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Fire Sensor Modelling and Simulation

1. Introduction

In automatic fire detection it is desirable to know exactly how fire sensors incl. their housing work.

A fire sensor in its housing is the *link* between *physical quantities* in the sensor housing environment and the usually *electrical signals* generated by the sensor. The *physical quantities* (fig. 1) in the room to be watched are converted into *elec-*

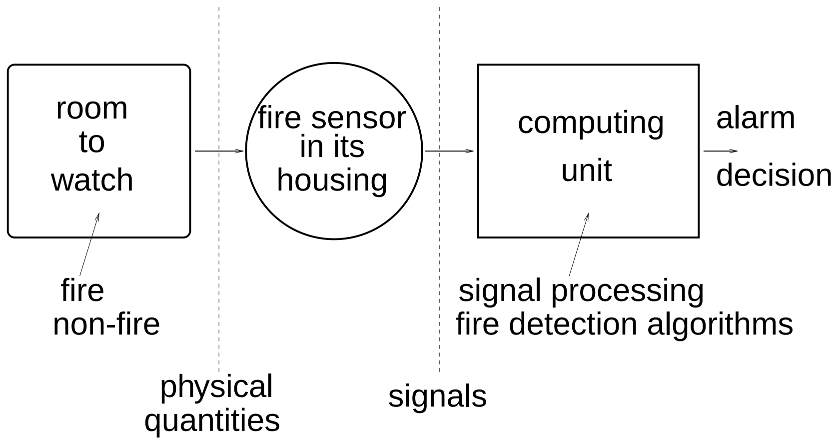

Figure 1: Automatic Fire Detection

trical signals by the *sensor element* itself. The physical quantities must penetrate through the housing, which surrounds the sensor element in order to protect it against touch, damage, dirt, etc. and, in case of optical sensors, against disturbing external light.

The actual measurement of the physical quantities as well as the process of entering the housing *have some influence on the measuring result*. Exact knowledge how these mechanisms work is required in order to correctly describe fire sensors and interprete their signals in a correct way.

The *computing unit* (fig. 1) represents the ”intelligence” of a fire detection system. It processes the sensor signals, it combines those of a group of sensors if necessary, watches for sudden changes or crossed thresholds etc. in order to form an *alarm decision*.

The sensor in its housing together with the computing unit represent the *fire detector*.

When it becomes possible to model and simulate the *fire sensor in its housing* then *complete fire detectors* can be simulated in computer program on the base of physical quantities which have been measured and recorded during test fires. This is even possible for a new fire detector while it is under development if the basic model is correct.

2. The sensor element

The sensor element is the device that actually measures physical quantities and converts them into an electrical signal.

2.1. Ionistaion chamber type smoke sensor

The ionisation chamber can be described according to HOSEMANN [12]

$$y = \frac{1}{\eta} \int_{d=0}^{\infty} d \, \mathrm{d}N^{(H)}(d) \qquad (1)$$

y = smoke density

η = chamber constant [12]

d = particle diameter

$$N^{(H)}(d) = \text{particle size distribution}$$

Though there are more accurate theories available HOSEMANN's formula [12] is used for simplicity. The chamber current i_k, which depends on the smoke density y according to

$$y = \frac{i_0}{i_k} - \frac{i_k}{i_0} \quad (2)$$

$$i_0 = \text{chamber current without smoke}$$

is also somewhat influenced by the velocity of the air through the chamber. This effect is not contained in HOSEMANN's formula. It can be described:

$$i_k(v) = i_k(v=0)\, f_v(\frac{v}{v_{Er}}) \quad (3)$$

$$f_v(x) = \begin{cases} 1 - \frac{1}{2}x & x < 1 \\ \frac{1}{2x} & x \geq 1 \end{cases} \quad (4)$$

$$v_{Er} = \text{constant}$$

2.2. Optical smoke sensors

Optical smoke sensors i.e. the scattered light sensor and the light extinction sensor, can be described using the MIE theory [16, 13]

$$I = I_0 \int_{d=0}^{\infty} \frac{V_{St}\lambda^2}{8\pi^2 r^2}(i_1(\frac{\pi d}{\lambda}, \underline{m}, \Theta) + i_2(\frac{\pi d}{\lambda}, \underline{m}, \Theta))\mathrm{d}N^{(H)}(d) \quad (5)$$

$$\sigma_{ext} = \int_{d=0}^{\infty} C_{ext}(d)\mathrm{d}N^{(H)}(d) \quad (6)$$

I = intensity of scattered light

I_0 = intensity of incoming light

d = particle diameter

V_{St} = scattering volume

λ = wavelength of incoming light

π = 3.1415926...

r = distance between observer and scattering volume

$i_{1,2}$ = MIE scattering functions [13]

$$\underline{m} = \text{complex refractive index}$$
$$\Theta = \text{scattering angle}$$
$$\sigma_{ext} = \text{extinction coefficient}$$
$$C_{ext} = \text{extinction cross section [13]}$$
$$N^{(H)}(d) = \text{particle size distribution}$$

2.3. Elektrostatic sensor

Electrostatic sensor can be described according to [9]

$$i = K \int_{d=0}^{\infty} P_D(\frac{d}{2}) q_T(\frac{d}{2}) \mathrm{d}N^{(H)}(d) \quad (7)$$

$$P_D(a) = \min\left\{ \frac{b(a)Uh}{vd_C^2}; 1 \right\} \quad (8)$$

$$i = \text{sensor current}$$
$$K = \text{sensor constant}$$
$$a = \text{particle radius}$$
$$d = \text{particle diameter}$$
$$q_T(a) = \text{electrical charge on a particle}$$
$$N^{(H)}(d) = \text{particle size distribution}$$
$$b(a) = \text{electrical mobility of a particle}$$
$$U = \text{voltage of sensor}$$
$$v = \text{velocity of air through the sensor}$$
$$h, d_C = \text{geometrical sizes}$$

2.4. Semiconductor gas sensors

Semiconductor gas sensors usually present an electrical output quantity according to:

$$g = c_1 K_1 + c_2 K_2 + \ldots + c_n K_n + c_T (T - T_0) \quad (9)$$

$$
\begin{aligned}
g &= \text{sensor output signal} \\
c_i &= \text{sensitivity constants} \\
K_i &= \text{volume concentration of gases} \\
T &= \text{temperature} \\
T_0 &= \text{reference temperature, usually room temperature}
\end{aligned}
$$

3. Particle filtering

The sensor housing can be interpreted as particle filter. It is a particle-size distinctive filter according to the five principles described by OGAWA [20, 21]:

- Inertia Deposition: decreases number of large particles
- Interception: decreases number of large particles
- Diffusion: decreases number of small particles
- Electrostatic attraction: decreases number of small particles
- Gravity settling: decreases number of large particles

Particle deposition also occurs in the inside of the sensor housing. Altogether, these effects result in a kind of particle size bandpass so that the particle size distribution in the inside of the housing differs from the particle size distribution outside:

$$
\begin{aligned}
N_i^{(H)}(d) &= N^{(H)}(d)\, f_{BP}(d) \qquad (10) \\
d &= \text{particle diameter} \\
N_i^{(H)}(d) &= \text{particle size distribution, inside} \\
N^{(H)}(d) &= \text{particle size distribution, outside} \\
f_{BP}(d) &= \text{bandpass function}
\end{aligned}
$$

Another way to achieve this is the following: In an abtract point of view, if the particle size distribution can be described by a set of parameters $p_1, ..., p_n$ the particle bandpass transforms these parameters into another set $p_{1i},...,p_{ni}$. For example, we can assume a logarithmic normal distribution with the parameters n_0 (volumetric number concentration), μ (geometric mean particle diameter), and σ (geometric standard deviation) which turn into n_{0i}, μ_i, and σ_i, respectively.

4. Entry lag

Entry lag was first decribed by HESKESTAD [11] and has been extended by CLEARY e.a. [5]. It is modelled as an air velocity dependent system with the impulse response

$$h(t) = A\varepsilon(t-t_0)ce^{-c(t-t_0)} \quad (11)$$

$$c = k_c v^{d_c} \quad (12)$$

$$t_0 = k_t v^{d_t} \quad (13)$$

$$A = \text{constant, area under the function}$$

$$\varepsilon(t) = \begin{cases} 1, & t \geq 0 \\ 0, & t < 0 \end{cases}$$

$$e = \text{Euler number}$$

$$k_c, d_c, k_t, d_t = \text{parameters}$$

$$v = \text{velocity of air through the sensor housing}$$

5. Combining things into a general model

For a complete spot-type fire sensor the following general model based on the model proposed by FISSAN and HELSPER [8] is proposed:

The model (fig. 2) consists of the four parts A, B, C, D while B is distributed into the two parts B1 and B2. The vektor $\vec{x}$, representing the model input, is a combination of all physical quantities important for fire detection. Fig. 3 shows an example.

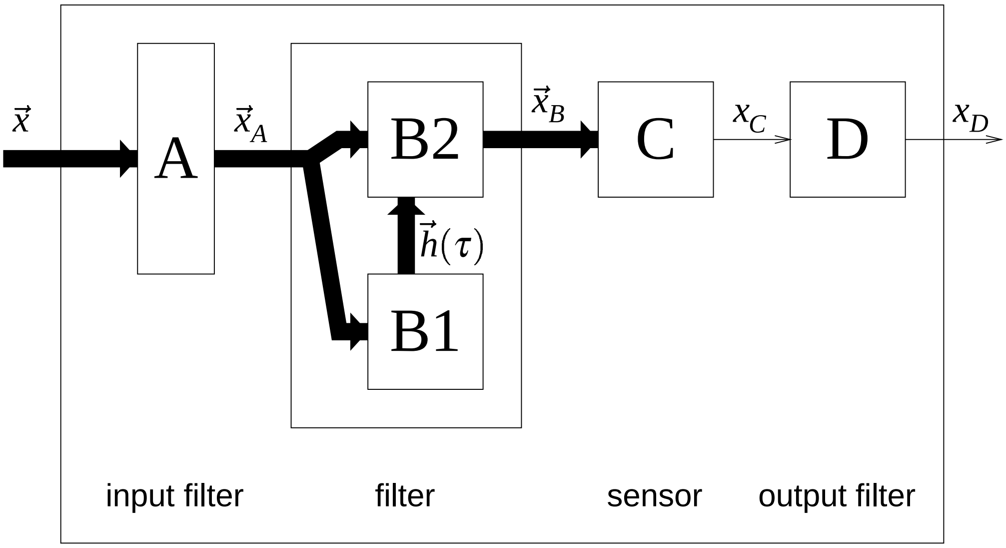

Figure 2: fire sensor in its housing

i	x_i	comment
1	n_0	volumetric particle number concentration
2	μ	geometric mean particle diameter
3	σ	geometric standard deviation
4	$\underline{m}$	complex refractive index
5	v	velocity of air
6	T	temperature

Figure 3: Example of physical quantities in vector $\vec{x}$

Part A is a memoryless system. Its output vector $\vec{x}_A$ is a vectorial function of $\vec{x}$ i.e. each component of the output vector may depend on each component of the input vector. The idea is that part A represents the particle filter.

Part B is a system with memory modelling the entry lag. It is based on the theory of linear and time-invariant systems though the system is not necessarily linear or time-invariant. First, part B1 constructs a function $h_i(\tau)$ for each component of the input vector. Then, this function is used as an impulse response in part B2. So the output vector $\vec{x}_B$ consists of components which are the results of the convolution of the respective component of $\vec{x}_A$ with the associated impulse resonse. Note that the impulse response may be time dependent because it is formed by part B1 which gets time dependent input signals.

Part C describes the sensor element itself. This means that it combines the components of its input vector $\vec{x}_B$ into a single-component output signal x_c according to the physical laws describing the sensor (MIE theory, HOSEMANN theory etc).

Part D is an output filter representing for example sensor signal amplifier characteristics (lowpass, limiter). It is optional.

6. Simulation results

Simulation results presented reflect the state of the study from July 2000 and are preliminary. The study is continued. Simulations are based on particle measurements by TAMM, MIRME, e.a. [23, 17] which result in a particle size distribution in the form of $N^{(H)}(d,t)$ during the test fires. All tests have been made in the fire detection laboratory at the Gerhard–Mercator–Universität Duisburg. Also, the air velocity has been recorded.

In the following figures 4 to 6, the measured output signals of industry–standard fire sensors are compared to the simulated signals according to the model proposed above. As an example, test fire TF1 according to EN54/9 [7] is shown. The results for other fires are similar.

7. Conclusion

A new, complete, and highly modular model for fire sensors including the housing has been introduced. The model is based on the work from HESKESTAD,FISSAN and HELSPER, CLEARY a.o. and has been designed to be suitable for computer simulation. Simulation results have been presented and compared to signals measured with industry–standard fire detectors.

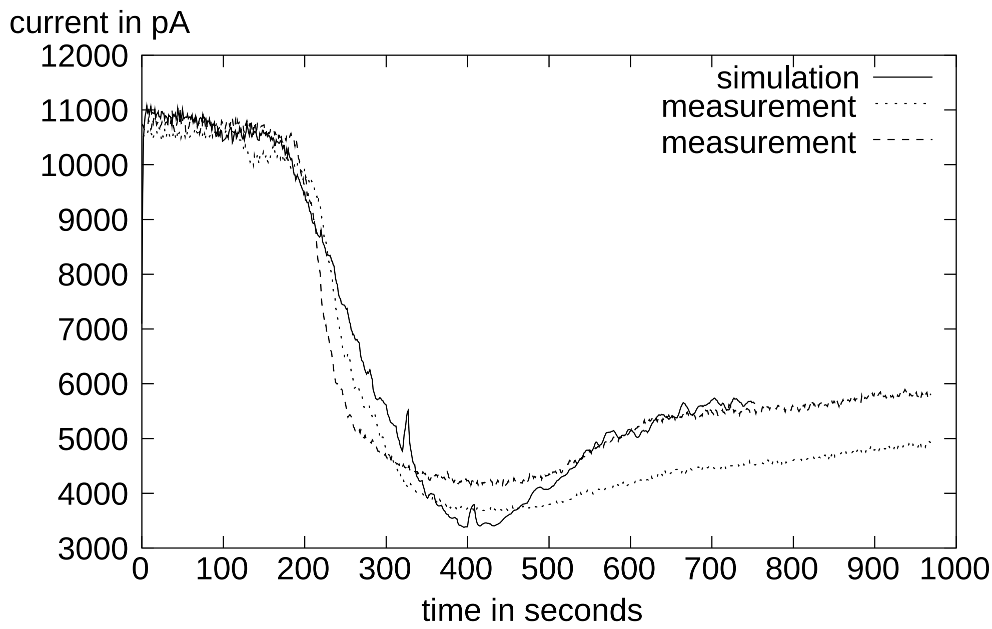

Figure 4: ionisation chamber response during TF1

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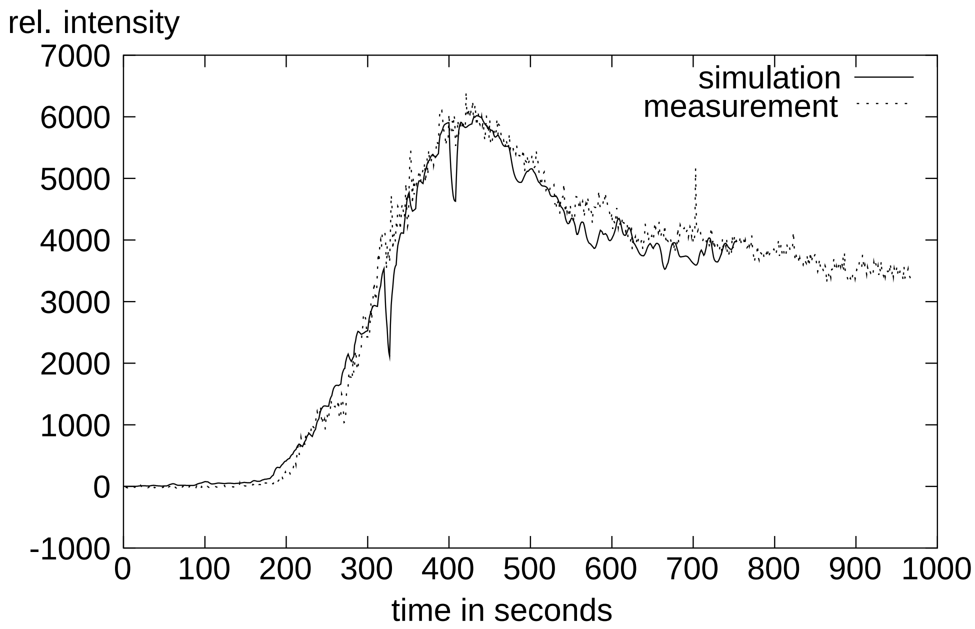

Figure 5: scattered light sensor response during TF1

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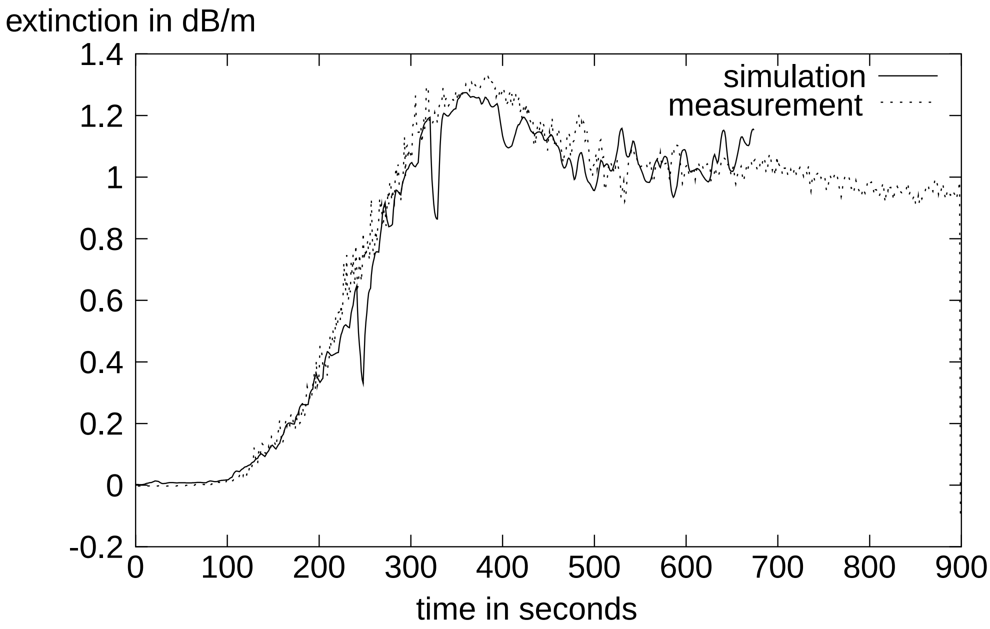

Figure 6: light extinction sensor response during TF1

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