the performed model tests, corresponding to the porosity factors $\phi = 0.1$ and $0.3\ cm^{1.1}$ with the stick thickness b = 25 mm and to the stick thicknesses b = 40 and 50 mm with the porosity factor $\phi \approx 0.5\ cm^{1.1}$. The inserted straight lines are described by Equations (5)-(7).

A fire process is, thereby, defined as ventilation controlled in the rigorous sense if the maximum energy, I_{Cmax}, is only determined by the air flow factor, $A\sqrt{H}$, the influence of variations in the properties of the fire load being practically negligible. For the corresponding I_{Cmax}-level the following relation is true

$$I_{Cmax} \approx 3560\ A\sqrt{H} \quad \text{MJ/h} \tag{5}$$

A fire process is defined as fuel bed controlled in the rigorous sense, if the maximum energy is only determined by the total heat content, M, of the fuel, the influence of variations in the air flow factor, $A\sqrt{H}$, and the other properties of the fire load being practically negligible. The corresponding relation for I_{Cmax} is

$$I_{Cmax} = 5.6\,M \quad \text{MJ/h} \tag{6}$$

Within the transitional zone $500 \leq M/A\sqrt{H} \leq 1000$ MJ/m$^{5/2}$, the maximum energy released per unit time, I_{Cmax}, is determined by the relation

$$I_{Cmax} = 1.52\ M + 2040\ A\sqrt{H} \tag{7}$$

which describes a fire process which is combined ventilation- and fuel bed controlled.

Ventilation- and fuel bed controlled fire processes or combined ventilation- and fuel bed controlled fire process exist for the porosity factor $\phi \geq \phi_c = 0.5$ cm$^{1.1}$ and the stick thickness $b \leq b_c = 30$ mm, with a precision which is satisfactory for practical use. For porosity factors and stick thickness outside these variation ranges, the fire process besides being influenced by the air flow factor, $A\sqrt{H}$, and the total heat content of the fuel is also influenced by the specific properties of the wood crib and, thereby, the fire process can be denoted as crib controlled - cf Thomas-Nilsson (1973).

In Section 8.5 of Publication /2/ a brief basis is given for determining the time curve of a complete fire process, for the energy released per unit time, I_C, using fire load of regular wood cribs, with a precision which is satisfactory for ordinary practical cases. The determination can be carried out with a rather far-reached differentiation with respect to the opening factor of the fire cell, $A\sqrt{H}/A_t$, size of the fire load, q, porosity factor, ϕ, and stick thickness, b. The basis embraces the maximum energy released per unit time, I_{Cmax}, plus the time magnitudes t_r, t_d, t_1, t_2 and t_g defined according to FIG 1. With known values for these basic magnitudes, the time curve of the complete fire process, for the energy released per unit time, I_C, can be given with a precision which is acceptable in ordinary cases. With a known energy-time curve, the gas temperature-time curve of the complete fire process can, thereafter, be calculated, with varying properties of the fire cell, using the heat- and mass balance equations of the cell.

For the maximum energy released per unit time, I_{Cmax}, the brief basis gives the following relations

$$\text{(a)}\quad I_{Cmax} = 5.6\ M \sqrt{\frac{\phi}{\phi_{0.5}}}\ \left(\frac{b_{25}}{b}\right) \quad \text{MJ/h} \tag{8}$$

for the fuel bed controlled range of the fire process, that is for $Mb_{25}/A\sqrt{H}\cdot b < 500\ \text{MJ/m}^{5/2}$

$$\text{(b)}\quad I_{Cmax} = \left(1.52\ M\ \frac{b_{25}}{b} + 2040\ A\sqrt{H}\right) \sqrt{\frac{\phi}{\phi_{0.5}}} \quad \text{MJ/h} \tag{9}$$

for the transition range between fuel bed- and ventilation controlled fire processes, that is for $500 \leq Mb_{25}/A\sqrt{H}\cdot b \leq 1000\ \text{MJ/m}^{5/2}$

$$\text{(c)}\quad I_{Cmax} = 3560\ A\sqrt{H} \sqrt{\frac{\phi}{\phi_{0.5}}} \quad \text{MJ/h} \tag{10}$$

for the ventilation controlled range of the fire process, that is for $Mb_{25}/A\sqrt{H}\cdot b > 1000\ \text{MJ/m}^{5/2}$.

In the above relations $\phi_{0.5}$ denotes the porosity factor 0.5 $\text{cm}^{1.1}$ and b_{25} the stick thickness 25 mm. The following side conditions are true for application of the relations. If the opening factor $A\sqrt{H}/A_t < 0.04\ \text{m}^{1/2}$, the real porosity factor, ϕ, is replaced by $\phi_{0.5} = 0.5\ \text{cm}^{1.1}$, all through. If the opening factor, $A\sqrt{H}/A_t > 0.07\ \text{m}^{1/2}$, ϕ assumes the real value within the range $\phi \leq 0.5\ \text{cm}^{1.1}$ while the real ϕ is substituted by $\phi_{0.5} = 0.5\ \text{cm}^{1.1}$ for $\phi > 0.5\ \text{cm}^{1.1}$. Within the range $0.040 \leq$ $\leq A\sqrt{H}/A_t \leq 0.070\ \text{m}^{1/2}$, ϕ is determined by linear interpolation, that is from the Equation

$$\phi = \frac{1}{3}\,(7\phi_{0.5} - 4\phi_v) - \frac{A\sqrt{H}/A_t}{0.03}\,(\phi_{0.5} - \phi_v) \qquad (11)$$

where ϕ_v is the real value of the porosity factor. The equation is true for $\phi_v \leq 0.5$ cm$^{1.1}$. For $\phi_v > 0.5$ cm$^{1.1}$, ϕ is replaced by 0.5 cm$^{1.1}$. As for the stick thickness, b, real value is used if $b \geq b_{25} = 25$ mm, while b is replaced by 25 mm for real b < 25 mm. The application of the relations is experimentally verified only up to $b \approx 50$ mm.

Assuming $\phi/\phi_{0.5} = 1$ and $b/b_{25} = 1$, the simplified I_{Cmax}-expressions according to Equations (5)-(7) are obtained which together describe fire processes that are fuel bed or ventilation controlled in the rigorous sense or combined fuel bed- and ventilation controlled.

For the time magnitudes t_r, t_d, t_1 and t_2, the brief basis gives the expressions:

$$t_r = \frac{0.7\; q\; A_t}{I_{Cmax}} \qquad (12)$$

$$\frac{t_d}{t_r} = 0.55\;[1 + 11(A\sqrt{H}/A_t - 0.08)(\phi - 0.4)] \qquad (13)$$

at which, for $A\sqrt{H}/A_t > 0.12$ m$^{1/2}$, the t_d-value corresponding to $A\sqrt{H}/A_t = 0.12$ is chosen

$$t_2 \approx t_r \qquad (14)$$

$$t_1 \approx 0.3\; t_2 \qquad (15)$$

The time magnitude t_g can finally be determined from the energy condition

$$\int_0^{t_g} I_C\, dt = M \qquad (16)$$

where t is the time in hours and M the total heat energy of the fuel in MJ.

In report /2/, a translation of the results from a fire process with fire load of regular wood cribs to a fire process with practically representative fire load is even discussed. The exemplary analysis carried out, illustrates how differentiated results obtained by model fire studies can be transformed to a description of realistic fire processes with practically representative fire load in the form of furniture, textile goods and other equipments in fires arising in flats, after some calibrating full scale tests. The translation parameters are composed of equivalent porosity factor, ϕ_e, and equivalent stick thickness, b_e, or equivalent parameters. Systematically performed calibrating tests in full scale with realistic fire load for common fire cells such as offices, schools, hospitals, stores etc. have a high degree of priority.

Size of the fire load, q, the porosity factor, ϕ, introduced by Gross (1962) and the stick thickness, b, have been used in the publications of this paper to characterize a fire load in the form of a regular wood crib. A disadvantage with this choice of parameters is, that the stick thickness, b, is included as an essential magnitude in the porosity factor, ϕ, at the same time that it is a parameter of its own. It is therefore necessary to develop more independent and functionally more well-defined magnitudes for a description of the fire load. A practicable solution seems to be a description focused on the parameters:

the free horizontal surface for vertical air flow through the pile, A_v,

the surface initially exposed to air, A_s, or alternatively the hydraulic radius, r,

wood crib volume in relation to the volume of the fire cell plus

thickness of the individual stick, b,

all the parameters, if possible, arranged in relation to some specific pile in order to achieve a dimensionless form. In a future report, which is intended to give a more complete description of the results of all the model tests performed, the possibilities for such a modified wood crib characterization will also be investigated more closely.

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