FIRE SUPPRESSION STUDIES

by

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The paper presents overview of the current state of fire suppression studies. Focus is made on water-based fire protection technology, such as sprinklers and mist systems. Mechanisms of suppression and performance of different types of systems are discussed. Both experimental studies and mathematical modeling techniques are reviewed. In particular, computational fluid dynamics models available for simulation of water sprays are discussed in more detail.

Key words: *fire suppression, water sprinklers, water mist, computational modeling*

Introduction

Active Fire Control systems are integral part of overall modern fire safety design. Increasingly challenging architectural environment and gradual introduction of Performance-Based (PB) fire safety regulations put intelligent design of suppression systems into focus of fire safety science. Today, fire safety engineers are also challenged to protect buildings from extreme and unusual events, such as, for example, terrorist activity. Environmental considerations and economic realities put further constraints on available levels of fire protection.

Further complications stem from the fact that fire (or flame) suppression is a very complicated physico-chemical process, which is not understood completely and hardly render itself to computer modeling. Quite often, delicate and non-obvious transition divides conditions of flame existence from conditions of extinction.

Finding themselves within mentioned constraints and faced with challenging scientific problem researchers need to continue efforts to better understand fire behavior and design fire fighting systems in intelligent way. Progress has been made over last decades, but a lot of further work is still needed.

In the present paper, an attempt is made to overview briefly some of major problems encountered in fire suppression research and draw attention to remaining problems. The review may be of interest to the readers who are not necessarily working in fire science area, but hopefully will find problematic interesting from the general mechanical engineering point of view.

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Not all areas of fire suppression are covered. For example, chemical suppressing agents, foam suppression and discussion of large tank fires, as well as aerosol generating systems are left out.

Much attention is given to mathematical modeling, in particular, to computational fluid dynamics (CFD) prediction of spray dynamics.

Water-based fire suppression systems

Experimental research

Sprinklers systems

Water sprinklers have a long history as a fire suppression tool. This technology have been shown to be capable of reducing significantly the number of deaths in compartment fires. The first sprinkler was apparently introduced in New Zealand to protect against ceiling fires in textile mills. In contrast to most modern sprinklers, it directed about half of water flow rate towards ceiling. This 13 mm diameter design survived almost unchanged until middle of the twentieth century.

Experimental testing has been essentially driven by the need to advance sprinkler technology. This essentially started in the 1950s when FMRC-developed “spray“ sprinkler replaced the “old style” New Zealand sprinkler.

Despite no shortage of commercial testing, truly comprehensive scientific data revealing major physical mechanisms involved and providing guidance for CFD model development, remain scarce.

Factory Mutual research program contributed greatly to sprinkler technology, and remain good source of reference. This program comprised several major stages, such as developments of Large-Drop Sprinkler system (1971-1980), Residential Sprinkler system (1976-1979), and Early Suppression Fast-Response system (1984-1986) [1].

Based on working principle, sprinkler performance can be characterized by the two groups of issues:

– activation conditions and activation time, and
– fire control/suppression itself.

Correspondingly, there are few major parameters that have attracted attention in the experimental research.

Activation time can be measured and compared to predictions, which are based on equation for the sprinkler heat sensing element. In most general form, this can be written as:

$$\frac{\mathrm{d}T_\mathrm{e}}{\mathrm{d}t} \quad \frac{\sqrt{U}\,(T_\mathrm{g} \quad T_\mathrm{e})}{RTI} \quad \frac{Q_\mathrm{r}}{mc} \quad \frac{C(T_\mathrm{e} \quad T_\infty)}{RTI} \qquad (1)$$

for the temperature, T_e, of the sensing element. Here U is the local gas velocity, T_g – the local gas temperature, Q_r – the radiative flux from fire, RTI – the sprinkler Response

Time Index, C – the conduction parameter. The other few parameters which are involved in this equation, are mass and specific heat of the sensing element, and ambient temperature.

Typical test results for activation times of different types of sprinklers can be found in [1].

Sprinkler action on fire is controlled by the few parameters that have been identified as Local Applied Density (LAD), Actual Delivered Density (ADD), and Penetration ratio (Pe).

LAD is the water density distributed per unit area over deigned coverage area by sprinkler under no-fire conditions. ADD is the water density of the spray actually penetrating given fire and delivering water on the top of burning fuel. This property is fire-specific, and varies even for sprinklers with the same LAD. Finally, Pe is the ratio between the two above properties, Pe = ADD/LAD. This ratio is obviously below one.

Important correlations have been discovered as a result of careful experiments. One of the principal findings is that the Pe is proportional to a specific combination of sprinkler head orifice diameter and sprinkler flow rate:

$$\text{Pe} \propto d_m \quad \frac{\sqrt[3]{D^2}}{\sqrt[3]{P}} \quad \frac{D^2}{\sqrt[3]{\dot{Q}_\text{w}^2}} \tag{2}$$

where d_m is the median droplet diameter, D – the orifice diameter, P – the water pressure, and $\dot{Q}_\text{w}$ – the water flow rate).

This situation is illustrated in fig. 1, based on the test data for two types of geometrically similar sprinklers.

The two regimes of droplet delivery are evident from this figure. These are *the gravity mode* and *the momentum mode*.

In the gravity mode, the plume flow is not affected by the spray, and penetration of droplets is determined by the droplet terminal velocity, and therefore, its diameter. Diameter obeys same scaling, so no deviation from straight line is seen in the gravity (upper) part of fig. 1. The plot effectively also presents dependence of Pe on droplet diameter.

In the momentum mode, spray exerts significant effect on the upward fire plume flow. The Pe in this mode is a function of the momentum parameter, M, which is the ratio of the downward momentum of the spray and the upward momentum of the plume. Deviations

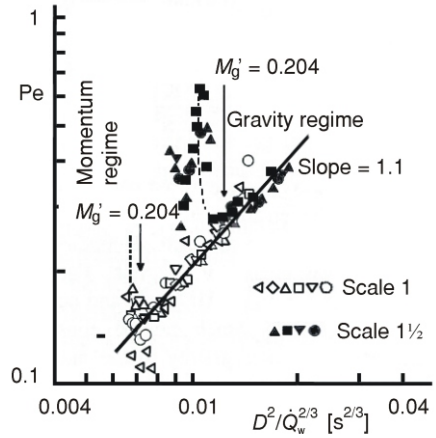

Figure 1. Penetration ratio for FMRC Geometrically Similar Sprinklers: Scale 1 – *D* = 13 mm, Scale 1½ – *D* = 16 mm; adopted from [1]; M_g is a critical momentum parameter for transition from the gravity to momentum regime

from straight line are seen in fig. 1 upon transition from the gravity regime to the momentum regime.

Pe determines amount of water delivered onto the fire base. Actual suppression is determined by the interaction of droplets with the burning fuel.

Correlation of practical tests [1] shows a universal exponential decay of fire burning rate under suppression conditions. This suppression behavior has theoretical explanation within the simple fire suppression model proposed in [1]:

$$\frac{\Delta Q_{\mathrm{a}}}{\Delta Q_{\mathrm{a0}}}(t) \quad \frac{1 \quad \mathrm{e}^{\quad k(t \quad t_0)}}{k(t \quad t_0)} \tag{3}$$

where ΔQ_{a} is the cumulative total heat release from the time t_0 of water application, and ΔQ_{a0} – the reference cumulative heat release, assuming fire heat release rate is "frozen" from the time of application.

The "suppression parameter" k

$$k \quad \frac{\alpha(\dot{m}_{\mathrm{w}} Q_{\mathrm{w}} \quad \beta \dot{m}_{\mathrm{f}} \Delta H_{\mathrm{c}} \quad \dot{m}_{\mathrm{f}} Q_{\mathrm{p}})}{\rho_{\mathrm{f}} c(T_{\mathrm{p}} \quad T_{\infty})} \tag{4}$$

depends on a number of thermophysical parameters, and also on water application density, $\dot{m}_{\mathrm{w}}$, and fuel burning rate per unit area, $\dot{m}_{\mathrm{f}}$.

The relevant parameter for suppression is Required Delivery Density (RDD). This is determined as water density that must be delivered on top of burning object to achieve a pre-defined degree of suppression. The degree of suppression can be defined as percentage of fuel consumed during the entire period of fire suppression (say, 10% of total available fuel).

Water mist systems

Water mist has received considerable attention as possible halon alternative. The idea behind water mist is to break water into much smaller droplets, compared to conventional sprinklers, in order to enhance evaporation rate, and therefore increase suppression capability. Water Mist Fire Suppression Systems (WMFSS) are increasingly popular component of active fire protection design in buildings, ships, transport systems, and other applications. Water mist is also generally considered to have good potential as a replacement for halons.

Performance of water mist has been studied in numerous tests; some of most consistent summary reports are due to Wighus [2] and Heskestad [3].

SINTEF [3, 4] has performed medium- and full-scale tests. One of striking findings was the conclusion that it is more difficult to extinguish small fires rather than large ones. This was demonstrated by looking at typical design concentrations required to suppress fire in closed compartments. Those can vary by an order of magnitude, from 60-70 g/m^3 for large fires to 400-600 g/m^3 for smaller ones. The performance of water mist is greatly affected by other conditions, such as obstructions in space and ventilation. In short, mist is much more "flexible" than sprinkler spray in a sense that it is able to fill the entire compartment volume, diffuse and be carried by convective flows. This behavior is in sharp contrast to well-defined shape of relatively coarse sprinkler spray. Therefore, mist can be considered as a total flooding agent, although its properties can never fully match the diffusive abilities of gaseous agents. This fact means that in order to achieve uniform volumetric distribution, specific design efforts must be taken. For example, mist nozzle locations and number of nozzles are of paramount importance. Ceiling mounted nozzles spraying downwards, typical for sprinklers, are not necessarily the best option.

The SINTEF test program with turbine hoods formed the background for standardization work, which has been reflected in the first available standard for water mist systems, NFPA 750.

Very different droplet concentrations at extinction limit imply that more insight is needed into suppression mechanisms in order to introduce suitable extinction criterion.

Extensive water mist tests have been also conducted by U.S. Naval Research Laboratory (NRL) over long period of time [5]. They found that large fires would entrain and vaporize mist very quickly, causing significant oxygen depletion and fire suffocation. Small obstructed fires with weak entrainment, on other hand, may be shielded from water mist action. This explains difficulties in suppressing such fires. In such situations, design for fire control rather than complete extinguishment may be reasonable.

One of significant limitations of mist is the inability to protect adequately against low flash point flammable liquids. Such liquids may continue to vaporize even while the mist is flowing and can be ignited by small fires, which remain unextinguished.

Some other tests are reported in the review of Grant *et al*. [6]. Heskestad [7] performed systematic investigation of gas and liquid pool fire suppression in unconfined spaces. In contrast to sprinklers, water mist is effective on such fires. Unconfined space makes suppression conditions very different from those of enclosure fires, in the first place because significant oxygen depletion cannot be achieved. Heskestad was able to correlate extinction data in the form involving volumetric water flow rate, Q_w, free-burn heat release rate, Q, height of the spray nozzle above burner, H, and so-called effective nozzle diameter D_{ne}. The latter is related to mass water flow rate, $\dot{m}_w$, and momentum of spray, M, via $D_{ne} \quad (4\dot{m}_w^2 / \quad M\rho_w)^{1/2}$. The scaling relationship, developed in [7], shows that the extinction water flow rate requirement is almost linearly proportional to the effective nozzle diameter, and increases with the power close to 0.4 with nozzle height and free-burn heat release rate.

It is clear that it is much more difficult to extinguish fires in open (or very larger) spaces, compared to confined spaces. In open space, high water evaporation and cooling rates may not be the dominant factors, but extinguishments is rather controlled by momentum effects and flammable vapor dilution by the spray may play major role [7].

Fire suppression regimes and mechanisms

Principal difference between sprinkler sprays and WMFSS lie in the droplet size distribution. It is customary, following NFPA 750, to define water mist as a spray where

99% volume diameter, D_{v99}, is below 1 mm. The latter is such a diameter that droplets with diameters less than D_{v99} account for 99% of total spray volume. By comparison, sprinkler sprays may typically have D_{v99} of the order of 5 mm. Further sub-classification of WMFSS is possible upon defining Class 1, Class 2, and Class 3 sprays as obeying restrictions D_{v99} < 0.2 mm; 0.2 mm < D_{v99} < 0.4 mm, and 0.4 mm < D_{v99} < 1.0 mm, respectively.

The bulk of droplets in a typical water mist spray have, therefore, relatively small diameters (<500 μm, and down to 100 μm). This results in a profound difference in suppression effects between water mists and sprinklers. While sprinklers typically aim at cooling the burning fuel, water mist is designed to suppress flame in the gaseous phase. Sprinkler spray may have relatively small effect on diffusion flame itself. Both systems reduce overall compartment temperatures, but again this effect is much more profound for water mist due to quick droplet evaporation in the gas phase.

Primary action of water mist is, therefore, on the flame and gaseous phase, with the exception, perhaps of Class 3 sprays that can also contribute to surface cooling.

Based on the mentioned differences, some generalization may be derived. As it is well known, the two physico-chemical processes drive fire: (1) pyrolysis degradation of solid fuel, and (2) diffusion gaseous flame. Correspondingly, the two primary modes of suppression have been introduced [8, 9]:

– *surface suppression* (suppression of pyrolysis which results in cessation of volatiles delivery to the gaseous phase), and
– *gaseous suppression* (suppression of turbulent flame purely in the gas phase).

For water based fire-fighting systems both modes are possible (in contrast, for example, to gaseous suppressants), and they generally may occur simultaneously.

From the point of view of water spray characteristics and dynamics, different regimes occur for different spray parameters. In most general schematic form this is illustrated in fig. 2.

For both regions A and B in fig. 2, critical water flux that would cause suppression may be achieved. Surface suppression generally corresponds to "large" droplets which would penetrate to fuel surface. Pyrolysis suppression would then occur due to fuel cooling. Gaseous suppression is primarily associated with "fine" droplets that would evaporate in the flame region. Flame suppression in this case would be primarily due to flame cooling and dilution with water vapor. As it follows from fig. 2, the transition between different regimes may occur as representative droplet diameter in the spray varies. Time scales, associated with each of the suppression regimes, are provided in [9].

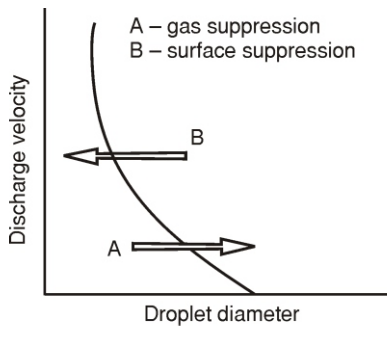

Figure 2. Schematic representation of different fire suppression regimes

For sprinklers, the major mechanism is suppression of pyrolysis, and therefore, such systems rely essentially on surface type of extinguishment.

Major mechanisms for mist are more complicated. Wetting of surface may still play a role, but constitutes a secondary effect. Primary suppression mechanisms are associated with affect on the gaseous phase. It has been demonstrated in several studies that those mechanisms are physical in nature, with chemical effects being negligible. This conclusion refers to pure water mist; upon introduction of chemical additives chemical effect becomes important.

Major physical effects involved in water mist suppression can be listed as:

– heat extraction,
– oxygen displacement, and
– radiation attenuation.

There is a current consensus that the first two mechanisms are dominant. Radiation attenuation may be important in circumstances where it prevents ignition of unburned fuel. This effect may also be quite important in prevention of fire flashover.

There is also an effect of flammable vapors dilution, which is normally of secondary importance, along with surface wetting. This effect may be important, however, in open spaces.

Based on these findings, a reasonable empirical correlation at extinction would involve a combination of limiting oxygen concentration and temperature.

Based on extensive testing, Wighus has suggested the correlation that has been later exploited in a number of zone models. Some of those models are referred to later in the text.

The correlation, proposed by Wighus [36] is of the form:

$$(O_2)_{\text{ext lim it}} \quad 20{,}9 \quad aT^n \tag{5}$$

where T is representative temperature of the gas entrained into combustion zone. This has been compared with experimental data to establish the two empirical parameters, a and n.

The limiting concentration $(O_2)_{\text{ext lim it}}$ in the experiments [36] varies within the range 10-18 vol.%, depending on temperature of entrained gas. Below that level the tests demonstrate extinguishment of the flame. Wighus extinction criterion, derived from medium-scale tests, demonstrates that oxygen starvation is likely to be primary suppression mechanisms in compartments.

In an open atmosphere, such in the study by Heskestad [7], the situation is of coarse, very different as no oxygen depletion occurs and extinction is entirely due to vapor dilution and flame stretching.

CFD mathematical models for water sprays

Analysis of current state of CFD modeling for fire suppression has been provided in [8-10]. Here, the key aspects of the techniques are analysed. Some examples of modeling are also provided.

Key problem in fire suppression modeling is interaction of water spray with surrounding gas (flame and plume), *i. e.* spray dynamics.

The computational models generally applicable for two-phase flows in question are Separated Flow (SF) models. The name implies that the phases under consideration are not in dynamic or thermodynamic equilibrium, and finite rates of transport between the phases must be considered. This is obviously the case for fire situations characterised by sharp gradients between the gas and liquid phases.

SF models fall into three major groups:
- Continuous Droplet Models (CDM),
- Discrete Droplet Models (DDM), and
- Continuum Formulation Models (CFM).

CDM models require solution of the transport equation for the continuous statistical distribution function, which describes droplet positions and velocities in the spray. Computational requirements are generally very high for these models due a large number of dimensions required to specify such a distribution. In addition, high gradients of temperature, droplet densities, velocities and evaporation rates impose stringent requirements for resolution in all dimensions in order to avoid numerical diffusion.

In practical fire suppression applications, the DDM or CFM models have been mostly employed.

They differ in whether the liquid phase is treated via Lagrangian (DDM) or Eulerian (CFM) approaches. With the Eulerian framework used for the gas phase, the corresponding two-phase models are conventionally referred to as Eulerian-Lagrangian or Eulerian-Eulerian models, respectively.

Eulerian-Lagrangian *vs*. Eulerian-Eulerian formulation has been discussed extensively [11, 12]. Besides the virtues or disadvantages of the models themselves, the criteria that should be taken into account in fire suppression studies is the rate of droplets removal from the computational domain. For the practical application of the Eulerian-Lagrangian models this rate must be comparable with the droplet discharge rate, $\dot{\Psi}$.

Eulerian-Lagrangian models

The most direct, and ultimately correct, description of the spray is achieved by DDM models. Convenience of the DDM formulation stems from the fact that Lagrangian reference frame is a natural frame for treatment of particles. A very substantial advantage of the DDM models is that they are free of numerical diffusion problems. They also seem to be easily adopted for polydisperse sprays, and the effect of turbulent dispersion is simulated directly. Due to these reasons, there is a current increasing trend in using DDM models for wide range of spray simulations, and for fire suppression modeling in particular. For sufficiently dilute sprays where droplets do not interact with each other directly such an approach produces quite accurate results. Turbulent dispersion of the droplets may also be taken into account.

As the total number of droplets in the spray is very large, not all but statistically sufficient number of droplets are tracked, and their overall effect on the gaseous phase is evaluated using appropriate two-phase coupling method, for example a Particle-Source-In-Cell model [13]. For the gaseous phase the conventional Eulerian formulation is to be used, either in the form of RANS or LES equations. DDM models may be coupled to either of these two formulations.

An apparent difficulty associated with the DDM approach is that the total number of the tracked particles becomes prohibitively large. There is no direct estimation as to how many particles is enough to represent the spray statistically, but it is obvious that unless some droplets are removed dynamically from the computational domain, their continuous injection will lead to prohibitively large computational costs. The number of particles also increases with the decrease of their diameter (number of particles under consideration is proportional to d^{-3}). There are two situations in which particles need to be removed: droplets can either (1) hit the solid surface (wall or fuel), or (2) they evaporate completely. Both mechanisms play essential role in fire suppression applications.

The Eulerian-Lagrangian models for two-phase flow have been an object of intensive investigations [14-16]. The essence of the method is solution of transport equation for a single spherical droplet in a turbulent flow field. In a very general form this may be found in [15] and generally involves the following contributions:

– drag,
– the force due to static pressure gradient,
– the force on sphere due to inertia of adjacent fluid being displaced by its motion (virtual-mass term),
– Basset force to account for effects of deviation of the flow from a steady flow pattern around the sphere, and
– external body-force, *e. g.* gravity.

Comprehensive analysis of the relative importance of different terms is provided by Faeth [15].

Virtual mass term and Basset forces are normally neglected for dilute sprays with $\rho_p/\rho_g > 200$.

The following simplified equation of droplet motion can be applied with a reasonable accuracy for sprinkler sprays:

$$\frac{\mathrm{d}\vec{U}}{\mathrm{d}t} = \frac{3\rho C_D}{4 d_p \rho_p}(\vec{U} - \vec{U}_p)\left|\vec{U} - \vec{U}_p\right| + \vec{g} \tag{6}$$

with the conventional correlations [17] for the drag coefficient as a function of droplet Reynolds number $\mathrm{Re}_p = d_p\left|\vec{U}_p - \vec{U}\right|/\nu$. There are a number of similar correlations in the literature.

In turbulent flows accompanying fire development, it is essential to model turbulent dispersion of droplets. In the framework of the Lagrangian formulation, this effect may be modeled by stochastic particle dispersion models, such as, for example, the method proposed by Gosman and Ioannides [14].

As droplet travels through the flow, it is supposed to interact with individual eddies. The easiest illustration is for the case of conventional k-ε model for the carrying gas flow. In this approach, the instantaneous gas velocity within the eddy is obtained using the computed value of the turbulence kinetic energy, k. If the turbulence is assumed to be isotropic with fluctuating components having a Gaussian distribution, then this distribution is sampled randomly to obtain the instantaneous velocity U'.

Each eddy along the droplet path deflects it according to the eddy's instantaneous velocity. Parameters necessary for the model are the eddy lifetime and the transit time required for droplet to traverse the eddy.

The eddy lifetime is taken as $t_e = L_e / |\vec{U}'|$ [14] or $t_e = L_e / (2k/3)^{1/2}$ [18]. Here the characteristic size of the eddy is assumed to be equal to the dissipation length scale, L_e, given by $L_e = C_\mu^{3/4} k^{3/2} / \varepsilon$.

The droplet transit time through the eddy may be found from the linearised equation of the particle motion in a uniform flow:

$$t_p = -\tau_p \ln\left(1 - \frac{L_e}{\tau_p |\vec{U} - \vec{U}_p|}\right), \quad \tau_p = \frac{4\rho_p d_p}{3\rho C_D |\vec{U} - \vec{U}_p|} \tag{7}$$

Here τ_p is the particle relaxation time. The time of interaction between the particle and the eddy is taken as the shortest of the times t_e and t_p. For $L_e > \tau_p |\vec{U} - \vec{U}_p|$ the equation has no solution, which can be interpreted as the eddy having captured a particle (the interaction time becomes equal to t_e).

Along with momentum equation, the heat transfer equation must be considered for the droplet. Assuming uniform temperature inside the droplet, this takes the form:

$$\frac{d(m_p c_p T_p)}{dt} = q + L \frac{dm_p}{dt} \tag{8}$$

and the rate of the droplet evaporation is given by:

$$\frac{dm_p}{dt} = -\mathrm{Sh}\, \pi d_p \frac{k_g}{c_{pg}} \ln(1 + B_m), \qquad B_m = \frac{Y_{vs} - Y_{v\infty}}{1 - Y_{vs}} \tag{9}$$

It may be assumed that the partial pressure of vapor at the droplet surface corresponds to the saturation conditions at a given temperature.

In order to estimate Nusselt and Sherwood numbers, conventional Ranz-Marshall correlations [19, 20] may be employed.

In order to get a coupled solution between gas and water spray, use is usually made of the Particle-Source-In-Cell (PSI-CELL) model [13]. The essence of the method is to solve equations for each phase interchangeably and update particle source terms until a converged solution is achieved.

PSI-CELL model allows multiple droplets to be taken into account as particle sources are summed up for each trajectory crossing a particular computational cell. In practice, all droplets in the spray can not be tracked due to computational limitations.

Therefore, each computed trajectory represents, in fact, a number droplets with the same initial conditions. All particle sources to the gas phase need to be multiplied by a number of droplets represented by a particular trajectory.

The specification of initial droplet size and velocity distributions is crucial for the accurate implementation of DDM methods, and computations are sensitive to these parameters [27, 28].

Eulerian-Eulerian models

In some cases, such as mist suppression, extinguishment time would depend on the filling of the whole compartment with droplets and ultimately achieving critical concentration. There would be significant amount of droplets present remotely from fire source. However, these droplets can later be entrained into flame by fire-induced flows, so that their accurate representation in calculations may be essential. In such situations, application of the Eulerian-Eulerian formulation seems to be natural.

This is an alternative, CFM formulation, where both phases are treated as interpenetrating continua. They are coupled together via inter-phase terms that describe processes of heat, mass and momentum transfer. This approach has been much less exploited in fire studies. Details of the general Eulerian-Eulerian formulation may be found in [21, 22].

Specific applications of this approach to the fire/sprinkler interaction modeling has been demonstrated, for example, in [23]. Generally, a closed set of equations can be developed involving unknowns, including gas phase and particulate phase velocity components, pressure, enthalpies of the gas and particulate phases, and others.

The governing equations are of the following general form:

$$\frac{\partial}{\partial t}(r_i \rho_i \phi_i) \quad (r_i \rho_i \vec{U}_i \phi_i \quad r_i \Gamma_{\phi_i} \quad \phi_i) \quad r_i S_{\phi_i} \tag{10}$$

where ϕ represents a general fluid property, such as velocity or enthalpy, r is the volume fraction, and the subscript i refers to the phase in question: gas (g) or liquid (l). The continuity equations and the space-sharing restriction for the volume fractions also apply. The source/sink terms S_{ϕ_i} take account of the mass being transferred between the two phases due to droplet evaporation. Precise form of diffusion coefficients Γ_ϕ and source terms S_ϕ may be found in [24].

Necessary correlations describing interactions between the phases must be introduced to close the problem. Under an assumption that water droplets are spherical, such empirical relationships are provided in [24].

Using this technique, Hoffmann *et al*. [23, 24] studied two sprinkler fire suppression scenarios for real compartments. The comparison between predicted and measured temperatures indicated rather good agreement near the sprinkler source, which deteriorated, however, in the far field. These studies demonstrated potential of the CFM methods in fire extinguishment studies. One of the major problems has been high computational cost involved in such simulations. This problem can be, however, overcome with the increasing use of parallel computations.

Examples of suppression prediction

Sprinkler systems modeling

In this section, some examples of water sprinkler modeling with Eulerian--Lagrangian methods are provided. Eulerian-Lagrangian formulation is rather successful for conventional sprinklers, and the majority of studies have used this approach.

Sprinkler interaction with fire is a complex phenomenon. Suppression mechanisms involve cooling of burning solid fuel, as well as cooling and dilution of flame region and fire plume. These interactions must be accurately predicted.

As discussed earlier, one of major parameters that need be accurately predicted is the ADD.

The detailed study [25] provides the validation of sprinkler models in terms of predicting ADD. The actual delivered densities for the two early suppression fast response sprinklers (ESFR) were predicted at four different water flow rates and different fire burning rates. The agreement between predictions and measurements was reasonably good. As expected, predictions over the larger area were more accurate than those over the smaller one. These computational tests clearly demonstrate that ADD can be predicted with sufficient accuracy in real fire situations. Importantly, spray interaction with the fire plume was also predicted reasonably well [25]. Momentum of the spray as a function of a distance from the deflector, axial velocity of the plume and axial temperature distribution in the plume were generally within few percent of the measured data.

Bill [26] conducted similar simulations of ADD and also found reasonable agreement with measurements. He found, however, consistent under-prediction of ADD for higher ceilings. The results [25, 26] suggest that the current sprinkler models are capable of quantitative predictions of water spray/fire interaction. These latter studies, however, have not addressed the process of extinguishment itself. For sprinkler suppression simulations, prediction of transient burning rate of solid material during suppression is of paramount importance. Processes on the burning solid surface and in the gas phase are inherently coupled: if the pyrolysis reaction stops, then the diffusion flame cannot be supported. On the other hand, inhibition of reactions in the gas phase decreases heat feedback to the surface that, in turn, results in the decrease of the pyrolysis rate or complete cessation of the pyrolysis reaction. It is clear, therefore, that generally extinguishment is a result of non-linear interaction between the pyrolysis and flame reactions. In the case of sprinklers, as explained earlier, the suppression is surface- (*i. e*. pyrolysis) controlled.

Examples of comprehensive fire suppression models that take account of fully coupled combustion, flow, water spray and solid material burning rate are provided by Novozhilov *et al*. [27, 28]. The extinguishments of polymethyl methacrylate (PMMA) sheets and simple wood cribs were considered. The predictions have been validated against large-scale fire extinguishment experiments, carried out in a wind tunnel. For both materials extinguishment is primarily caused by cooling of the solid fuel, as has been confirmed by experiments and simulations. Therefore, the suppression in these cases is surface-controlled. The only effect of flame cooling is the reduction of heat feedback from the flame and surrounding environment.

The results are illustrated here using example of simplified wood crib [27]. The sample consisted of staggered wood slats. Burning rates were predicted as part of solution making use of solid material combustion model. The volatilization model was based on solution of heat transfer and mass conservation equations. Further details are available in [27].

Prior to extinguishment, flame temperature distribution for free-burning fire was compared to predictions, and the reasonable agreement was demonstrated. Upon sprinkler activation, burning rate decreases monotonically until extinguishment is achieved. Typical flame profile during extinguishment period is presented in fig. 3. Flame video images show that under spray action the regions of maximum temperature move gradually to the back surface, and the flame disappears almost completely in about two minutes. The same trend is observed for computational distributions. Figure 4 shows total burning rate for the crib during extinguishment. Different water flow rates were used in the experiment. Computations performed for such different rates showed very little sensitivity to this parameter. The reason for such behavior lies in the nature of wood pyrolysis process, as explained in [27].

An important issue that needs to be addressed in surface cooling is the rate of heat transfer between water spray and burning material. Studies [27, 28] assumed in-

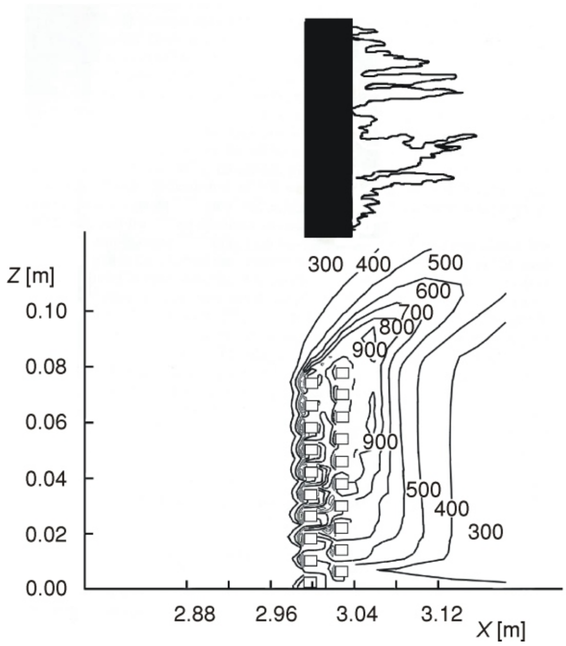

Figure 3. Instant measured flame shape and computed temperature (K, stretched 4 times in a horizontal direction) distribution 30 s after the start of extinguishment. Experimental flame shape is shown in the upper part of the figure in the same scale. Wood slats are seen as hollow squares in the bottom part; (adopted from [27])

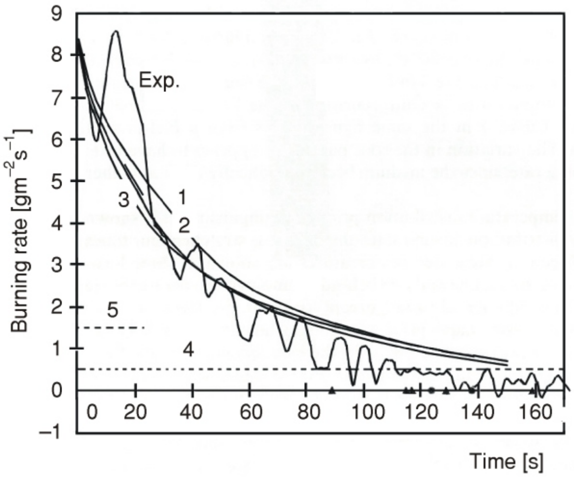

Figure 4. Burning rate histories during extinguishment for different water application rates and experimental extinguishment times. Sprinkler activated at *t* = 0 s. Water application rates:
(1) – 2.0 g/m²s, (2) – 6.65 g/m²s, (3) – 20.0 g/m²s, (4) – extinguishment criterion 0.5 g/m²s, (5) – small scale extinguishment criterion 1.5 g/m²s; Exp. – experimental burning rate; ▲ – Experimental extinguishment time with water application rate of 20.94 g/m²s, ● – Experimental extinguishment time with water application rate of 4.49 g/m²s; (adopted from [27])

stantaneous evaporation of droplets at impact. However, it has been demonstrated by experiments [28] that the heat transfer effectiveness from a single droplet is substantially reduced for droplets bouncing off the surface due to Leidenfrost phenomenon. This effect significantly reduces the effectiveness of heat transfer from water sprays to burning surfaces. This effect is especially important in the case of vertical burning walls. The effective heat transfer rate may decrease to as low as 15-30% of that of the complete evaporation, depending on the burning sample size and material. The heat transfer effectiveness of 0.33 was incorporated in the case of PMMA fire suppression [28], based on the experiments with the steel plate. In the case of wood [27], this factor has been shown to have much smaller effect.

More accurate modeling of surface cooling due to droplet impact may be developed along the lines provided in studies [29-31]. A recent study [32] has provided very careful and valuable computations of heat transfer between droplets and hot surface, taking into account the effect of droplet bouncing. With the help of such studies, the appropriate models of surface cooling and extinguishment should be available in CFD codes in the future.

The studies [27, 28] probably remain the only complete models (*i. e.* taking into account three phases, and making full coupling between spray, flow and burning rate) up to the moment. Such detailed modeling as presented in [27, 28] is possible since surface cooling is the major controlling mechanism.

The situation is significantly more difficult for water mist suppression.

Mist modeling

Along with the spray modeling, the ultimate problem is extinction modeling itself. The answer depends on particular mode of extinguishment. For the extinction due to pyrolysis suppression, modeling is relatively straightforward. The opposite mode of the turbulent diffusion flame suppression, on the other hand, is extremely difficult. This is the type of extinguishment observed for water mist systems. There are no totally acceptable models for this mode of suppression at the present moment.

It is relatively straightforward to model mist effect on *laminar* flames. As is done usually in basic combustion investigations, counterdiffusion flames have been studied extensively for this purpose. The results of simulations are reported, for example, by Lentati and Chelliah [33]. Such modeling allowed effects of water mist on suppression conditions, *e. g.* on flame extinction strain rate to be evaluated. The important observation is that the extinction strain rate behaves non-monotonically as a function of droplet diameter in monodisperse sprays.

On a real turbulent scale, where consistent suppression models are yet to be developed, significant simplifications must be employed. Since it is quite difficult to model extinguishment in the gaseous phase from fundamental principles, it is natural that simplified models of extinction have appeared.

Notable models developed up to moment are due to Vaari [34] and Li and Chow [35]. Both are based on one-zone approach, where water mist spray is allowed to mix with the gas inside compartment.

Vaari [34] treats gas-mist mixture as a well-stirred reactor and solves unsteady conservation equations for gas species, droplet number density and total mixture energy. It is assumed that injected droplets instantaneously assume surrounding gas temperature, and their lifetime in the gas is estimated from the d^2-law. This allows source terms due to droplet evaporation to be estimated.

Of coarse, of primary importance is an extinction criterion, which is based by Vaari on critical adiabatic flame temperature for laminar flame. It can be argued that although such criterion is very reasonable for extinction of laminar flames, its application to turbulent fluctuating flames, where time-averaged temperature is much lower, is highly questionable and needs further investigation.

Upon application of his model, Vaari has been able to predict transient gas temperatures and also oxygen and carbon dioxide concentrations. Gas temperatures and oxygen concentrations were in reasonable agreement with measurements. However, significant deviations were observed from experimental extinguishment times. This can be attributed primarily to inadequacy of the applied extinction criterion.

In contrast to previous study, Li and Chow [35] based extinguishment criterion in their model directly on the cut-off oxygen molar fraction (0.14). This seems to be better justified since it is related directly to the criterion proposed by Wighus [36], based on medium-scale measurements. It should be noted that the Wighus criterion (cut-off oxygen concentration) is temperature dependent (critical oxygen concentration decreases with the increase of combustion zone gas temperature). This modification can be easily included into the Li and Chow model. The model itself is similar in philosophy to the one developed by Vaari. Using the one-zone approach, Li and Chow were able to investigate systematically effects of fire size, ventilation, pre-burning time, droplet size, and discharging rate on the extinguishment process. Reasonable agreement was demonstrated

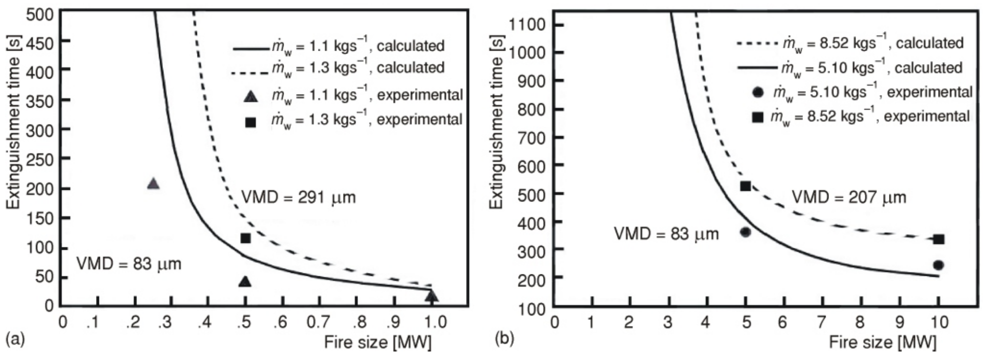

Figure 5. Extinguishment times predicted by zone model [35] for different water mist systems: (a) test in a 100 m^3 compartment with a nominal 0.5 MW fire and ventilation factor of 2.4 m$^{5/2}$; (b) test in 3000 m^3 compartment with a nominal 5 MW fire and ventilation factor of 21 m$^{5/2}$; (adopted from [35])

with experimental data, although the latter was rather limited. Typical predictions are illustrated in fig. 5.

CFD approach to the problem has been exploited in the studies of Prasad *et al.* [37, 38]. In these studies, the effect of water mist on small-scale diffusion flames and pool fires, and also on large-scale compartment fires has been studied. Eulerian formulation for water mist has been employed in the form of "sectional" model, which divides droplet size domain into a number of zones. Cross-sectional fluxes occur as a result of droplet evaporation. Each of droplet sections is assumed to have a unique velocity, different from that of the gas. Momentum conservation equations are written for each section and coupled to the flow equations through the drag terms.

The suppression effect of water mist has been expressed in terms of ratio between total flame heat release rate in the presence of water mist to total heat release rate for free-burning flame. Different injection configurations were studied, and it was found that asymmetric mist injection results in lower degree of suppression even for higher injection densities.

The studies [37, 38] produced quite valuable insight into dynamical interaction between water mist and fires. However, since apparently laminar form of governing equations was used, the effect of turbulence, and in particular, quenching conditions for turbulent diffusion flame were not clearly identified.

Potential of water mist in preventing flame spread was investigated in [39]. The modeling of laminar diffusion flame spread over solid material was performed and critical (quenching) conditions for such spread in the presence of water mist were derived. This proposed localized way of water mist application seems promising, for example, in preventing quick flame spread on vertical walls or linings.

Conclusions

Considerable efforts have been put recently into research on fire suppression systems. The developments in water-based suppression systems have been discussed.

Notions of surface and gaseous suppression regimes have been introduced and briefly discussed. Fire extinction regimes are very different even in situations where only physical effects are involved. Careful experiments are required for understanding of interplay between different suppression mechanisms.

Progress in mathematical modeling has been mostly achieved in application to water sprinkler systems, where it is now possible to model turbulent fire suppression involving rather complicated burning objects and taking into account coupling between different phases (spray, flow and solid combustible).

In the other areas, such as water mist, the progress on modeling is not so impressive. Ultimately, it is hindered by inability to model reasonably well turbulent diffusion flame suppression. There are also clear technical problems with accurate simulation of spray-flow dynamics for fine-dispersed sprays. Simplified zone models have been put forward to predict extinction by water mist on the basis of empirical correlations. Although these demonstrated some degree of success, it is most likely that full CFD approach needs be considered.

Work is still required to transform fire extinguishment models into reliable engineering tools. Experimental research will greatly assist in these future developments.

Nomenclature

B_m – Spalding's mass transfer number, [–]
C_D – drag coefficient, [–]
c – specific heat, [$Jkg^{-1}K$]
d – diameter, [m]
$\vec{g}$ – gravity acceleration, [ms^{-2}]
ΔH_c – heat of combustion, [Jkg^{-1}]
k – turbulence kinetic energy, [m^2s^{-2}]
L – latent heat of phase change, [Jkg^{-1}]
L_e – dissipation length scale, [m]
m – mass, [kg]
Q_p – heat of pyrolysis, [Jkg^{-1}]
q – heat flux, [Js^{-1}]
Re_p – particle Reynolds number, [–]
r – volume fraction, [–]
Sh – Sherwood number, [–]
S_ϕ – source term for variable ϕ, [–]
T – temperature, [K]
t – time, [s]
t_e – turbulence eddy lifetime, [s]
$\vec{U}$ – velocity, [ms^{-1}]
Y – mass fraction, [–]

Greek symbols

α – fuel geometric factor, [–]
β – fraction of total heat release rate transferred to fuel surface, [–]
Γ_ϕ – exchange coefficient for variable ϕ, [–]
ν – kinematic viscosity, [m^2s^{-1}]
ε – turbulence kinetic energy dissipation rate, [m^2s^{-3}]
ρ – density, [kgm^{-3}]
ϕ – any variable, [–]
τ_p – particle relaxation time, [s]

Subscripts

f – fuel, [–]
g – gas, [–]
p – particle, pyrolysis, [–]
s – surface, [–]
v – vapor, virgin wood [–]
w – water, [–]
∞ – ambient, [–]

Superscript

′ – fluctuation with respect to Reynolds mean, [–]

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