Combination of a Fire Model and a Fire-Sensor Model

Abstract

An interface between a fire model and a fire-sensor model has been developed. For the realization of the combined fire and fire-sensor model, output parameters of the fire model have to be converted into input parameters of the sensor model. The developed model gives the opportunity to simulate the response of a fire-sensor from the beginning of the fire up to the output signal of the fire-sensor. Results of numerical simulations of the combined model are presented and discussed.

Introduction

The principle of an over-all modelling in automatic fire detection was stated by Luck [2] at the AUBE’99 conference. The idea of this over-all modelling is to simulate the process of automatic fire detection from the beginning of the fire up to the alarm decision at the output of the fire detector. This over-all model can be divided into three parts. The first part is the observed environment where a fire or a non fire situation exists. The second part of the model represents the fire-sensor including its housing, where the conversion from the physical properties observed in the environment to electrical signals takes place. The third part is the detector unit where the sensor signal is processed and the alarm decision is made. For this different parts of the over-all fire model separate realizations exist, but the interfaces between the different model parts are still missing. This paper deals with the realization of an interface between a fire model and a fire-sensor model [4]. This interface is a first step to develop an over-all model for automatic fire detection.
Fire and Fire-Sensor Model

For the fire simulations the ‘Fire Dynamics Simulator (FDS)’ software of the National Institute of Standards and Technology is used [5]. The basis of the FDS is a computational fluid dynamics model specialized for fire simulations. Compared to other fire simulation programs the FDS gives the possibility to define the combustion material and a combustion reaction to calculate the different combustion products. This is important for a detailed simulation of the smoke development during the fire.

The model of a fire-sensor in its housing has been developed at the University Duisburg-Essen [1]. The model output gives the signal of a fire-sensor determined by a given fire situation. This fire situation is defined by the input parameters given to the model. With this simulated sensor signal the detector unit can decide whether there is a fire situation or not. Different types of sensors can be simulated with the sensormodel.

In this paper emphasis is given to smoke sensors. To simulate smoke sensors several input parameters are needed for the sensor model. These parameters are usually taken from measurements and shall now be simulated by the FDS. Table 1 shows the output parameters of the fire model and the necessary input parameters for the smoke sensor models.

Looking at the smoke properties the FDS only calculates the mass density as mass per volume, while the sensor model needs informations about the particle size distribution. Therefore a model has been developed to obtain the particulate smoke properties from the

<table>
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<th>fire model</th>
<th>sensor model</th>
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<td>smoke mass density</td>
<td>particle number concentration</td>
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<td>geometric mean particle diameter</td>
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<td>geometric standard deviation</td>
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<td>-</td>
<td>complex refractive index</td>
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Table 1: Results of the fire model and input parameter of sensor model
smoke mass density. Also processes which affect the particle size distribution but not the mass density of smoke and which are therefore not considered in the fire simulator have been implemented. The complex refractive index of the smoke particles, needed for the simulation of optical smoke sensors, can not be simulated so far and has to be taken from other studies.

**Particle Number Concentration**

The particle number concentration shall be computed from the results given by the FDS. A log-normal size distribution of the particle sizes is assumed.

\[
n(v_t) = \frac{N}{3\sqrt{2\pi} \cdot \ln(\sigma_r)} \exp \left( \frac{\ln^2(v/v_g)}{18\ln^2\sigma_r} \right)
\]

where \(v_g\) is the geometric mean volume of the particles and \(\ln \sigma_r\) is the geometric standard deviation of the distribution. As shown in table 1 the FDS gives the smoke mass density as a result of the simulation. The smoke sensor model needs the particle number concentration, the geometric particle diameter and the standard deviation as input parameters. The particle number concentration can be computed from the smoke mass density using the first order moment of the distribution. The relation between the particle size distribution and the smoke mass density is given by

\[
N_0 = \frac{\rho_{\text{smoke}}}{\rho_{\text{part}}} v_g^{-1} \exp \left( -\frac{9}{2} \ln^2\sigma_r \right).
\]

Where \(\rho_{\text{smoke}}\) is the smoke mass density and \(\rho_{\text{part}}\) is the specific density of the smoke particles, which is a material property. Figure 1 shows the simulated particle number concentration compared with measurement results. It can be seen that the amplitudes of the results are nearly the same, but after the fire burned out at about 200s the measured particle number concentration decreases strongly, while the simulated one decreases very slowly.

**Implementation of Coagulation**

With eq.(2) the particle number concentration is calculated from the smoke mass density, assuming that the specific soot density, the geometric mean volume and the standard
deviation of the particle size distribution are known. The reason for the decrease of the particle number concentration after the fire burned out is the coagulation of the smoke particles. Due to relative movements collisions between particles occur and with a certain probability these colliding particles coagulate to one particle. The coagulation has no effect on the smoke mass density, therefore the coagulation is not considered in the fire model and can not be considered using eq. (2). In the following an approach for implementing coagulation in the calculation of the particle number concentration \( N \) and the geometric mean volume \( v_g \) is given. The given solution holds for polydisperse particles. A continuous particle size distribution is considered, and it is assumed that the probability that two particles which collide also coagulate to one particle is equal to 1. The decay of the particles due to coagulation can be written as follows [2]

\[
\frac{\partial}{\partial t} n(v,t)_{\text{coag}} = \frac{1}{2} \int_0^{v} \beta(u,v-u)n(u,t)n(v-u,t)du - n(v,t) \int_0^{\infty} \beta(u,v)n(u,t)du, \tag{3}
\]

where \( \beta(u,v) \) is the so called coagulation kernel.

In this paper a solution for particles which are large compared to the molecules of the surrounding gas is given. In this case the coagulation kernel \( \beta(u,v) \) in eq. (3) is given as [2]

\[
\beta(u,v) = K_c (u^{1/3} + v^{1/3}) \left( \frac{1}{u^{1/3}} + \frac{1}{v^{1/3}} \right), \tag{4}
\]
with \( K_c = 2kT/(3\mu) \) the collision coefficient, \( k \) is the Boltzmann constant, \( T \) the temperature and \( \mu \) the dynamic viscosity.

One method to solve eq. (3) is the moments method [2]. With this method eq. (3) is expressed in terms of the moments of the particle size distribution.

This method leads to the following solutions for the particle number concentration \( N(t) \), the geometric mean particle volume \( v_g(t) \) [2].

\[
\frac{N(t)}{N_0} = \frac{1}{1 + [1 + \exp(\ln^2 \sigma_{r,0})] \cdot K_c N_0 t},
\]

with the initial values \( N(0) = N_0 \) and \( \ln \sigma_r(0) = \ln \sigma_{r,0} \). Furthermore, the solution for the change of the geometric mean particle volume [2] is given as

\[
\frac{v_g(t)}{v_{g,0}} = \frac{\exp(9\ln^2(\sigma_{r,0})/2) \cdot [1 + \{1 + \exp(\ln^2 \sigma_{r,0})\} K_c N_0 t]^{3/2}}{[2 \cdot (1 + \{1 + \exp(\ln^2 \sigma_{r,0})\} K_c N_0 t) + \exp(9\ln^2 \sigma_{r,0}) - 2]^{1/2}},
\]

with \( v_{g,0} = v(0) \) the initial geometric mean particle volume for the lognormal distribution. The variable \( t \) of the equations is the particle age.

**Simulation Results**

The initial particle number concentration depends on the initial particle volume respectively on the initial particle diameter, which goes into calculation by the power of three, so it has to be chosen attentively. The initial particle diameter can be taken from measurements, but this measured diameter is influenced by the measurement procedure to a certain degree and the measured particles are already grown due to coagulation. Therefore, a variation calculus was made to find the suitable initial diameter. Simulations of the particle number concentration were compared to measurement results and a value of 68nm was found for the initial particle diameter for the simulation of an EN 54 part 9 n-heptane fire. Figure 2 shows the simulated and the measured particle number concentration for n-heptane fire following EN 54 part 9. The simulated particle number concentration has a sudden increase at the beginning of the fire but reaches the maximum at nearly the same time as the measured one does.

The sudden increase can be explained by the fact that in the case of liquid fires, like n-heptane, the whole surface starts burning at the moment the liquid is ignited and a smoke
Figure 2: Simulated and measured particle number concentration for an n-heptane fire cloud arises from the burning surface. At the measurement the smoke is sucked through a tube, diluted by clean air and then supplied to the measurement apparatus. During this process a certain amount of particles will deposit in the tube and there also may be other effects that influence the measurement results. In the simulation of the fire the smoke mass density, from which the particle number concentration is calculated, is computed at a chosen position in the environment of the fire. No effect of any measurement equipment or housing is considered in the simulation, which gives the opportunity to investigate their influence on measurements.

Figure 3 shows that the simulation of the geometric mean diameter for n-heptane fires gives reasonable results. For the measured as well as for the simulated geometric mean particle diameter there is a sudden increase at the beginning of the fire. After the fire burned out both diameters start to increase. This is caused by the fact that the particles become larger due to coagulation, but no new smaller smoke particles are produced.

Results of Sensor Simulations

In the following part simulation results for a scattered light sensor and an ionization chamber are given, whereby the input parameters of the sensor model are simulated with the
Figure 3: Simulated and measured geometric mean particle diameter for an n-heptane fire

introduced model. The scattered light sensor is sensitive to small changes in the input parameters, for it measures the intensity of the light that is scattered in a defined direction, which is a very small part of the incoming light. This way even small changes in the particle number or size have strong effects on the sensor signal. Figure 4 shows a correlation between the measured intensity and the simulated one at the very beginning of the fire. Both signals show a sudden increase in the beginning. But after a short period of time the simulated intensity starts to increase at a higher degree than the measured one. At about 180s both signals reach nearly the same value. The results show that after the fire burned out (200s) the scattered intensities show the same progression.

The results of the chamber current are measured with a measurement ionization chamber (MIC) at the fire detection laboratory at the University Duisburg-Essen. The simulation of the chamber current of a MIC monitoring an n-heptane fire (see figure 5) gives good results compared to measurements. Especially in the starting phase of the fire. At the beginning of the fire the measured chamber current as well as the simulated chamber current show a sudden increase. From the beginning of the fire up to 200 seconds the measured chamber current and the simulated chamber current have nearly the same progression.
When the fire burns out (200s) the over-all simulated current starts to increase, while the measured one stays nearly the same. This could be caused by the measurement procedure of the MIC.

**Conclusion**

A combination of a fire model and a smoke-sensor model is introduced. The simulation results of the presented fire and fire-sensor model give good results compared to measurements. The developed model gives the opportunity to simulate different smoke sensors from the fire up to the output signal of the smoke sensors. Contrary to measurements the simulations allow to investigate the influence of a single environmental parameter on the sensor output. In addition to the presented simulations of a fire, the model gives the opportunity to simulate defined non-fire situation, which can lead to a false alarm of a smoke detector. This gives the possibility to investigates this non-fire situations to prevent such false alarms. With development off the combined fire and smoke-sensor model a first is made to an over-all model for the automatic fire detection.
Figure 5: Chamber current for n-heptane fire

References


