International Collaborative Project to Evaluate Fire Models for
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A NEW MODEL FOR TIME LAG OF SMOKE DETECTORS

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ABSTRACT

For smoldering fires existing time lag theories and observations of smoke detectors are reviewed shortly and shown to be unsatisfactory. The author showed earlier by that fluid dynamic phenomena cannot explain in an acceptable manner the observed controversy. Using general theory of filtering a model is proposed for time lag, where small smoke particles partially separate from the carrier fluid while penetrating into the smoke detector. At small flow velocities the separation seems so effective that detection time is delayed much or smoke may remain undetected totally. Since only scattered direct experiments are available for comparison, and no resources for own measurements were avialable at this phase, the model is presented for fire science community to be tested and evaluated.

INTRODUCTION

Earliest possible detection of fires has been the goal of active fire prevention through ages by any possible means. Since the introduction of numerical room fire simulation codes there has been detailed tools to predict conditions and times for fire detector response. Majority of these tools treat phenomena outside the detector. The long chain from the incipient fire to detector has been modelled at different degrees of sophistication starting from experimental plume models combined with zone type room fire models and ending with various kinds field model simulations. At the moment large eddy simulation (LES) techniques (McGrattan et al. 1998) to determine smoke properties at detector location presents possibly the heaviest end of the calculation tools available for the problem (Cleary at al. 1999, Farouk et al. 2001).

Despite that there are links not yet modelled to the same degree of accuracy as LES simulation treats smoke transport and coagulation; one of these is smoke penetration into the detector. A smoke detector has partially permeable walls separating the gas volume in the detector from the volume around it. Walls of commercial detectors consist mostly of mesh, or perforated plates. In each form they delay fire detection as compared to a fully open detector. Heskestad (1977) modelled coupling of conditions inside the detactor to outside conditions based on scaling principles. Since then practically all modelling of smoke penetration into detectors has based on his work.

TIME LAG THEORIES AND DATA

Heskestad (1977) drafted a theory using dimensional analysis arguments for the time lag Δt of a products-of-combustion fire detector

$$\Delta t = \gamma \, l / \bar{v} \tag{1}$$

where $\bar{v}$ is the mean convective flow velocity around the point detector, l the characteristic length scale, and γ a non-dimensional coefficient characteristic for the geometry. According to Heskestad Equation (1) is valid presuming 'viscosity effects are not considered important'.

Bukowski (1975) as well as Johnson and Brown (1986) observed large delays of fire detection for artificial cold smoke or smoldering smoke in a real size room although the behaviour was neither quantified nor fully systematic. Brozovsky's (1991) measurements showed, that the simple relationship predicted by Equation (1) did not hold for low ceiling jet velocities. In Figure 1 his observations (dots) are plotted as a function of velocity $\bar{v}$. Thin solid lines represent exponential fits by Brozovsky (1991) on his limited set of data; his exponential fit at low values ($\bar{v} < 0.13$ m/s) is a plausible approximation. Unfortunatelly, he did not extend measurements to speeds exceeding 0.2 m/s. Therefore, it is very uncertain, what the behaviour would be at higher velocities. Thus the curve crossing the point (0.4 m/s; 1 s) is only an extrapolation without experimental confirmation beyond 0.2 m/s. No single set of data was available covering the whole interesting region of velocities. More recently Qualey at al. (2001a,b) observed long detection times for low velocity ceiling jets as a result of smoldering fires. Unfortunatelly they did not measure ceiling jet velocities at detector location or other relevant data to allow quantitative comparison.

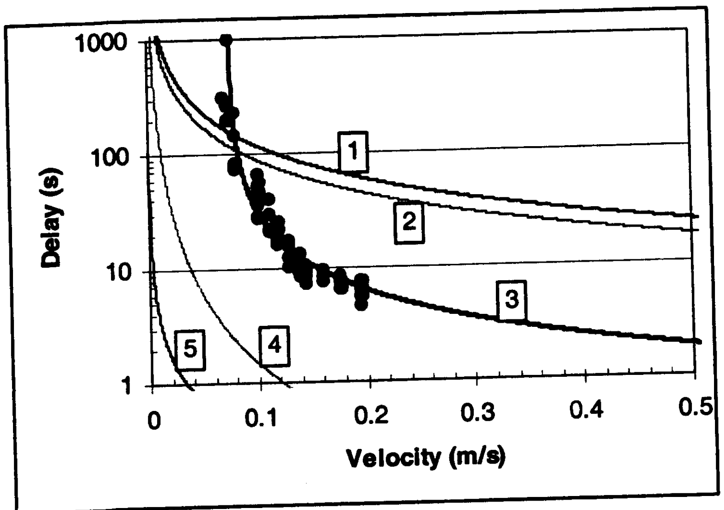

Figure 1. Entry lag time dependence on flow velocity past a detector. Dots (experimental data, Brozovsky 1991). (1) and (2): The delay time according to Equation (1) as explained in text. (3): Fit according to Equation (2), critical velocity $\bar{v}_0$ = 0.075 m/s). (4) and (5): Calculated models (Keski-Rahkonen 2001) explained in text.

EXPERIMENTAL DATA REDUCTION FOR FIRE MODEL VALIDATION

Due to power law dependence on velocity an *ad hoc* modification of Equation (1) was attempted (Keski-Rahkonen 2001)

$$\Delta t = \gamma l / (\bar{v} - \bar{v}_0) \qquad (2)$$

This fit seemed plausible as shown in by line 3 in Figure 1. Since Brozovsky's data cover only a rather limited range, Equation (2) is only one of the many possible fits on the data set. Fits of Equation (2) on another data set (Cleary et al. 2000) is shown in Figure 2. Again, plausible fits were obtained for the delay times. P1 was an optical detector ($\bar{v}_0$ = 0.01 m/s) and I1 ionizing detector ($\bar{v}_0$ = 0.02 m/s). Unfortunatelly, experimental errors seem still to be rather high.

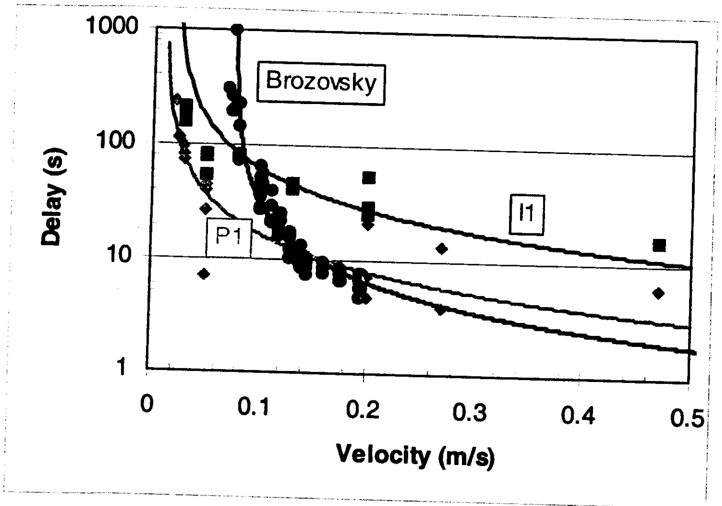

Figure 2. Detector time lag as a function of ceiling jet velocity according to experimental observations (dots: Brozovsky 1991, squares: I1 by Cleary et al., 2000 diamonds: P1 by Cleary et al. 2000). Full lines arbitrary fits on data using Equation (2).

These examples show, critical flow velocity exists, but is hard to explain. The behaviour described by Equation (2) seems to indicate, if the the fluid is taken as a continuum, the flow has non-newtonian character plugging at velocities lower than $\bar{v}_0$. Qualitativelly, such a flow occurs, if the fluid, which here is actually an aerosol, behaves collectivelly like a non-newtonian continuum fluid of Bingham plastic (Irvine and Capobianchi, 1998). The analytical theories of such fluids would in principle allow calculation of the flow in and out of the detector (Kawase and Moo-Young 1992, Patel and Ingham 1994). However, there seemed not to be available experimental data of rheological properties of smoke, which could settle this question. The tacit assumption has always been smoke, like air, behaves as an almost perfect newtonian fluid. Looking smoke as an aerosol and rejecting one phase approximation seemed to shed new light on the problem, and to make non-newtonian flow both unlikely and unnecessary as is shown below. The method is fully described by Keski-Rahkonen (2002), and is shortly depicted here.

THEORY ON FILTRATION MECHANISMS

In a filter, like in a dense mesh, particles deviate from streamlines due to several mechanisms. That property has been used for particle size separation for long (Fuchs et al. 1962, Sinclair et al. 1979), but it is still a subject of intense studies (Lee et al. 1990, Sasse et al. 1994). Particles may collide with the wires on the mesh and stick on them. The main mechanisms of deposition are diffusion, inertial impaction, interception and gravitational settling. In the first approximation efficiences due these factors add linearly when estimating total efficiency of filtration. Approximating the filtering element by a cylindrical body, simple partial differential equations can be derived for the aerosol concentration in laminar flow region (Cheng 1993). For derivation of the equation it is assumed: (1) The concentration is in a steady-state condition; (2) the flow field in the device is a fully developed laminar flow; (3) the effect of diffusion in the direction of flow is neclected; (4) no production or reaction of aerosol occures in the device; and (5) the sticking coefficient of the particle is 100% on the collection surface.

Penetration P of aerosol through these devices can be expressed in a power series of exponential functions in the form

$$P = \sum_{n=1}^{\infty} a_n \exp(-\beta_n m) \tag{3}$$

where a_n is a numerical expansion coefficient, β_n an eigenvalue of the differential equation describing particle diffusion, and m nondimensional argument of the driving mechanism. Since the eigenvalues β_n grow fast with n, for real devices a few lower terms in the expansion of Equation (3) yields sufficent accuracy.

For diffusion batteries, used here as a model for a wire screen, Cheng and Yeh (1980), and Yeh at al. (1982) derived an equation

$$m = A_0\, Pe^{-2/3} + A_1 R^2 + A_2\, Pe^{-1/2}\, R^{2/3} \tag{4}$$

The pressure drop Δp through the screen is (Yamada et al. 1988)

$$\Delta p = \frac{16\eta\alpha h u}{\kappa d_f^2} \approx \frac{32\eta\alpha}{\kappa}\frac{u}{d_f} \tag{5}$$

FLOW THROUGH THE SCREEN

To estimate the flow of smoke through the detector the problem is divided into two formally different modes: flow of air, and flow of smoke particles. The detector is idealized to a hemisphere surrounded by an insect screen. From air flow in the outer field modelled using potential flow the continuity equation in steady state form yields the pressure inside the detector p_i. Once it is known, filtration theory can be applied in the sense of perturbation theory to calculate penetration of smoke particles through the screen to estimate the detection time. Spherical coordinates are selected such a way, that flow enters into the detector for azimuthal angle $0 \le \varphi \le \varphi_0$.

The pressure difference Δp through the screen is given by (Truckenbrodt 1980)

$$\Delta p = \begin{cases} p - p_i & = q(1 - a - c\sin^2\varphi) \quad 0 \le \varphi \le \varphi_s \\ p_s - p_i & = (b - a)q \qquad\qquad \varphi \ge \varphi_s \end{cases} \tag{6}$$

where a is a constant to be determined. Applying Equation (6) into Equation (5) a similar set is obtained for the flow velocity

$$u = \frac{\kappa d_f q}{32\alpha\eta}\begin{cases} 1 - a - c\sin^2\varphi & 0 \le \varphi \le \varphi_s \\ b - a & \varphi \ge \varphi_s \end{cases} \tag{7}$$

By a straightforward calculation one can derive an approximate equation for the air inflow $\dot{V}_i$ into the detector

$$\dot{V}_i \approx 0.460\, \pi r^2 q \frac{\kappa d_f}{32\eta} \tag{8}$$

The used symbols are deltailed in the full paper (Keski-Rahkonen 2002)

SOOT FLOW THROUGH THE SCREEN

(To be completed)

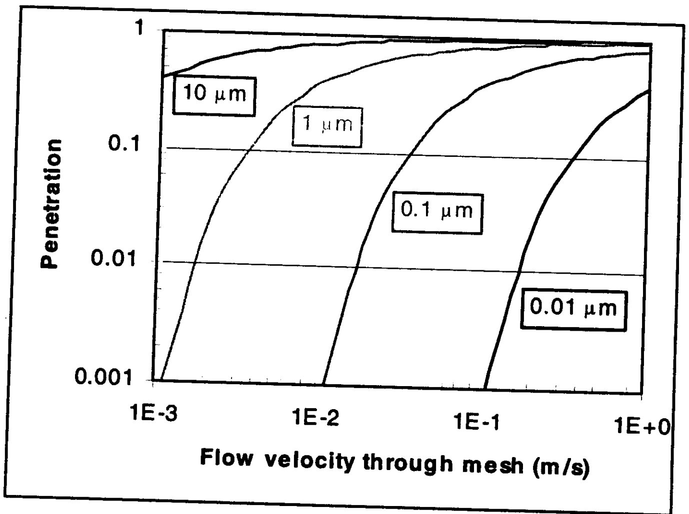

Figure 3. Penetration through a mesh as a function of flow velocity for different diameters of particles.

CONCLUSIONS

Long reaction times of smoke detectors for cold smoke has been known for long. Reviewing a series of measurements it was shown, there is a finite value of ceiling jet velocity, below which the time lag becomes large. It was shown by the author, that neither any presented model nor also in principle any newtonian single fluid model is able to explain this threshold. A two phase model is proposed here, where ideal fluid (air) carries solid smoke particles. At small ceiling jet velocities these particles are selectivelly filtered out of the flow, as smoke penetrates in the detector through the insect screen. The presented model was carried over from, and verified in aerosol reaearch. Still, detailed experiments should be carried out for smoke detectors for direct comparison with the predictions of the proposed theory.

ACKNOWLEDGEMENTS

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- Time lag theories and data
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- Flow through the screen
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- Conclusions

Introduction

- Smoke detection links from the source to the detector only partially modelled
- Smoke measurements difficult
- Large detection delays observed
- Smoke penetration into the detector still a problem

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Time lag theories and data

- Heskestad 1977

$$\Delta t = \gamma l / \bar{v}$$

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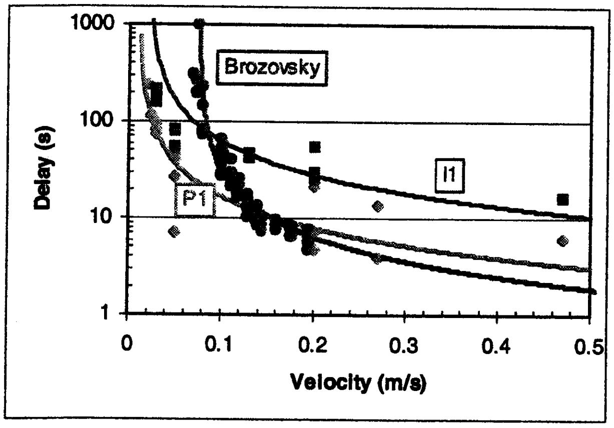
Experimental observations



Data:

Brozovsky 1991

Cleary at al. 2000

Fits:

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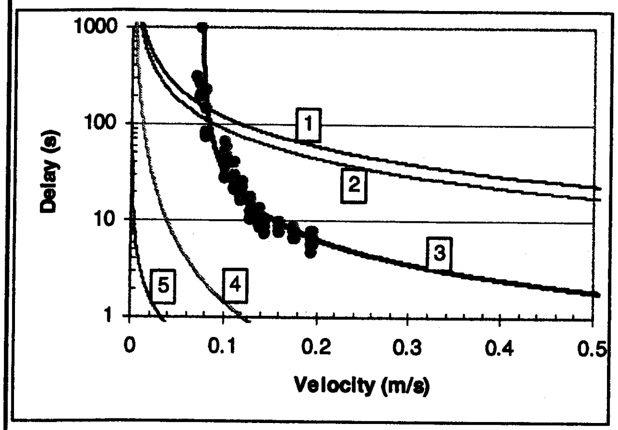
Confirming finite ceiling jet velocity

Modelling of time lag



Calculations:

Heskestad 1977 (1,2)

Keski-Rahkonen 2001 (4,5)

No newtonian fluid dynamic theory able to explain finite critical velocity

New modelling ideas

- Simplified hemispherical detector body
- Insect screen separates inner from outer field
- Outer field from potential flow
- Screen penetration from diffusion battery models
- Air flow in the detector from the continuity equation
- Selective separation of smoke particles on the screen

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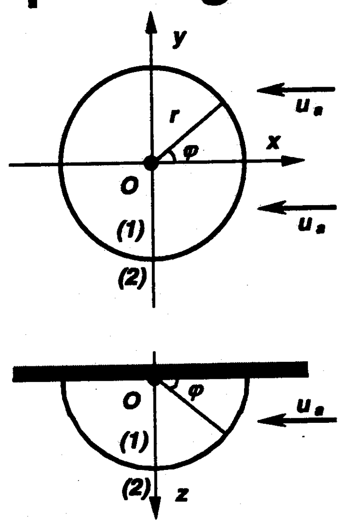
Simplified geometry



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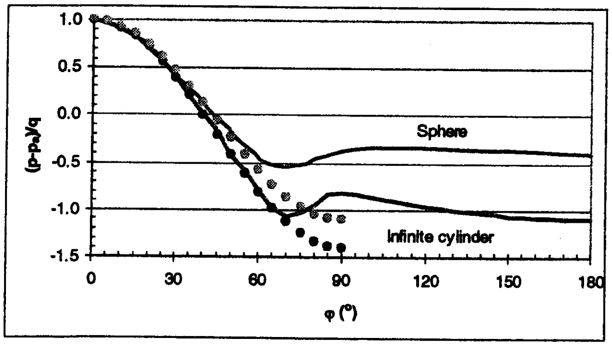
Outer pressure field



Curve fitting on experimental and potential flow models around the stagnation point

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Diffusion batteries

- Cheng and Yeh 1980, Yeh et al. 1982

$$m = A_0\ Pe^{-2/3} + A_1 R^2 + A_2\ Pe^{-1/2}\ R^{2/3}$$

- Closed form solution available for smoke particle penetration

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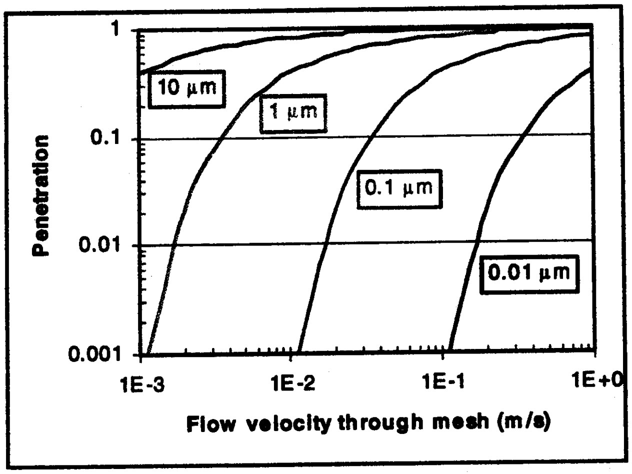
Smoke particle penetration



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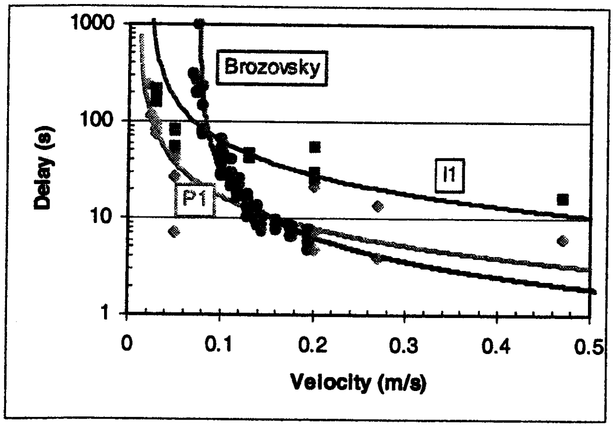

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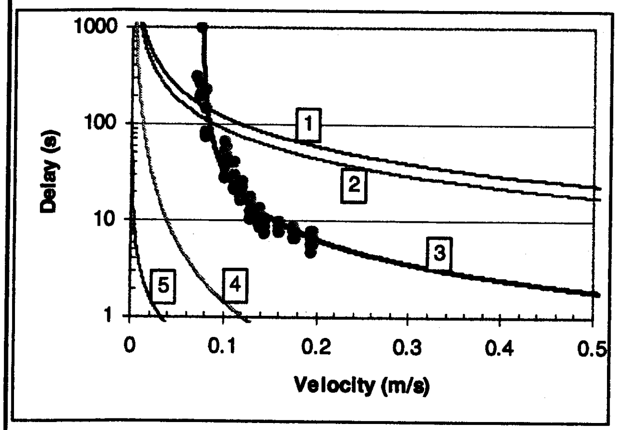

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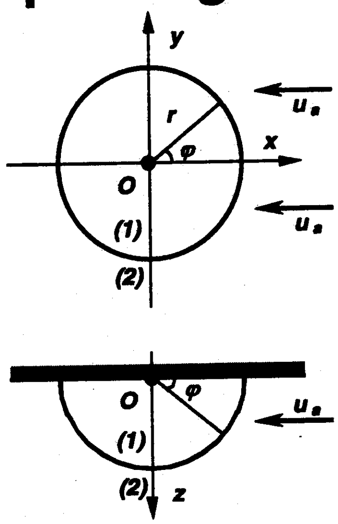

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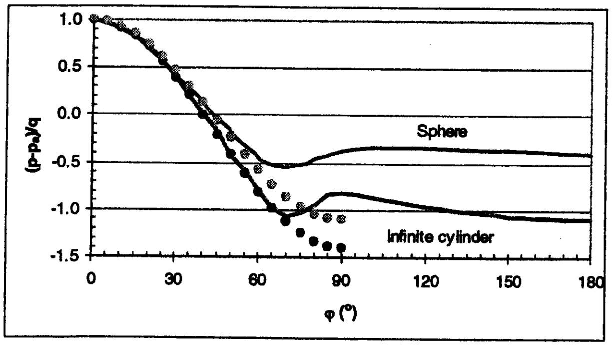

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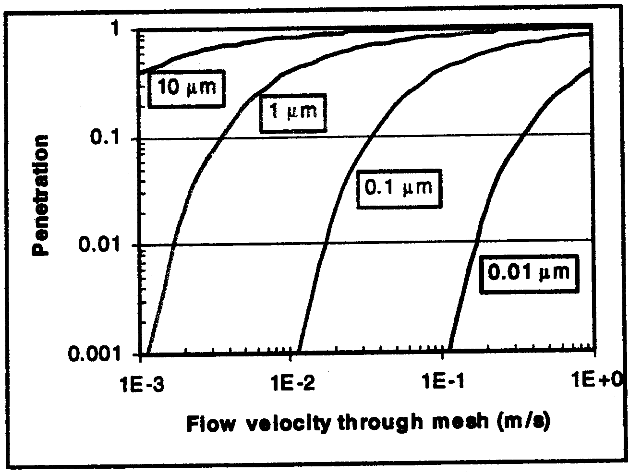

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