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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. Reliable mathematical models are necessary tools when predicting fire behaviour from tests.

In 1982 a series of twelve full-scale furniture experiments was conducted. 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 one object igniting another. One advantage with the Harvard programme is that it is written in FORTRAN without using machine-dependent code.

The Harvard Computer Fire Code Mark V model for the simulation. 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 Harvard programme is used to simulate ignition of a secondary object. Changes were made in the code to include heating of the lower surfaces in the room.

SOFA EXPERIMENTS
The series of full-scale experiments reported in reference 2 are conducted in a well-instrumented room with internal dimensions of 2.4 x 3.6 m² and a height of 2.4 m. It had one opening, 0.8 x 2.0 m², 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 sofa, constructed of metal frame with loose cushions as upholstery. The seat cushion was 0.65 x 1.8 x 0.12 m³ and the back cushion 0.42 x 1.8 x 0.12 m³. 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 were 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)

<table>
<thead>
<tr>
<th>Sofa (not burning)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X-co-ordinate</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Y-co-ordinate</td>
<td>2.4 m</td>
</tr>
<tr>
<td>Height (floor-burning surface)</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Angle with horizontal</td>
<td>(0)</td>
</tr>
<tr>
<td>Angle with XZ-plane</td>
<td>(0)</td>
</tr>
<tr>
<td>Thickness</td>
<td>(0.1 m)</td>
</tr>
<tr>
<td>Density</td>
<td>34 kg m⁻³</td>
</tr>
<tr>
<td>Initial mass</td>
<td>7 kg</td>
</tr>
<tr>
<td>Initial radius</td>
<td>0.024 m</td>
</tr>
<tr>
<td>Object radius</td>
<td>0.69 m</td>
</tr>
<tr>
<td>Maximum burning radius</td>
<td>0.69 m</td>
</tr>
<tr>
<td>Specific heat</td>
<td>(1900 J kg⁻¹ K⁻¹)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>(0.054 W m⁻¹ K⁻¹)</td>
</tr>
<tr>
<td>Emissivity</td>
<td>(0.98)</td>
</tr>
<tr>
<td>Fraction of heat released</td>
<td>0.9</td>
</tr>
<tr>
<td>Heat of combustion</td>
<td>(28.7 MJ kg⁻¹)</td>
</tr>
<tr>
<td>Heat of vaporization</td>
<td>(2.05 MJ kg⁻¹)</td>
</tr>
<tr>
<td>Ignition temperature</td>
<td>(727 K)</td>
</tr>
<tr>
<td>Air/fuel mass ratio</td>
<td>(14.45)</td>
</tr>
<tr>
<td>Stoichiometric mass ratio</td>
<td>(9.85)</td>
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<tr>
<td>Smoke mass/fuel mass</td>
<td>(0.241)</td>
</tr>
<tr>
<td>Fire-spread parameter</td>
<td>0.022</td>
</tr>
<tr>
<td></td>
<td>(0.011)</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Heptane burner (pool fire)</th>
<th></th>
</tr>
</thead>
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<tr>
<td>X-co-ordinate</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Y-co-ordinate</td>
<td>3.09 m</td>
</tr>
<tr>
<td>Height</td>
<td>0.3 m</td>
</tr>
<tr>
<td>Initial mass</td>
<td>600 kg m⁻³</td>
</tr>
<tr>
<td>Object radius</td>
<td>0.0684 kg</td>
</tr>
<tr>
<td>Maximum radius</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Specific heat</td>
<td>(1900 J kg⁻¹ K⁻¹)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>(0.054 W m⁻¹ K⁻¹)</td>
</tr>
<tr>
<td>Emissivity</td>
<td>(0.98)</td>
</tr>
<tr>
<td>Fraction of heat released</td>
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<tr>
<td>Heat of combustion</td>
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<td>Heat of vaporization</td>
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<td>Ignition temperature</td>
<td>(740 K)</td>
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<tr>
<td>Air/fuel mass ratio</td>
<td>(14.45)</td>
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<tr>
<td>Stoichiometric mass ratio</td>
<td>(9.85)</td>
</tr>
<tr>
<td>Smoke mass/fuel mass</td>
<td>(0.241)</td>
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</table>

<table>
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<tr>
<th>Room</th>
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<tbody>
<tr>
<td>Length along x</td>
<td>2.4 m</td>
</tr>
<tr>
<td>Length along y</td>
<td>3.6 m</td>
</tr>
<tr>
<td>Height</td>
<td>2.4 m</td>
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<tr>
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<td>0.04 m</td>
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<tr>
<td>Density</td>
<td>500 kg m⁻³</td>
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<tr>
<td>Specific heat</td>
<td>(1002 J kg⁻¹ K⁻¹)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>(0.134 W m⁻¹ K⁻¹)</td>
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</tbody>
</table>

<table>
<thead>
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<td>Width</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Height</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Transom depth</td>
<td>0.4 m</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Constants</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature</td>
<td>(300 K)</td>
</tr>
<tr>
<td>Specific heat of air</td>
<td>(1004.1 J kg⁻¹ K⁻¹)</td>
</tr>
<tr>
<td>Absorption coefficient of flame</td>
<td>(1.65 m⁻¹)</td>
</tr>
<tr>
<td>Plume-entrainment coefficient (layer–wall)</td>
<td>(0.1)</td>
</tr>
<tr>
<td>Maximum heat-transfer coefficient (layer–wall)</td>
<td>(50 W m⁻² K⁻¹)</td>
</tr>
<tr>
<td>Minimum heat-transfer coefficient (layer–wall)</td>
<td>(5 W m⁻² K⁻¹)</td>
</tr>
<tr>
<td>Discharge coefficient</td>
<td>(0.68)</td>
</tr>
</tbody>
</table>

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
MODELLING OF FURNITURE EXPERIMENTS WITH ZONE MODELS

Moss

Time

RHRIMWI

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

The 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 TEMP001 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 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.
A change in INPUT3 to allow the input of IFNR.

(3) In TMPO02Z (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 RNWO02Z (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,\(^\text{11}\) 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

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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.
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 x 3.5 m
with a 0.9 m wide door-opening. The measured tempera-
ture close to the ceiling and the result of the simulations
by Rockett are shown in Fig. 3(a). The improved simula-
tion included door-mixing and a less abrupt burn-out of
the fuel than in the standard growing fire.9

The importance of the heating of the lower surfaces
was checked by running both the original Mark V pro-
gramme 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 corres-
ponding 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 tempera-
ture–time curve quite close to the measured one.

COMPARISON WITH FOVER SIMULATIONS

FOVER is a zone model developed by Hågglund.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

\[ n_{\text{pl}} \sim \dot{Q}^{1/3} (Z + Z_0)^{5/3} - Z_0^{1/3} \]

where \( \dot{Q} \) = heat release
\( Z \) = plume height
\( Z_0 \) = plume height offset.
I.

BLOMQVIST AND B. ANDERSSON

Temperature [K]

0 60 120 180 240 300

Time [s]

0 60 120 180 240 300

Time [s]

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. have given full discrptions 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

\[ \dot{m}_p \sim DZ^{1/4} \] (initial region)

\[ \dot{m}_p \sim Q^{1/3}(Z + Z_0)^{5/3} \] (far field)

where \( D \) = fire diameter.

The calculated plume origin offset in this model is small compared with the offset in the Harvard model. 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
The big difference between a simulation without the heat- 
ing effect included and experimental results indicates that conclusions can be drawn concerning the Harvard Mark V compressive sensitivity study of this code would be a very code. The most promising result obtained is that, 
dictive capability of a computer programme. Such a study of the programme and comparisons with a wide time-consuming task. 
entrainment, obtaining a 
small number of simulations as are described in this paper cannot give very much information on the pre-
desired precision. The big difference between a simulation without the heat-
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 165s 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. 
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 
We express our thanks to Bengt Hägglund, FOA, for his simulations of the test fires with the FOVER programme. 

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