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Modelling of Furniture Experiments with Zone Models

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The Harvard Computer Fire Code Mark V has been used to simulate full-scale furniture fires. Simulations were run with one sofa burning in the open and another burning in a small room. To obtain better agreement between experiment and simulation, changes were made in the code to include heating of the lower surfaces in the room. A simulation of a mattress test, conducted at NBS, is included. Comparison with a zone model using a different plume equation is also presented.

INTRODUCTION

Fire growth was studied in a joint project between Lund Institute of Technology and the Swedish National Testing Institute. The ultimate aim was to develop test methods for surface lining materials and furniture from which the behaviour of the material or product in a natural fire scenario can be predicted.[1] Reliable mathematical models are necessary tools when predicting fire behaviour from tests.

In 1982 a series of twelve full-scale furniture experiments was conducted.[2] These experiments were well instrumented, including, for example, rate of heat release measurements. A mock-up sofa, consisting of a standard PU foam and an acrylic fabric, was chosen as the prime object to be simulated in the work here reported because it was the only item that burned with an intensity level high enough to obtain significant feedback effects from the room to the specimen.

The intention was to use only the Harvard Mark V model for the simulation.[3,4] This programme can simulate fires in a single room with several venting openings. Fire objects are allowed in the room with the possibility of one object igniting another. One advantage with the Harvard programme is that it is written in FORTRAN without using machine-dependent code.

The fires used at Harvard for testing the programme have been mainly the full-scale bedroom fires conducted at the Factory Mutual Research Corporation in 1973–5.[5–7] Rockett has used the programme to simulate the tests on mattresses made by Babrauskas.[8,9] During the course of this work it was of interest to make some comparative runs with Rockett's simulations, again choosing a fire which reached a high rate of heat release.

SOFA EXPERIMENTS

The series of full-scale experiments reported in reference 2 were conducted in a well-instrumented room with internal dimensions of $2.4 \times 3.6\,m^2$ and a height of 2.4 m. It had one opening, $0.8 \times 2.0\,m^2$, and the walls were made of lightweight concrete, 0.15 m thick.

The test compartment was instrumented for measurement of gas temperatures, mass burning rate, rate of heat release, heat fluxes, smoke production and analysis of the combustion products. The gas temperatures were measured with thermocouples of chromel–alumel with a diameter of 0.25 mm. The rate of heat release was determined by measuring oxygen consumption with an accuracy to within 10%. A full description of the instrumentation and of the measuring techniques is given in reference 2.

Of the twelve full-scale experiments, ten were performed inside the test compartment and two outside the room under the hood, which was constructed to collect all smoke and combustion products. The latter experiments were intended to give information about the feedback from the room.

The experiments selected for comparison are designated test 5 and test 12 in reference 2. The sofa was a full-size mock-up model with three seats, constructed of a metal frame with loose cushions as upholstery. The seat cushion was $0.65 \times 1.8 \times 0.12\,m^3$ and the back cushion $0.42 \times 1.8 \times 0.12\,m^3$. The seat was 0.3 m from the floor at the front and 0.24 m at the back. The filling material was a commonly available standard polyurethane foam with a density of $30\,kg\,m^{-3}$ and the cover material was a textile of 100% acrylic fibres with a surface weight of $300\,g\,m^{-2}$.

The two reference tests were performed with two identical mock-up sofas. Test 5 was performed inside the room and test 12 outside. These two experiments where chosen as reference examples, as they release a suitable amount of energy for simulation with the Harvard Code. The series of full-scale experiments also contain two tests with two chairs. The distance between the chairs was varied in order to give some indication of when one burning chair was able to ignite a second chair. These experiments might also be used to study the ability of the Harvard Code to simulate ignition of a secondary object.

Simulation of the sofa burning in the open

The growing-fire routine in the Harvard programme describes a fire which is growing as a function of time. The pyrolysis rate and the growth rate are controlled by the heat flux reaching the surface. The fire has a rather abrupt end, which can lead to large-differences between

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Table 1. Input data for the sofa in room simulation. (Programme default values in parentheses)

Sofa	X-co-ordinate	1.2 m	
(not burning)	Y-co-ordinate	2.4 m	
	Height (floor-burning surface)	0.4 m	
	Angle with horizontal		(0)
	Angle with XZ-plane		(0)
	Thickness		(0.1 m)
	Density	34 kg m^{-3}	(48 kg m^{-3})
	Initial mass	7 kg	(6.852 kg m^{-3})
	Initial radius	0.024 m	(0.037 m)
	Object radius	0.69 m	(0.8598 m)
	Maximum burning radius	0.69 m	(0.9677 m)
	Specific heat		(1900 J kg^{-1}K^{-1})
	Thermal conductivity		(0.054 W m^{-1}K^{-1})
	Emissivity		(0.98)
	Fraction of heat released	0.9	(0.65)
	Heat of combustion		(28.7 MJ kg^{-1})
	Heat of vapourization		(2.05 MJ kg^{-1})
	Ignition temperature		(727 K)
	Air/fuel mass ratio		(14.45)
	Stochiometric mass ratio		(9.85)
	Smoke mass/fuel mass		(0.241)
	Fire-spread parameter	0.022	(0.011)
Heptane burner	X-co-ordinate	1.2 m	
(pool fire)	Y-co-ordinate	3.09 m	
	Height	0.3 m	
	Density	600 kg m^{-3}	
	Initial mass	0.0684 kg	
	Object radius	0.1 m	
	Maximum radius	0.1 m	
	Specific heat		(1900 J kg^{-1}K^{-1})
	Thermal conductivity		(0.054 W m^{-1}K^{-1})
	Emissivity		(0.98)
	Fraction of heat released	1.0	
	Heat of combustion	44.7 MJ kg^{-1}	
	Heat of vapourization	33 kJ kg^{-1}	
	Ignition temperature		(740 K)
	Air/fuel mass ratio		(14.45)
	Stochiometric mass ratio		(9.85)
	Smoke mass/fuel mass		(0.241)
Room	Length along x	2.4 m	
	Length along y	3.6 m	
	Height	2.4 m	
Wall	Thickness	0.04 m	(0.0254 m)
	Density	500 kg m^{-3}	(800 kg m^{-3})
	Specific heat	1000 J kgK^{-1}	(1062 J kg^{-1}K^{-1})
	Thermal conductivity	0.15 W mK^{-1}	(0.134 W m^{-1}K^{-1})
Door-opening	Width	0.8 m	
	Height	2.0 m	
	Transom depth	0.4 m	
Constants	Ambient temperature		(300 K)
	Specific heat of air		(1004 J kg^{-1}K^{-1})
	Absorption coefficient of flame		(1.55 m^{-1})
	Plume-entrainment coefficient		(0.1)
	Maximum heat-transfer coefficient (layer–wall)		(50 W m^{-2}K^{-1})
	Minimum heat-transfer coefficient (layer–wall)		(5 W m^{-2}K^{-1})
	Discharge coefficient		(0.68)

experiments and simulations after maximum intensity has been reached. In the simulations here reported no attempt was made to study the behaviour of the model after the maximum temperature was reached.

As a first step in the sofa-fire simulation the code was run a number of times to find input data that simulate the burning behaviour of the sofa and the heptane burner in a room large enough to avoid any feedback effects from the enclosure. The heptane burner was modelled with the pool-fire routine. For the simulation of the sofa with the growing-fire routine four input data—the initial burning radius, the maximum burning radius, the fire-spread parameter and the fraction of heat released—can be varied to produce the desired fire-behaviour. The

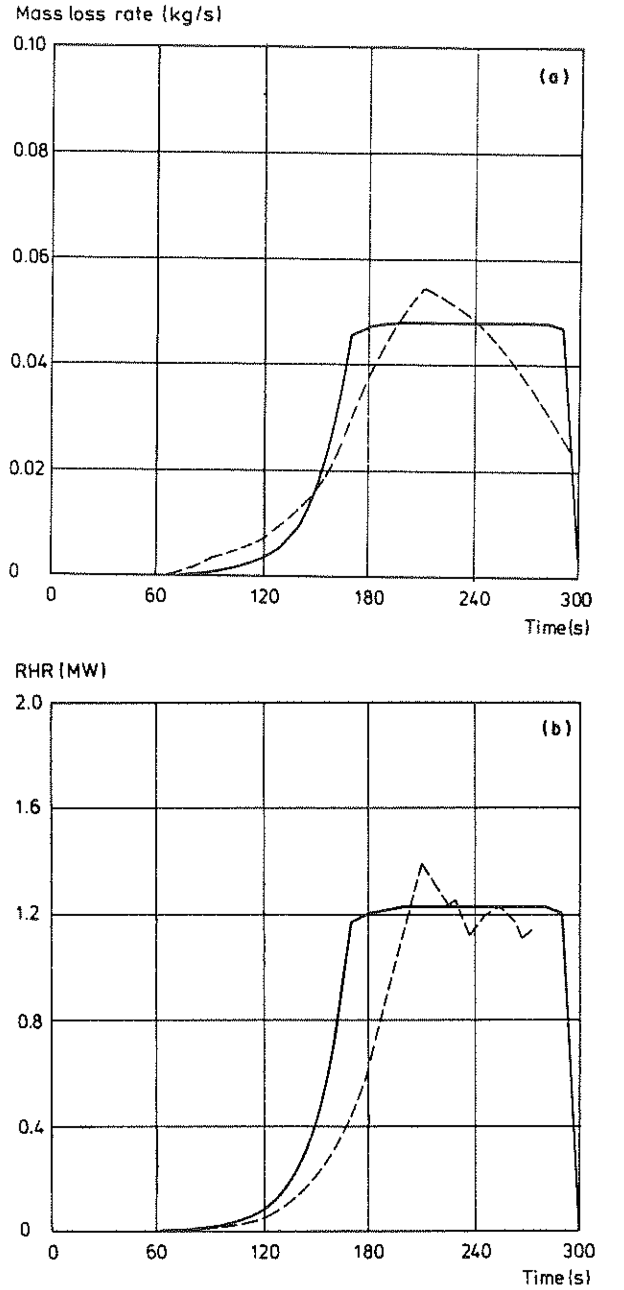


Figure 1. (a) Mass loss rate and (b) rate of heat release (RHR) for the sofa burning in the open. ——— Harvard simulation; ---- experiment.

best simulation of the mass loss rate and heat release during the experiment under the hood was achieved with the input data in Table 1 (objects 1 and 2). In this table all default values are given in parentheses. Compared with the default input for a burning polyurethane slab, this fire starts smaller but grows much faster, and has a higher combustion efficiency. This is not surprising, since the sofa was covered with an acrylic fabric, which causes a rapid flame-spread and has a higher heat of combustion than polyurethane.

The results of the simulation and experimental results are shown in Fig. 1(a) and (b). The two mass loss-rate curves are quite close. There is a time difference between the two rate of heat release curves, and this can be explained partly by the transportation time of the exhaust gases into the oxygen meter.

Simulation of the sofa burning in the room

The next step in the attempts to simulate the sofa experiments was to run the Harvard programme with the room geometry used in the experiment and data for the sofa and burner described in the previous section. The complete set of input data for this run is given in Table 1. The walls and floor are described as being only 0.04 m thick because the temperature calculations for a wall in TMPW01 and for an object in TEMPO02 are less accurate when the thickness given is large compared with the depth penetrated by the thermal wave. The results from this simulation are presented in Fig. 2(a)–(c) together with experimental data. The agreement between the experiment and the simulation is fairly good, but the gradient of the upper-layer temperature and mass loss-rate tend to decrease more quickly in the simulation. Oxygen-starvation occurs at 222 s in the simulation. This is in agreement with the visual observations of limited flaming outside the opening during the most intense phase of the experiment.

When simulating bed fires Rockett obtained temperatures much lower than in the experiment for a fast-burning twin-size bed. In the simulation the fire was limited by oxygen-starvation, and after that the layer temperature increased quite slowly. This is the same behaviour as in the sofa simulation, but is much more marked because of the larger burning item.

To improve his calculations Rockett included the mixing effect[10] at the door-opening, and with this change his results moved somewhat closer to those of the experiments. Another possible change that would lead to higher temperatures is to allow the floor and lower part of the walls to heat up. In Harvard Mark V the lower surfaces and gas layer remain at ambient temperature, which causes too high a radiation loss from the upper parts and thus limits the upper-layer temperature. The sofa experiment in the room was equipped with thermocouples, giving an approximate measurement of the surface temperature of the floor. A maximum higher than 400 °C was recorded in the experiment (Fig. 2(d)). This high temperature indicated that in this case the heating of the lower surfaces should not be neglected.

CHANGES IN THE CODE TO INCLUDE HEATING OF THE LOWER SURFACES

To give a full description of the heating of the lower surfaces, both the lower wall- and lower gas-layer temperature would have to be changed into variables. A simplified way of including the heating effect is to use an extra object in floor position and use the calculated surface temperature in the sub-routines that deal with the radiation from the upper parts to the floor. This was achieved by the following changes in the programme:

(1) A new common *TLOW*, *IFNR*, where *TLOW* is the lower surface temperature and *IFNR* is the object number of the 'floor' object.

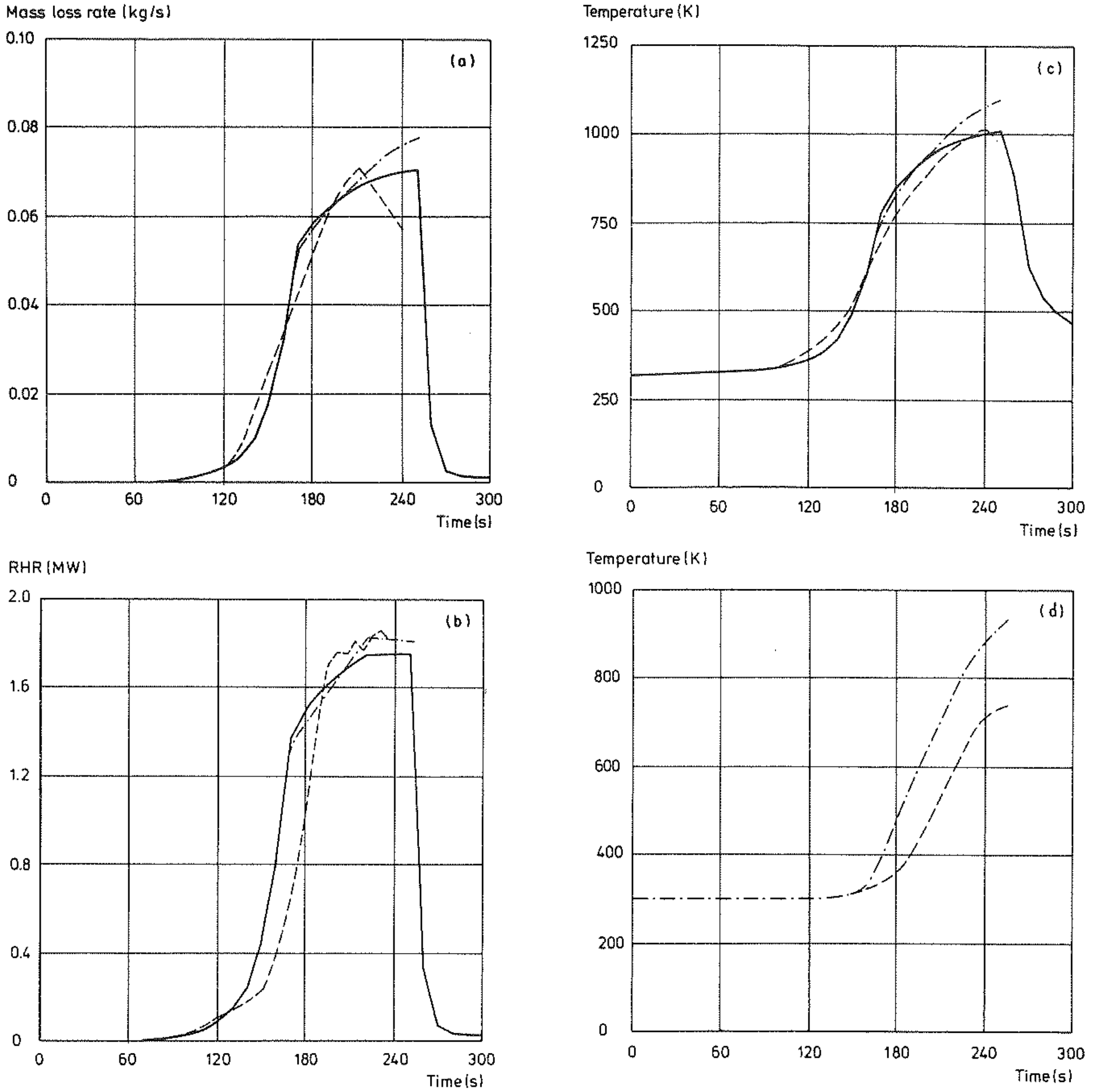


Figure 2. (a) Mass loss rate, (b) rate of heat release (RHR), (c) upper gas-layer temperature and (d) surface temperature of the floor for the sofa burning in the room. ——— Harvard simulation; –·–·– Harvard simulation including heating of the lower surfaces; – – – experiment.

(2) A change in *INPUT3* to allow the input of *IFNR*.
(3) In *TMPOOZ* (which calculates the temperature of the objects) a statement was added so that
TLOW = *ZKOZZ1 (KO)* when *KO* = *IFNR*
where *ZKOZZ1* is the surface temperature of object *KO*.
(4) In *RDNL* (which calculates the net power gain of the layer via radiation) *ZKAZZ* (ambient temperature) was replaced by *TLOW*.
(5) In *RNWO02* (which calculates the net radiative flux to an object from the ceiling and upper part of the walls) *ZKAZZ* was replaced by *TLOW*.

As a result of these changes the radiative exchange between the upper parts and the floor becomes correct if the position of the 'floor' object is chosen in such a way that $(TLOW)^4$ is a good approximation of the average of the fourth power of the lower surface-temperature distribution. When running the modified code no attempt was made to study the effect of varying the object's position.

The convective heat loss from the lower surfaces is neglected. Hence, the lower gas layer stays at ambient temperature. The effect of this simplification was checked with the FOVER code,[11] which is discussed below, and proved to be insignificant.

The programme with the modifications described was run with the input data for the sofa and burner. For the 'floor' object the thermal data of the wall were used and it was positioned approximately 0.5 m from one of the inner corners. The result is shown in Fig. 2. The mass loss-rate and upper gas-layer temperature is now closer to the experiment. Oxygen-starvation occurs at time 203 s.

SIMULATION OF NBS MATTRESS TEST (M01)

Very high temperatures were recorded in some of the NBS mattress tests. In the experiment designated as M01 in reference 8 a twin-size polyurethane mattress and bedding was burned in a room approximately 3.4 × 3.5 m with a 0.9 m wide door-opening. The measured temperature close to the ceiling and the result of the simulations by Rockett are shown in Fig. 3(a). The improved simulation included door-mixing and a less abrupt burn-out of the fuel than in the standard growing fire.[9]

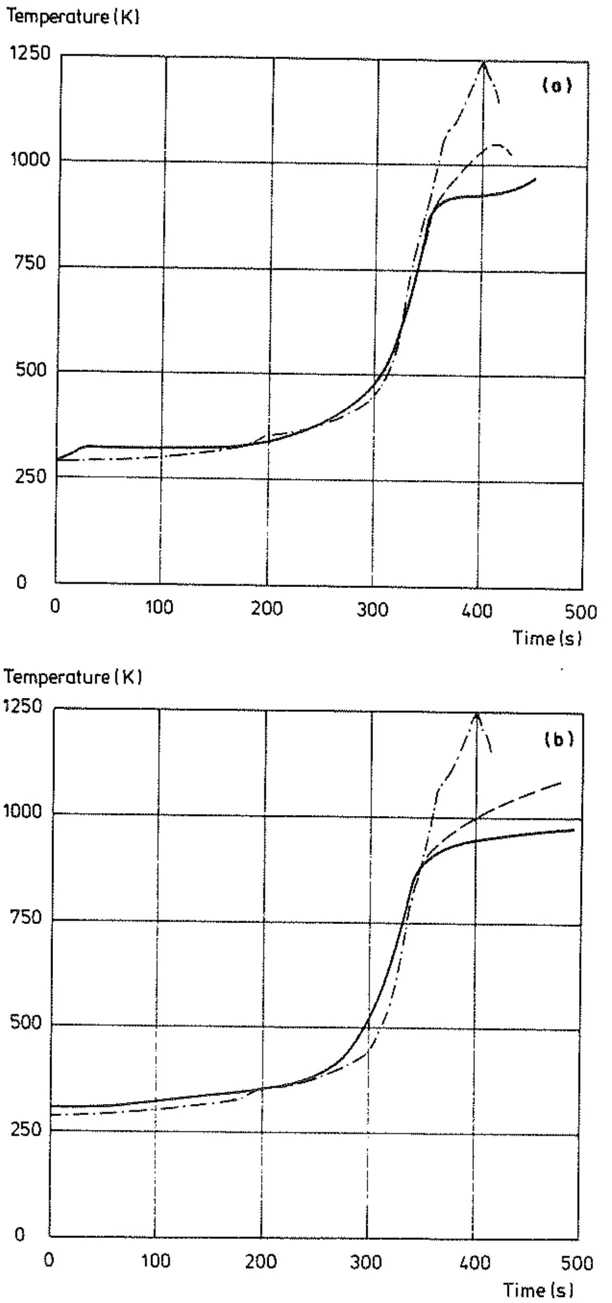


Figure 3. Upper gas-layer temperatures for the NBS mattress test (M01). (a) ——— Rockett simulation; —— Rockett simulation with mixing; –·–·– experiment. (b) ——— Harvard simulation; ––– Harvard simulation with heating of the lower surfaces; –·–·– experiment.

The importance of the heating of the lower surfaces was checked by running both the original Mark V programme and the modified one. As far as possible input data were chosen from the report by Rockett. The results of the simulations are given in Fig. 3(b). It can be seen that the heating of the lower surfaces causes an increase in upper-layer temperature greater than that calculated for the mixing effect. The temperature curve calculated with the original code is very close to Rockett's corresponding calculation. The temperature with heating is still well below the experimental observation, but the shape of the curve with a marked gradient also during the period of oxygen-starvation is similar to the experimental result. It seems plausible that a combination of mixing and heating of the lower surfaces could produce a temperature–time curve quite close to the measured one.

COMPARISON WITH FOVER SIMULATIONS

FOVER is a zone model developed by Hägglund.[11] This includes both the heating of the lower surfaces and the mixing at openings. The fire mass loss-rate and fire area as a function of time are needed as input data. There is no coupling between the fire and the fire room. The far-field plume equation suggested by Cetegen *et al.*[12] is used. In this work, FOVER was introduced as a tool for checking the changes made in the Harvard code.

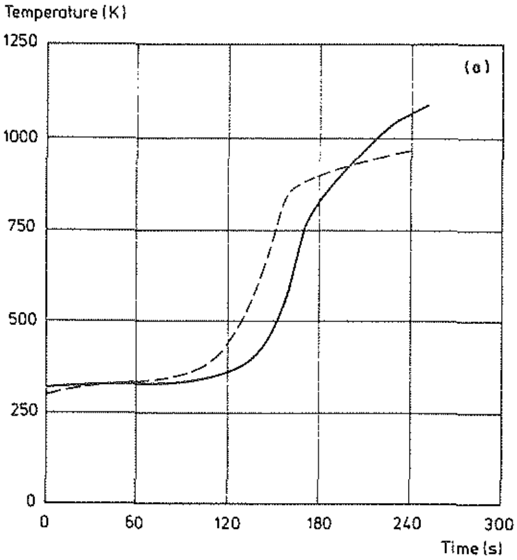
The FOVER programme was run with a mass loss-rate input corresponding to the calculation result of the Harvard simulation of the sofa fire including heating of the lower surfaces. The first FOVER run with no mixing resulted in an upper-layer temperature (Fig. 4(a)) approximately 150 K below the Harvard calculation. The explanation for this was that the calculated air flow was too low, resulting in an energy release limited to a large extent by the entrained air into the plume. To observe the effect of a higher entrainment rate, FOVER was run with the entrainment increased a factor of four, which gave the results in Fig. 4(b) and (c). These were in much better agreement with the Harvard simulation. The relation between the temperatures in the upper layer, ceiling and floor is about the same as in the corresponding Harvard code calculation. The conclusions drawn from this were that the attempt to include heating of the lower surfaces in the Harvard code seemed to produce realistic results and that the choice of plume equation needed some attention. The FOVER code was also run with mixing and with varied convective loss from the lower surfaces. For this single fire the effect on the upper layer temperature was < 10 K.

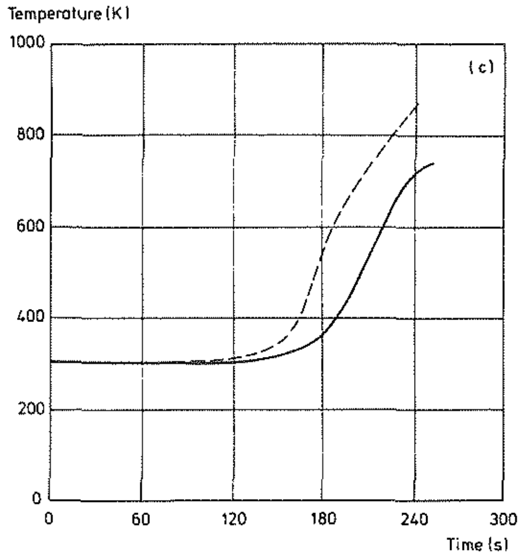
PLUME EQUATIONS

In the Harvard code the plume is described as a cone with a virtual point source. The form of the equation is

$$\dot{m}_{\mathrm{pH}} \sim \dot{Q}^{1/3}[(Z+Z_0)^{5/3} - Z_0^{5/3}]$$

where $\dot{Q}$ = heat release
Z = plume height
Z_0 = plume height offset.





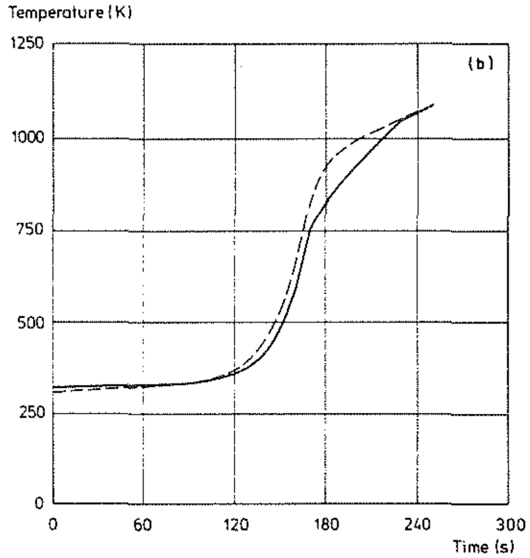


Figure 4. (a) and (b) Upper gas-layer temperatures for the sofa burning in the room. (a) ——— Harvard simulation; ---- FOVER simulation with an entrainment coefficient $\alpha = 0.25$. (b) ——— Harvard simulation; ---- FOVER simulation with an entrainment coefficient $\alpha = 1.0$. (c) Surface temperature of the floor for the sofa burning in the room. ——— Harvard simulation with heating of the lower surfaces; ---- FOVER simulation with an entrainment coefficient $\alpha = 1.0$.

The plume origin offset is proportional to the fire radius. With the default entrainment coefficient the offset is approximately eight times the fire radius. For fires with a large area and low plume height this model gives a very high entrainment rate.

Cetegen *et al.*[12] have given full discriptions of the entrainment based on extensive experimental work and theoretical analysis, and divide the problem into three areas—initial region, turbulent flame and far field. For a large fire and low plume height only the initial region and far-field solutions are of interest. The equations are of the form

$$\dot{m}_{pi} \sim DZ^{3/4} \qquad \text{(initial region)}$$
$$\dot{m}_{pf} \sim \dot{Q}^{1/3}(Z + Z_0)^{5/3} \qquad \text{(far field)}$$

where D = fire diameter.

The calculated plume origin offset in this model is small compared with the offset in the Harvard plume. The effective origin may also be above the surface of the burning material.

Figure 5 shows the difference between the plume models as well as the Harvard equations with varying fire radius and the Cetegen equations for a 0.7-m radius and a heat release of 1.7 MW. At maximum intensity of the sofa experiment, simulation the fire was of this size and the plume height was approximately 0.5 m. The entrainment in the Harvard code is almost three times the entrainment according to Cetegen, and it is much more sensitive to changes in plume height. Quintiere *et*

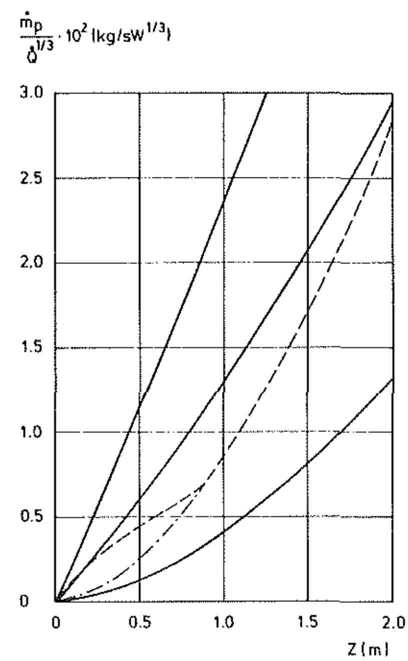


Figure 5. Plume models. ——— Harvard equations with varying fire radius (r_f): $r_f = 0.7$ m (upper), $r_f = 0.25$ m (middle), $r_f = 0.0$ m (lower); ---- Cetegen equations: $r_f = 0.7$ m, $Q_f = 1.7$ MW; –·–·– Cetegen equations: far-field solution for small plume heights, $r_f = 0.7$ m, $Q_f = 1.7$ MW. This is used in FOVER.

al.[13] have studied the effect of room-openings on the entrainment, obtaining a two- to three-fold increase over the undisturbed values. The difference between the two plume models in the range studied for the sofa fire is of the same order. This means that the Cetegen model, corrected for disturbances because of the opening and the Harvard plume model in this particular case, gives a good approximation of the entrainment. When modelling fires such as the sofa fire the height of the fire is difficult to determine. The upper limit is the top of the back at 0.75 m and the lower limit is zero since some material burns on the floor. The difference in rate of heat release between the calculations at the height of 0.4 m, which was the first choice, and the height of 0.3 m was approximately 5%.

CONCLUSIONS

Such a small number of simulations as are described in this paper cannot give very much information on the predictive capability of a computer programme. A sensitivity study of the programme and comparisons with a wide range of experiments is necessary to obtain a good understanding of its limitations. The Harvard code is relatively complex and the list of input variables is long. A compressive sensitivity study of this code would be a very time-consuming task.

With the limitations of this study in mind, certain conclusions can be drawn concerning the Harvard Mark V code. The most promising result obtained is that, with a description of an open fire, the modified programme with heating of the lower surfaces simulates the fire behaviour of the same item in a room with reasonable precision. The big difference between a simulation without the heating effect included and experimental results indicates that the heating of the lower surfaces should not be neglected. The quality of the simulation could be further improved by also including the mixing effect at the openings. If the fire course of an item burning in the open is known, the programme can be used to simulate how it would burn in different room environments. This possibility is useful when evaluating the fire risk of, for example, furniture in room environments, but it is, of course, limited to room sizes for which the basic assumptions of the zone modelling technique are valid.

Another way of observing the importance of a good description of the free-burning fire is to compare the rate of heat release in the open and in the room. During the first 165 s there is a very small difference between the simulations. At this time the calculated heat release is 1.2 MW. Up to this point the fire growth in the simulation is controlled only by the fire itself. For this particular room there is no need to use a fire routine with feedback for a fire that does not reach heat-release levels above 1.0 MW when burned in the open.

The FOVER simulations revealed the effect of using different plume models. One interesting experiment would be to incorporate Cetegen's plume formula into both the Harvard code and the FOVER programme. FOVER will probably soon be available, with this plume model as an alternative.[14]

This study has indicated that the zone models are useful as predictive tools. An improved Harvard version should probably include heating of the lower surfaces, mixing at the openings and the Cetegen plume formula. There is also a great need for an extensive sensitivity study of the code so that the importance of different input variables can be described in some detail.

Acknowledgement

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