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Abstract

This paper shows how a quantitative risk analysis method may be used to evaluate the risk to which the environment of a warehouse may be subjected if a fire breaks out. The purpose of this paper is to present the results the numerical simulations performed with the code FDS [1] in a large volume representative of a warehouse. Evolution of the thermodynamic system is governed by the equations of conservation (mass, energy and chemical species) and by the ideal gas law equation. The results and findings have implications for the modeling of flame spread in warehouse, and for the identification and the assessment of the risks associated with the product storage. Both quantity and type of combustible materials, once ignited, play a major role on the flame height (thermal impact) and on the emission of toxic chemical species, such as carbon monoxide (CO) and soot (C). The present work has been undertaken to study the aspect of gas temperature, velocity, chemical species and radiative intensity during combustion in the case of warehouse fire.

Keywords: warehouse fire, combustible materials, flame spread, thermal impact, toxic effects

Introduction

Warehouse fires are particularly serious. Warehouse fires are usually much more highly localized but behave as intense emitters of heat, smoke and other combustion products. In the warehousing field, fire safety is fundamental for the protection of human beings and the environment. In this paper, a methodology for simulating the near field hazard associated with the flame height and toxic chemical species as a function of the combustible materials is presented. The spread fire along the solid surface has always been occupied a large proportion of the research effort in fire science. The model described here is a numerical implementation of a thermal and fluid-dynamic theory to predict the rate of flame spread. Assessing the hazard of combustible materials requires an understanding of the effect of such geometries on flame height. However, task of obtaining the experimental data or analytical solution for a large warehouse fire is not possible to describe the flame-surface heat flux which is responsible for the fire to spread. It is now relatively expensive to perform a CFD calculation in the design phase for safety consideration of a warehouse. Therefore, engineering methods have become important with the development of tools to assist in the design procedure. However, in the case of warehouses, fire safety engineering techniques are less developed, there is no method available which will reveals whether this calculation is sufficiently safe and economic.

A collaborative projet between LCD and INERIS was set up that aims at evaluating and improving fire modeling methods and engineering tools for use in warehouse fire safety. The first task of the collaborative projet is to evaluate the current capability of fire models to analyse the warehouse hazard. INERIS is specificaly covering safety issues of industrial premises and related to the environment. This carries out studies for fire safety purposes in France and intervenes as a technical support to the authorities for the evaluation of fire safety of the industry.

CFD theoretical analysis

The gas phase model consistes of the conservation equations for total mass, momentum (full Navier-Stockes), energy, and species mass fractions (fuel and oxygen), formulated as,

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_j}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}+\frac{\partial p}{\partial x_i}-\rho g_i=\nabla \tau_{ij,SGS} \tag{2}$$

$$\frac{\partial \rho h}{\partial t}+\frac{\partial(\rho u_i h)}{\partial x_j}-\frac{Dp}{Dt}=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{Pr_t}\frac{\partial h}{\partial x_j}\right)+\dot{q}_c+\dot{q}_r \tag{3}$$

Here, u is the velocity, p the perturbation pressure from ambient, ρ density, g_i the acceleration of gravity, $\dot{q}_c$ the rate of heat release per unit volume due to combustion, $\dot{q}_r$ the radiant energy flux, and Pr_t (=0.5) the turbulent Prandtl number.

The Large-Eddy-Simulation method is used in which the large-scale eddies that govern the mixing of the gases are directly simulated. The sub-grid scale motion is calculated by use of the Smagorinsky model [1] which relates the unknown subgrid scale (SGS) Reynolds stresses, $\tau_{ij,SGS}$, to the local large scale rate of strain.

$$\tau_{ij,SGS}-\frac{1}{3}\tau_{kk,SGS}\delta_{ij}=2\mu_t S_{ij} \quad \text{with} \quad S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{4}$$

The eddy viscosity is given as,

$$\mu_t=C_s^2\rho\Delta^2|S_{ij}| \text{ with } C_s\approx 0.21 \tag{5}$$

where the length scale, Δ, is tied to the grid used in the calculations, and the time scale is determined by the local resolvable dissipation. The perfect gas law is used to describe the equation of state,

$$p_0=\Re\rho T\sum_i\frac{Y_i}{W_i} \tag{6}$$

Here, $\Re$ is the universal gas constant, T the temperature, w_i the molecular weight of species i, and Y_i mass fraction of species i.

The following global one-step irreversible chemical reaction for complete combustion of a hydrocarbon fuel is assumed,

$$C_xH_yO_z+\nu_{O_2}(O_2+3.75N_2)\rightarrow \nu_{CO}CO+\nu_{CO_2}CO_2+\nu_{H_2O}H_2O+\nu_s C+3.75\nu_{O_2}N_2 \tag{7}$$

Combustion process is assumed to be controlled by diffusion, permitting a mixture-fraction-based modeling approach,

$$\frac{\partial \rho f}{\partial t}+\frac{\partial(\rho u_j f)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\mu_t}{Sc_t}\frac{\partial f}{\partial x_j}\right) \tag{8}$$

where Sc_t (=0.5) denotes the turbulent Schmidt number.

The heat release rate is directly proportional to the rate of consumption of oxygen,

$$\dot{q}_c=-H_o\dot{\omega}_o \tag{9}$$

which is calculated from the local mixture fraction and a state relation [1]. Here, H_o is the heat release rate per unit mass of oxygen consumed.

Radiation model

The radiant flux vector in the energy equation (3) is calculated by integrating the radiation intensity over all directions. The radiation intensity is found by solving the following Radiative Transfer Equation (RTE) without scattering,

$$\vec{\nabla}.\vec{\Omega}I + \kappa I = \kappa\frac{\sigma T^4}{\pi} \qquad (10)$$

The absorption coefficient, κ, is a function of the mixture fraction.

Pyrolysis model

It is assumed that the solid material is thermally thick, homogeneous and its thermal properties are independent of temperature. A one-dimensional heat conduction for the condensed phase temperature, T(n,t), is applied in the direction n,

$$\rho_s c_s \frac{\partial T_s}{\partial t} = k_s \frac{\partial^2 T_s}{\partial n^2} \qquad (11)$$

where ρ_s, c_s and k_s are the density, specific heat and conductivity of the material. The mass loss rate, $\dot{m}_s$, of volatiles from the surface is assumed to obey the simple Arrhenius equation,

$$\dot{m}_s = A\, e^{-E/RT} \qquad (12)$$

Method of resolution

The boundary condition at the solid surface (n=0) is

$$-k_s \frac{\partial T_s}{\partial n}(0,t) = \dot{q}''_c + \dot{q}''_r - \dot{m}_s \Delta H_v \qquad (13)$$

where $\dot{q}''_c$, $\dot{q}''_r$ are the convective and radiative heat fluxes, and ΔH_v is the heat of vaporization (1.61×10^3 kJ/kg for PMMA). The mixture fraction at the burning surface is adjusted as follows,

$$(1 - f_s)\dot{m}_s = -\frac{\mu_t}{Sc_t}\frac{df_s}{dz} - \Delta t\, u_s \frac{d(\dot{m}_s f_s)}{dz} \qquad (14)$$

Here, Δt is the time step, and u_s the fuel injection velocity (m/s). Zero gradient conditions are used at the free boundary and the inert solid surface. The finite-difference technique is used to discretize the partial differential equations and the associated boundary conditions (13-14). All the spatial derivatives are approximated by a second-order central differences scheme and the flow variables are updated in time using an explicit second-order Runge-Kutta scheme. The pressure is found by applying the divergence condition to the momentum [1].

CFD results and discussion

At first, the work was focused on using the FDS code to model the flame spread rates primarily controlled by radiation from the turbulent flame to the unburnt fuel surface. As an exemple, let us consider a rack fire of PMMA, as shown in Figure 1, with the fuel sizes of 1.0 m in the x and y directions, and with the total stack height of 5.2 m. Figure 1 shows the inherently time dependent fire situation at four consecutive infinitesimal time steps from t=30 (ignition), 60, 90 to 150 s. The phenomenological analysis of flame spread between adjacent stacks is made to gain insight into the mechanisms governing the fire growth. The ignition delay time is about 30 s for a level of irradiance of 50 kW/m^2, and can be reduced at higher heat flux. The result is a fully coupled solution to both the fluid dynamics and radiative transport equations. During a fire, convective and mainly radiative heat transfers from the flame towards the solid or liquid fuel lead to the vaporization of the fuel. In case of fire, the

pyrolysis fuel and the oxygen are initially separated. Combustion takes place in the zone of mixture of fuel gases and oxidant in proportions close to the stoichiometry. The structure of a turbulent diffusion flame is composed of two areas: 1) a reaction area (flame zone) of higher temperature where the temperature is higher than 500 °C; the velocity of the fire-induced flow can increases up to 15 m/s; 2) an inert area, the thermal plume located above the flame zone composed of a hot mixture of air and combustion products. Once ignited, the flame height, H_f, is proportional to the rate of the heat release. As shown in Figure 2, a linear time-dependent of the fire growth rate is observed before t=120 s, which corresponds to 3200 kW. From the time t>120 s, the flames start to accelerate upward from the ignition source, the fire growth rate increases with an exponential function, $Q \propto e^{\alpha t}$, up to 20 MW. The total heat release rate generated (Q) is convected (Q_c) upwards by the fire plume and radiated (Q_r) away from the combustion region with a radiative fraction lower than 0.3. The surface temperatures of solid combustible (PMMA) in the fire growth period are presented in Figure 3. PMMA is assumed to ignite and burn at a given temperature of 653 K. The upward time-dependent velocity of the flame front is written as, $V_f(t)=dz/dt$ (m/s). The estimates of upward flame spread velocity from Figure 3 for a rack height of 5.2 m is found to increase from 0.01 m/s for t<135 s to 0.2 m/s as t>140 s.

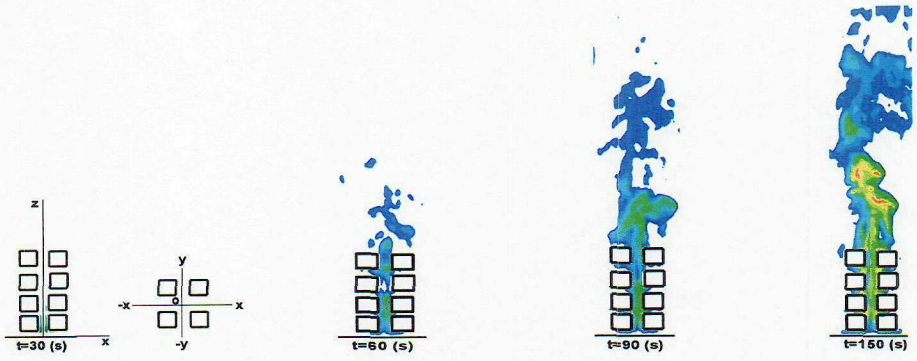

Figure 1. Fire growth in storage arrays between adjacent stacks

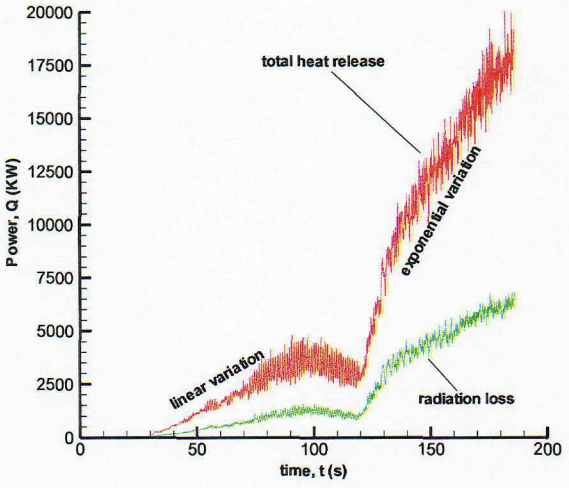

Figure 2. Fire growth rate and radiation loss

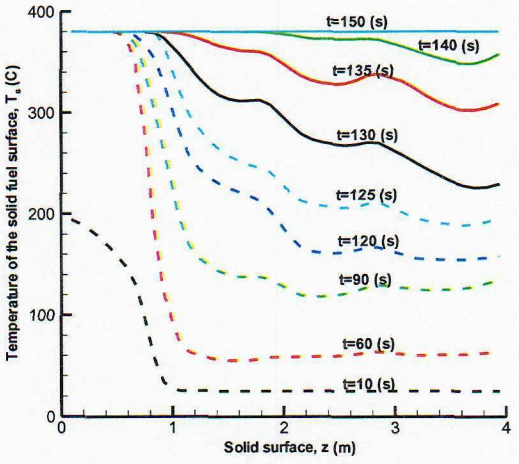

Figure 3. Fuel surface temperature with height

From the above description of the fire growth in storage arrays, it can be seen that the vertical channels between adjacent stacks offer an ideal pathway for fire growth. In rack storage fire, the flame reachs rapidly the ceiling as the fire growth rate becomes extremely important. The plume fills the overall warehouse in less 10 minutes. As the time elapses,

collapse of the roof (usually steel) occurs due to the material heating by heat feed back from the fire. Two warehouse configurations, differing each other by the ratio between length and width, L/W, are considered. The length (L) and width (W) of the warehouse are 150 m and 75 m for L/W=2, and 250 m and 30 m for L/W=8 with a warehouse height (H) of 13 m. The scenario chosen here is as follows: 1) a fire is generalized over a whole warehouse with a surface of 7500 m^2; 2) a large number of racks (49 in this study) with a width of 2 m in the x direction, a length of the warehouse width, W, in the y direction, and a height of 10 m is considered; 3) the whole surfaces of the solid or liquid materials stocked in each rack are in combustion with a mean surface burning rate of 7 g/m^2s. The value of surface burning rate is provided by FDS [1] Database file for a large rack fire of plastic products in warehouse. This scenario is chosen both for its intrinsic importance and because it illustrates the data needed to generate a relatively realistic simulation of such an event.

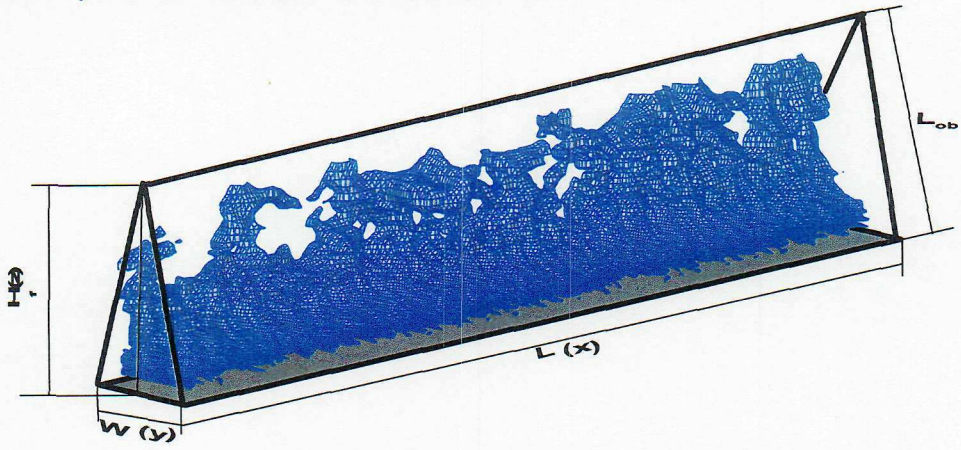

Figure 4. Schematic representation of a warehouse open fire

Figure 4 shows a schematic representation of a warehouse open fire from a computation of the reacting fluid dynamics with about 600000 grid cells. Volatiles originating at the combustible materials due to heat feed back from the fire, mix with the surrounding air to form a diffusion flame. The simulated instantaneous visible flame shape corresponding to a gas temperature of about 500 °C for L/W=8 on the median plane perpendicular to racks is presented in Figure 5. The mean temperature contours in the cross-section parallel to racks is shown in Figure 6. Two distinct regimes are observed leading to a persistent flame zone (T>500 °C) established above the solid fuel (PMMA) and a buoyancy plume zone. The criterion of 500 °C is used for determining the predicted mean flame height. The numerical results show that flame height, H_f, in rack storage is a parameter depending on both the stored materials (heptane, PMMA, wood and sugar) and the warehouse length/width ratio, L/W. For the same material (for exemple, heptane), the flame height, H_f, increases from about 30 m for L/W=8 up to 75 m for L/W=2. In general, heptane and PMMA are with a high energy density, giving a flame height more important as compared to the other type of materials, such as wood and sugar. We wish to validate the computations results by comparing with the correlations. Among relations for the flame height which have been proposed, the MacCaffrey correlation [2] derived for the particular purpose of fire applications appears most suitable. A comparison between the predictions and analytical correlation for the flame height as a function of the heat release is presented in Figure 7 that shows a relatively good agreement. Moreover, it should be noted that near the fire, over a distance comparable to the flame height, the radiant energy flux can be sufficiently high to threaten both the structual integrity of neighboring buildings, and the physical safety of firefighters and personnel.

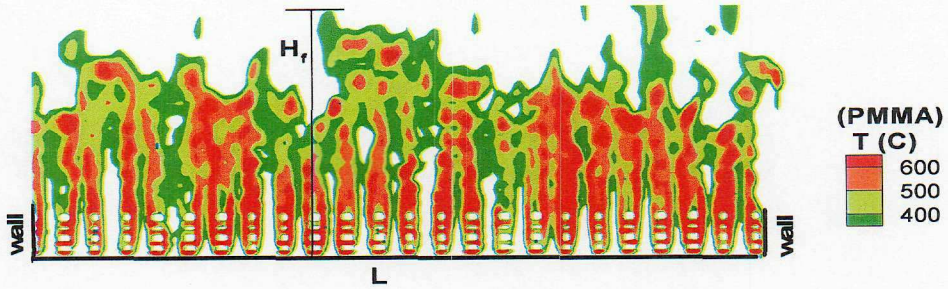

Figure 5. Temperature contours on the median plane perpendicular to racks

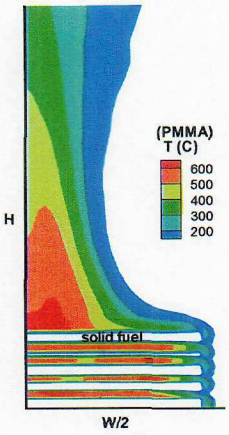

Figure 6. Temperature contours in cross-section parallel to racks

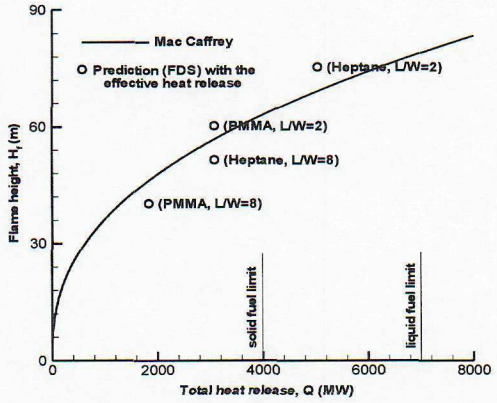

Figure 7. Comparison between correlation and prediction for flame height

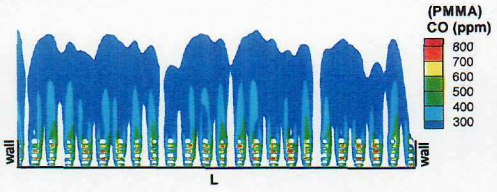

Figure 8. CO concentration contours

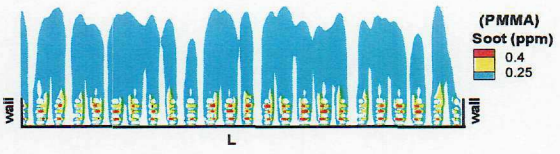

Figure 9. Soot concentration contours

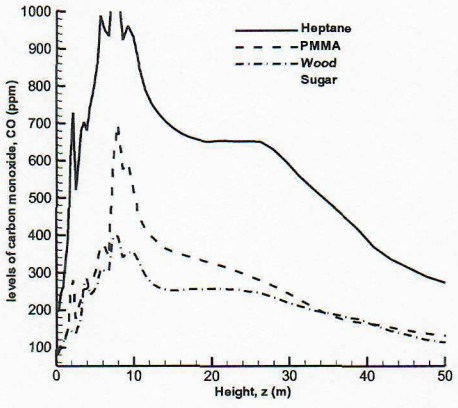

Figure 10. Evolution of the CO concentration with height

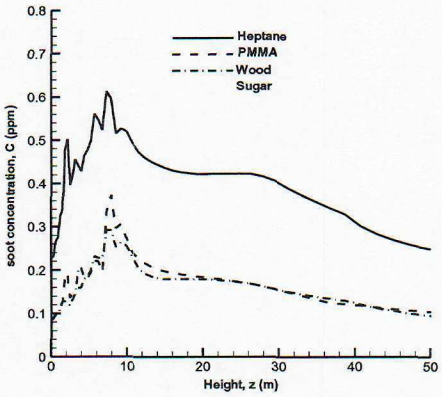

Figure 11. Evolution of the soot concentration with height

The predicted soot and CO concentrations contours on the median plane for PMMA are presented in Figures 8 et 9. Variation of CO and soot concentrations with height for four different materials, such as heptane, PMMA, wood and sugar is presented in Figures 10 and

11. In general, for hydrocarbons fuels, a large fraction of the fuel mass is converted to soot, and the soot introduced is allowed to absorb radiant energy. Thus, the soot generation rate is assumed to be 10% of the consumption rate for heptane, 2%for PMMA, and 1% for wood and sugar. In a warehouse, fuel-rich conditions for liquid hydrocarbons fuels (heptane) result in large concentrations of CO (1000 ppm) and soot (0.04 ppm) due to a significant decrease of combustion efficiency (about 0.3). It should be noted that inhalation of carbon monoxide is the main cause of fire fatalities, and air pollution. The mass flow rate in the plume at a particular elevation consists almost entirely of air entrained at lower elevations, resulting in an increase of the vertical velocity up to 30 m/s for L/W=8 and 50 m/s for L/W=2. CO and soot formed during combustion can be transported up to a height of 30-50 m by the buoyant plume through the vertical convection process. Such fires interact strongly with the vertical distribution of wind and temperature in the atmosphere. Moreover, the ambient wind and temperature fields must play a significant role as they do in the downwind smoke dispersion. Typically, much longer length scales than plume height intervene for consideration of fire plume dispersion problems. Depending on various parameters, remaining concentrations of fire gases and soot may be a source of concern at ground levels for environmental reasons.

Analytical approach

Despite this knowledge however, the complexity of the problem is such that a general CFD solution encompassing realistic, arbitrary conditions remained intractable. Fire safety design has been highly reliant on prescriptive rules in warehouse codes which specify the maximum allowed distance to a fire exposed personnel. The relevant fire safety design values shall be chosen so as to cover the credible worst-case scenario. INERIS has developped an analytical software, FNAP [3] based on the flame solid concept which permits to investigate easily a large number of events. This code specifies only some parameters, such as radiation intensity (ϕ_0) from flame, transmission in air (τ) and adds the relevant view factors (F) to obtain the local heat flux,

$$\phi = \phi_0 F \tau \qquad (kW/m^2) \tag{15}$$

As shown in Figure 4, the warehouse fire is rather similar to a cone with a rectangular warehouse base. For the perpendicular sides to racks, the flame shape can be considered as a fire wall with a surface of $L_{ob} \times L$ m^2 where L_{ob} is the oblique side of the cone, given as :

$$L_{ob} = \sqrt{(0.5 \times W)^2 + H_f^2} \qquad (m) \tag{16}$$

For the parallel sides to racks, the flame shape can be considered as a triangular fire wall with a surface of $0.5*H_f*W$ m^2. The volume of the cone with a rectangular base can be obtained as :

$$V_{cone} = 0.5\, W \times H_f \times L \quad (m^3) \tag{17}$$

The warehouse walls can be accounted for by blocking portions of the radiation through the reduction in the cone volume. The radiation intensity from flame is obtained by,

$$\phi_0 = \frac{\chi_r \chi_c \dot{Q}_c}{S_f} \qquad (kW/m^2) \tag{18}$$

According to FDS simulation, the maximum effective heat release generated by a warehouse fire with a surface of 7500 m^2 can reach to 3000 MW for a solid material (PMMA), and 5000 MW for an hydrocarbon fuel (heptane), which account for about 30 percent of the theoretical total heat release (that is, $\chi_c = 0.3$). In FDS code, the radiative fraction, χ_r, is assumed to be 0.35 for the large-scale fire. For L/W=2, the warehouse fire can be simulated by a cylindrical pool-like fire with an equivalent diameter obtained from,

$$D_{eq} = \sqrt{4V_{cone}/(\pi H_f)} \quad (m) \qquad (19)$$

The equivalent flame surface is calculated by,

$$S_f = 0.5\pi D_{eq}^2 + \pi D_{eq} H_f \quad (m^2) \qquad (20)$$

However, for L/W=8, the cone with a rectangular warehouse base, as shown in Figure 4, shall be considered for the view factors (F). The flame surface corresponding to the cone est,

$$S_f = 2L_{ob}L + LW + WH_f \quad (m^2) \qquad (21)$$

It is important to understand how much radiant energy is emitted by flame. The radiation intensity calculated from Eq. (18) is plotted in Table I for different products.

Table I. Radiation intensity for four diffrent products

ϕ_0 (kW/m^2)	Hydrocarbon products	Plastic products	Cellulosic products	feeding products
L/W=2	68	41	36	23
L/W=8	45	26	22	15

Once the parameters, such as the flame height, H_f, from the MacCaffrey correlation, the radiation intensity, ϕ_0, from Table I, and the view factors, F, from a cone configuration, are specified, the risk analysis software, FNAP [3] can be used for determining the location for the physical safety of the humans where the heat flux from flame should be lower than 3 kW/m^2 for personnel and 5 kW/m^2 for firefighters.

Conclusion

According to this study, the flame spread velocity is found very fast along the rack, and increases with the rack height. The calculated mean flame height is about 3 times the pyrolysis (rack) height for L/W=8, and however, 7 times the rack height for L/W=2. For the rack fire, contribution of radiation is higher than 90%. As compared to the numerical results, the mean flame height is correctly determined by Mac Caffrey correlation.

However, there is still a lack in understanding in full details about how a rack fire is evolved spatially and temporally in a confined fire configuration. The results as presented here cannot yet be regarded as complete. It can therefore be stated, that despite the relatively simple analytical solution to achieve a fire safety design, they are inflexible and may lead to unnecessarilly expensive warehouses. It would be highly desirable to relate the burning rate to the total heat flux from the flame to the fuel surface. Also, future development should relate the soot generation rate to the local oxygen and temperature fields for determining the real radiative fraction.

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