Fire Simulation in Nuclear Power Plants with the Code MRFC

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ABSTRACT

The code MRFC (Multi Room Fire Code) has been developed since 1984. Its applicability has been proved by comparison with a number of full scale tests performed in a nuclear research reactor with the HDR Safety Program. During the whole test program calculations were made with different fire codes as to check their applicability. Four of those codes use zone modeling as a physical basis (MRFC, DOB, CCFM, FAST). The other codes used field models and system models. The system code were especially developed in reactor industry as to simulate thermodynamically processes in containment e.g. hydrogen distributions. At the beginning of the research program a wide range of computer results was obtained with partly large differences compared to the experimental data. After specific improvements in the codes the spectrum of calculation results became much smaller and reflected the experimental data at least at several points. The results obtained with zone models were comparable to those of the much more complicated field models and system codes, i.e. the last were not superior as to be expected. It has been learned from the tests, that the temperatures of the fire gases reduce rapidly after fire compartment due to very high entrainments of cold gases into the hot gas layers and by a significant heat transfer to the concrete structure.

The fire model MRFC describes different fire situations according to actual conditions using six different zone models variations for every compartment of the multi room configuration. up to now 10 compartments on different levels with 100 different connections can be handled during one simulation. The pressure rise in a closed compartment can be calculated as well as the composition of gases of every gas layer. Different burning models are included. Some of them are related to prescribed fire types, others are developed according to empirical observations or test results. The formation of gas species and the heat release rate are being calculated with respect to

the actual oxygen supply. The energy terms for convection and radiation between the parts of the compartment (plume, gas layer, ceiling, wall and floor) and to adjacent rooms are being considered by physical models for each term. The heat adsorption of the concrete structure is being calculated using the Fourier equation for structural elements.

The main reasons for the development of MRFC arose from the experience that

- the application of zone models for practical purposes is comparatively cheap compared to field models and system codes
- the existing zone models e.g. FAST, CCFM can not easily be applied to the complex geometry of a nuclear power plant,
- compared to common zone models certain physical features like upward and downward mixing between gas layers must be considered in addition in the physical flow models,
- an adequate calibration of the zone model with respect to the geometry, burning model and ventilation system is necessary and a prerequisite before practical use.

During the HDR experiments in 1988 to 91 the code MRFC was permanently checked and improved using the results of pre- and post-test-calculations and experimental data. The report contains one example of such calculations. Adequate results have been obtained for gas burner and oil fire simulations. It is now intended to develop a burning model for cable fires in a reactor building. A first application for a real nuclear power plant is shown in a second example for fire simulations in the reactor building of a German boiling water reactor.

1. INTRODUCTION

Some computer codes have been developed as multi room fire simulation during the last several years. Most of them are improvements of existing zone codes for single compartments [3] others are new models using the same technique [1,2,5]. The advantage of zone models in comparison to field model is, that a calculation takes less computer and man power for building up the configuration and extracting practical conclusions from the numerous results. The main problem, which these models address, is the question of smoke and hot gas movement in a complex building. Two aspects are of major interest. First it is important to know, how the structure of the building is stressed during the fire. Second is the impact of fire on people, who are inside the building when the fire starts.

The computer code MRFC is under development at University of Kassel since 1984. The first version was a single compartment fire solution, which was extended to a multi room version up to 1987 [6]. The code has been verified by some full scale fire tests, which have been carried out for 7 years. The tests are done in a nuclear power test facility. Up to 5 series with different configurations are finished. The most important fact is, that the experiments are accompanied by simulations with different national and international codes. The tests provided a lot of data, which are useful for every fire modeler to verify the model with real test results.

The code MRFC has reached a stage of development meanwhile, that makes the application for other fire problems possible. It has been used for fire simulations, which are used to improve the German Standards for fire safety in industrial buildings.

The physical basis of the model will be described briefly in this paper. Some results of a comparison between measured and calculated data will be reported further. At last an example is given for a code application with fire simulations for a German boiling water reactor.

2. PHYSICAL BASIS OF THE MODEL MRFC

2.1 Model Assumptions

The basic model assumptions are mostly common to other zone models as BRI [1], CFC [3], FAST [2], CCFM [5], DOB [10] or COMPBRN [4]. The first five of them are more known in the area of conventional fire science while COMPBRN is more known in the area of nuclear fire protection. There is no basic reason for the preferred use of COMPBRN, because the other codes are enhanced considering multi room configurations and improved physical phenomena in the model.

The most obvious improvement in MRFC compared to other zone models are different scenarios for every compartment at every time step during the simulation. Every room of the configuration is described according to different conditions during the fire. The six assumptions for the formation of the up to two gas layers in the room are shown in Figure 1. The code shifts between these model assumptions, if the validation for the actual used model is reached. (E.g. the lower layer vanishes, if the hot layer touches the floor of the compartment, and only one hot layer is considered further.)

Every room of the configuration consists of one homogeneous gas layer at the beginning of the fire (case 1). The initial conditions according temperature, pressure and species concentration are set up. The plume is built up in the fire compartment over the building area (case 2 a). The ceiling jet

Figure 1 Element of Multi-Room fire scenario and different modulation of gas layers.

starts then to spread over the whole area of the compartment (case 2 b). If the ceiling jet covers the whole ceiling the hot layer is built up, which then starts to move downwards to the floor (case 3 a). If warmed and smoky gases flow out of the fire compartment into another room a hot gas layer is built up there, too (case 3 b). Caused by large ventilation area in the ceiling it may happen, that the hot gas layer gets thinner and reaches the ceiling at last. In this case the model according case 2a has to be used to describe the fire in the fire compartment. On the other side the hot gas layer may increase so fast and reach the floor at last. In this case the room is represented by one homogeneous "hot gas" layer (case 4). The volume of the hot gas layer is determined as the volume of the layer itself and the volume of the plume additional for simplification of the model. This is done because growing large plumes as well as small ones should be handled by the model.

Using this model assumptions all mass- and energy-flows between the rooms of the building and between the building and outside can be described, if further physical simplification are made. The temperature of the gas layers, the interface height and a reference pressure are unknown in the set of equations. Two variables (temperature and interface height of reference pressure) and two equations (mass and energy balance) are available for every gas layer. The pressure rise inside a containment is calculated for such closed systems without connection to outside.

2.2 Mass flows and Mass balance

According to the different model assumptions in Figure 1 the mass flow through various connections have to be formulated. The following classes can be handled

- natural ventilation
 - mass flow through vertical openings
 - mass flow through horizontal openings
 - mass flow through ducts
- forced ventilation
 - with constant volume flow
 - regulated according to fuel supply

Figure 2 Pressure distribution for a vertical opening with both interface heights.

All of them may be changed during the simulation time. The size of the openings with natural ventilation may vary between totally open and totally closed thereby. This change is caused by

- prescribed time
- pressure difference
- ceiling temperature
- upper layer temperature

The destination of the flow (hot or cold gas layer) is determined by a combined temperature pressure criterion. The entrainment of gases of this layer is calculated according to the formulas of McCaffrey [11], if the flow crosses a layer before it reaches his destination.

The assumption of uniform temperature in every gas layer leads to pressure distribution over height in every compartment shown in Figure 2. Starting with the reference pressure p_u at the floor of the compartment i and j the pressure drops according to lower layer density, gravitational acceleration and distance from the floor of the compartment. The density of the gas layer changes instantaneously at the interface height according to the temperature of the hot gas layer (T_{g1}) using ideal gas

Figure 3 Pressure distribution at large horizontal vents with thin hot gas layer.

law. The example shown in Figure 2 leads to 3 intervals between bottom and top of the opening with constant conditions on both sides in rooms i and j. Only one flow may occur in every intervals from one room to the other, or there may be two flows vice versa between the two rooms with a neutral place in between fixed by the same pressure in room i and j.

The same pressure distribution is used for every other kind of opening with natural ventilation as horizontal opening or ducts. The thickness of the upper layer is of high interest for large horizontal openings, because flows of both layers of the room or even flows vice versa between both rooms may occur. This is a different approach to large horizontal openings, which is not included one of the noted zone models.

The pressure distributions are shown in Figure 3 at different vertical cross sections at the opening p_o and somewhere else in room with the common model assumptions for the two layer case p_i . The resulting pressure differences at the edge of the opening $\bar{p}$ is shown there also. The pressure difference cause hot gases in the hot gas layer flowing to the opening. There may arise different configurations of mass flows out of the room and into the room depending on it's size across the opening and the thickness and density of the hot and the cold gas layer. The limiting depth of the hot gas layer D_{gr} is given by

$$D_{gr} = \sqrt[3]{\frac{g \cdot A^2 \cdot \Delta p}{4 \cdot U^2 \cdot g \cdot \Delta p}} \dots (1)$$

with

A = area of the opening

U = perimeter of the opening

Δp = pressure difference at the opening with common zone model

assumptions

$\Delta \rho = \rho_l - \rho_u$ = density difference of lower and upper gas layer

g = gravitational acceleration

This is determined by the fact, that the cross flow in the hot gas layer caused by $\bar{p}$ is just the same as the flow caused by Δp at the opening. The total flow is coming out of the upper layer is deeper than D_{gr} . The flow origin and destination are determined according to the different pressure distributions for other cases.

In Figure 4, the distance between opening and layer interface in the lower room i is thinner than $D_{gr,i}$ and the pressure at the opening in this room (p_i) is greater than in the upper room j (p_j). The pressure difference $\Delta p(p_i - p_j)$ is greater than zero. Three different configurations may occur. Case 1.1 is the usual case with no change of flow direction across the opening. The pressure drops acc. Figure 3 is less than Δp . Two flows are going into the upper room j, one out of the hot gas layer in room i, while an other flow is directed vice versa out of the lower layer in room j into room i. The reason is a pressure drops greater than Δp . The pressure in room j

Figure 4 Massflows at large horizontal vents with original flow out of thin upper layer in room i.

gets greater than in room i. For case 1.3 it is assumed that the flow out of room j is coming out of the upper layer, because the lower layer is thinner than $D_{gr,i}$.

If the pressure in room j is greater than in room i an original flow is going out of the lower layer in room j. If the distance between opening and layer interface in room j is now lower than $D_{gr,j}$ acc.Eq.(1) determined by the fact that the flow in the lower layer to the opening is sufficient for the original flow with similar assumptions to Figure 3. Again three different configurations may occur depending on the pressure differences $\Delta p(p_i - p_j)$ and the pressure drop $D_{gr,j} \cdot (\rho_{l,j} - \rho_{u,j}) \cdot g$ between interface height and opening (Figure 5). In the usual case with small pressure drop in room j two flows from each layer of room j are present. Flows vice versa are to be observed for greater pressure drops coming out of the upper layer (case 2.3), if the upper layer is thicker than $D_{gr,i}$, or out of the lower layer (case 2.2), if the upper layer is thinner.

Figure 5 Massflows at large horizontal vents with original flow out of thin lower layer in room j.

This mass balance for every upper (u) and lower (l) zone in every compartment is given by

$$\frac{dm_{u,i}}{dt} + \sum \dot{m}_{u,out} - \sum \dot{m}_{u,in} - \sum \dot{m}_{u,prod} = 0$$

.....(2)

the sum of changes of mass and flows out of the zone minus flows into the zone and massflows produced within the zone, which can be the burning rate or the mass rates brought into the system by extinguishing devices. Between the two zones of every compartment mixing flows are considered. At vents or at the fire plume cold gases from the lower layer can be entrained into the hot gas layer. On the other side hot gases from the upper layer may be entrained into the lower layer at vents. A configuration for one room with three adjacent rooms or outside is shown in Fig. 6. Room 2 is assumed on the left hand side, room 3 on the right hand side and room 4 above the ceiling of room 1.

Figure 6 Massflows in fire compartment with two gas layers in connection with three other rooms.

Figure 7 Energyflows in fire compartment with two gas layers in connection with three other rooms.

2.3 Energyflows and Energybalances

The energyflows considered in the model are:

- energy transported by flowing gases
- energy transferred between solids and gases at surfaces by
 - convection and
 - radiation by
 - fire plume or
 - radiating gas layers
- other losses to equipment and by cooling systems

The energybalances of every gas layer is determined by these terms and the change of inner energy of the gases. A configuration for room and three other rooms or outside is shown in Figure 7.

2.5 Burning Models

Different burning models for the calculation of the burning rate are included in the program. Some of them are different definitions of prescribed fire, which are very useful to simulate a fire experiment. The burning rate is an input parameter for the code in these cases. A geometrical algorithm is used for large buildings with the assumption that the fire spreads with

constant velocity and the specific burning rate is constant on the whole area covered by the fire. A flashover is considered by a significant rise of the spread velocity. This would be feedback of the results of the calculation. A burning model for wooden cribs is derived according to literature. Only geometrical input data for the ventilation are needed. Two other burning models are derived according to German test series for oil- and cablefires. The functions are set up empirically considering the temperature rise and the oxygen supply. The burning rate is a result of the calculation in these cases.

The entrained massflow at the plume over the fire is calculated according to the formulas of Mac'Caffery [11] for small flame heights and according to the formulas of Thomas [12] for large flame heights. The effective heat release rate is calculated according to oxygen supply with the assumption, that the whole fuel is burnt, if more oxygen is available than is needed for stoichiometric combustion. Otherwise the available oxygen limits the combustion. The fuel is turned to different reaction products, which are calculated according to oxygen supply, too. Six gas components of this reaction are handled in the moment. (This depends only on the assumptions for the creation of products in the fire model, which is the source term for every gas component at the fire.) At last the production of soot is calculated assuming a constant part of the burning rate to be turned into soot. This factor is an input parameter.

2.6 Species Concentration and Visibility in every Gas Layer

The spread is calculated for the components of gaseous products by the fire. The basic assumption is the homogenous composition of every gas layer which means total mixing of the considered gaseous components and soot. So the

solution of the differential equations for every component is decoupled of the heat balance calculation. The concentration of every gaseous component and soot is obtained for every gas layer.

The load of filters of the ventilation system is of major interest for fires in nuclear power plants. Most of them are possible oil and cable fires with high production of soot. Therefore the deposition of soot on the structure, in the ventilation system and in filters has to be known, because the time for manual interaction is very important. It is determined by temperature, concentration of hazardous gaseous components and visibility near the fire and along the fire fighting route.

Calculating the visibility it is worst case assumed, that no deposition of soot takes place. The reaction is, that only little data are available concerning the behavior of filters in case of fire. The development

of such models in a task for further work especially concerning cable fires.

3 VERIFICATION OF MRFC DURING HDR - TEST PROGRAM

A large number of full scale fire tests has been carried out during the last 7 years in a German research reactor [e.g 9]. The facility is of cylindrical shape with a volume of about 11 000 m³. Nonrectangular rooms are placed on different levels. The connections of the rooms are horizontal and vertical openings as well as shafts. Some of them were of variable size during the test. Different fire components on different levels have been used for the tests up to now (Figure 8). The burning material changed during the tests. First gas burners with a power of 160 to 1000 kW have been used to test the facility with forced ventilation to be sure, that complete combustion will occur.

Figure 8 Vertical cross section of the facility with diferernt fire levels.

Tests with wooden cribs have been done after the first tests with natural ventilation and a power of up to 3000 kW. At last oil pool fire tests on a low level and near the dome of the facility have been carried out with a power of up to 9000 kW. Cable fire tests are planned in the future to finish this research program.

During the whole test program calculations have been done with different simulation codes. Three of them were zone models (MRFC [7], DOB [10] and CFC VI [3]). Others were so called system codes developed especially for the simulation of thermodynamical processes in nuclear power plants. At the beginning a wide range of result was obtained with partly large differences to the experimental data. After some improvements in the codes the range of the results got much smaller and included the test data. The result of the models were comparable to the much more complicated system codes. It could be learned from the tests, that the influences of the fire concerning temperature distribution were reduced very rapid after the fire compartment due to very high entrainment of cold gases into the hot gas layers and due to heat transfer to the structure.

Some result of calculation with the codes MRFC, FAST [2] and CCFM [5] are presented in comparison to experiment. The experiment T52.14 is chosen for calculations. This test was done near the dome (room 1 in Figure 9) with an oil pool fire on an area of 2 m² with a maximum power of 3000 kW. The density of the oil was 756 kg/m³. The heat of combustion was 42500 kJ/kg. The fire compartment was 4.50 x 1.75 x 3.00 m with a vertical opening of 0.95 x 3.00 m. The assumed 10 room model of the calculations is shown in Figure 9. The noted reference points are gas temperature (CT), structure temperature (CQ), gas velocity

Figure 9 Reduced geometry for calculation of oil fire test T52.14 with reference points in the containment.

(CF) and mass flow measurement and calculations. The following number indicates the location of the reference point according to [13].

The results for upper layer temperature and the thickness of the lower layer are shown in Figures 10 and 11. It can be seen, that the results of the models do agree very good with the experimental data for temperature, which are drawn in dashed lines. The results for layer depth calculated by FAST changes very often between 0 and 0.75 m. This may be an indication for numerical problems solving the questions. The temperature of more than 1200 °C in the fire compartment are reduced very rapidly. They reach about 100 °C in the dome (room 3 in Figure 9). This temperature is overpredicted by CCFM about 150 °C and by MRFC about 40 °C and under-predicted by FAST about 40 °C. At a lower level (room 7 in Figure 6) the measured temperature were less than 40 °C, which was nearly predicted by CCFM while FAST calculated a higher temperature of up to 150 °C changing very often during time, which is a higher temperature than in the

Figure 10 Temperature of hot gas layer in fire compartment calculated with MRFC, FAST, and CCFM and test results.

Figure 11 Thickness of the lower layer in fire compartment calculated with MRFC, FAST and CCFM and test results.

Figure 12 Temperature room 3 (dome), calculated with MRFC, FAST and CCFM and test results.

Figure 13 Temperature room 7 (far field), calculated with MRFC, FAST and CCFM and test results.

dome. The results for the temperature in this two rooms are shown in Figures 12 and 13.

The test T52.14 was done with oxygen depletion. This is documented by vanishing oxygen in the fire compartment and production of carbonmonoxide. The time

history of oxygen and carbondioxide for measurement and MRFC-calculation is shown in Figures 14 and 15. The vanishing of oxygen with production of CO is predicated between 2 and 8 minutes. A small content of about 4 Vol.% is assumed after

Figure 14 Oxygen concentration in fire compartment calculated with MRFC, FAST and CCFM and test results.

Figure 15 CO₂ concentration in fire compartment calculated MRFC, FAST and CCFM and test results.

10 minutes with falling tendency caused by recirculation of smoky gases inside the containment. Oxygen vanished during the test between 3 and 35 minutes with CO-production between 3 and 10 minutes.

4 APPLICATION OF MRFC TO FIRE SIMULATIONS FOR A GERMAN BOILING WATER REACTOR

The model was checked during many other tests of this experimental research program. The improved model was applied to calculations of fire scenarios in the reactor building of a German boiling water reactor. The setup for the 2-room calculations is shown in Figure 16. Room 1 represents a large room surrounding the reactor safety vessel. Room 2 represents the adjacent staircase. The connections between the considered two rooms and the rest of the containment are marked by crossed rectangles. It is assumed, that all openings are vertical 2.0 x 0.5 m. The massflow caused by forced ventilation are drawn by an arrow

with the number of the constant volume flow in m³/h.

The considered fire load was a rectangular 24.7 x 2.0 m vertical cable rack placed along the wall with 4000 kg PVC. It was assumed, that the fire starts at the bottom of room 1 with an initial size of 1.0 x 1.0 m. The fire spread in horizontal (v_H) direction was varied between 0.05 and 0.1 m/min. A range of 0.2 to 2.0 m/min was assumed for vertical spread (v_V). The burning rate was determined by the actual fire area and a specific burning rate between 20 to 60 kg/m²h.

It was found during the calculations, that temperature are to be expected in a wide range between 200 °C and about 350 °C for room 1 depending on the assumed fire spread scenario. It could be learned, that the hot gas layer reaches it's final depth after about 10 minutes, which is almost independent of fire spread scenario.

The calculated temperature and layer depth for room 1 and room 2 are shown in

Figure 1 is a line graph titled "layer depth and temperatures in room 1". The x-axis represents "time [min]" from 0 to 60. There are two y-axes: the left y-axis represents "layer depth [cm]" from 0 to 25, and the right y-axis represents "temperatures [°C]" from 0 to 350. The legend indicates three data series: "layer depth" (dashed line with diamond markers), "temperature upper layer" (solid line with circle markers), and "temp. lower layer" (dotted line with square markers). The layer depth starts at 25 cm, drops sharply to 10 cm by 10 minutes, and then remains constant. The temperature upper layer starts at 0°C, rises to 15°C by 10 minutes, and then remains constant. The temperature lower layer starts at 0°C and remains constant.

time [min]	layer depth [cm]	temperature upper layer [°C]	temp. lower layer [°C]
0	25	0	0
5	15	5	0
10	10	15	0
15	10	17	0
20	10	17.5	0
25	10	17.8	0
30	10	18	0
35	10	18.2	0
40	10	18.5	0
45	10	18.8	0
50	10	19	0
55	10	19.2	0
60	10	19.5	0

layer depth and temperatures in staircase

○ layer depth + temperature upper layer □ temp. lower layer

layer depth [m]

time [min]

temperatures [°C]

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Figures 17 and 18. A vertical fire spread of 2.0 m/min and a horizontal spread of 0.1 m/min was assumed for this calculation. The specific burning rate was 40 kg/m²h. This resulted in a heat release rate of 10 MW. 35 % of this energy was absorbed by the structure and the installations of room 1. The rest of 65 % went into convection to the ventilation system, to the staircase and to the rest of the containment. A cold gas layer of about 7 m remains at the bottom of room 1.

5 CONCLUSIONS

The code MRFC (Multi Room Fire Code) is a zone model for the simulation of fire influences in large buildings. 10 rooms with up to 100 connections of variable size can be considered up to now. The species concentration of 6 gaseous component and the optical density and the visibility of every gas layer can be calculated. Different burning models are included some for fires with known burning rates and others for special applications. The thermodynamical modulation of every gas layer is done according to the development of the fire by assuming one or two gas layers in every room. The code is under development since 1984. During this time many calculations have been done, which were compared to experimental data, which are obtained by full scale fire tests in a German research reactor. The number of calculated results increased with the development of the code. The agreement to experimental data was very good in the near fire field and good in the far fire field during a series of calculation.

Meanwhile different applications for nuclear power plants and industrial buildings are carried out. An application for calculations of cable fires is a German boiling water reactor is shown in this paper. The code has been used to calculate an equivalent fire duration for structures of

common industrial buildings. The results are now under discussion for German standard DIN 18230 (Fire Safety in Industrial Buildings). The handling of the code has been improved last time. The code is now used for practical fire design by some people.

6 LITERATURE

- 1) Tanaka T.: A Model of Multiroom Firespread, National Bureau of Standards, Gaithersburg, MD (USA), NBSIR 83-2718, 1983.
- 2) Jones, W.W.: A Model for the Transport of Fire, Smoke and Toxic Gases (FAST), National Bureau of Standards, Gaithersburg, MD (USA), NBSIR 84-2834, 1983.
- 3) Gahm, J.B.: Computer Fire Code VI - Volume 1 and 2, National Bureau of Standards, Gaithersburg, MD (USA), NBC-GCR-83-451, 1983.
- 4) N.O.Siu: COMPBRN - A Computer Code for Modelling Compartment Fires, UCLA-ENG-8257 (1982), and NUREG/CR-3239 (1983).
- 5) Cooper, L.Y.; Forney, G.P.; Moss, W.F.: The Consolidated Compartment Fire Model (CCFM) Computer Code Application CCFM. VENTS, Part I-IV, National Institute of Standards and Technology, Gaithersburg, MD (USA).
- 6) Schneider, U.; Max, U.: Fire Calculations for the HDR-Nuclear Power Plant in Comparison to Experiment, Workshop CIB W14, Berlin, March 1987.
- 7) Max, U.: Zur Berechnung der Ausbreitung von Feuer und Rauch in komplexen Gebäuden, Dissertation, Kassel, 1990.
- 8) Schneider, U.; Kerskan-Bradley, M.; Max, U.: Abschlußbericht Untersuchungsvorhaben Flucht- und Rettungs-

- swege, AG Brandsicherheit, Kassel, Sep. 1989.
- 9) Schnider, U.; Max, U.: Fire Calculations for Oil Fire Tests in The HDR-Nuclear Power Plant with the Code MRFC, HDR Safety Program, PHDR-Paper No.5 139/88, Kernforschungszentrum Karlsruhe, Karlsruhe 1988.
 - 10) Dobbernack, R. ; Heins, T: Experimentelle und rechnerische Untersuchungen natürlicher Brände in Mahrraumsystemen, Braunschweig, 1989.
 - 11) McCaffrey, B.J.: Momentum Implication for Buoyant Diffusion Flame, Combustion and Flame Journal, Vol.52, 1983.
 - 12) Thomas, P.H. et al: Investigations into the Flow of Hot Gases in Roof Venting, Fire Research Technical Paper No. 7, HMSO , London, 1963.
 - 13) Valencia, L.; Müller, K.: Auslegungsbericht Brandschutzversuche T52.1 /T52.2, PHDR Arbeitsbericht Nr.5.507 /86, Kernforschungszentrum, Karlsruhe, 1987.