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Large-scale fire suppression modeling of corrugated cardboard boxes on wood pallets in rack-storage configurations

Ning Ren*, Jaap de Vries, Xiangyang Zhou, Marcos Chaos[1], Karl V. Meredith, Yi Wang

FM Global, Research Division, 1151 Boston-Providence Turnpike, Norwood, MA 02062, USA

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ABSTRACT

In this study, the fire growth and suppression models in FireFOAM were validated for rack-storage commodities consisting of two solid fuels, namely corrugated cardboard boxes and hardwood pallets, which are referred to as Class 2 commodity. Validation experiments included two fire-growth and two fire-suppression configurations with different rack-storage array heights (3 and 5 tiers). In the suppression study, standard-response upright ceiling sprinklers (K-factor of 160 lpm/bar$^{1/2}$) were used. The time-resolved chemical heat release rates obtained from the experiments were used to validate the fire growth model. The observed sprinkler activations and fire-spread patterns were used to validate the suppression model. This study identified that lateral flame spread is primarily enabled by flames impinging on the commodity's bottom surfaces. This study also showed that obstructions, such as wood pallets, can significantly impede convective and radiative heat transfer to the underside of the commodity, reducing the lateral flame spread rate. Fire-suppression modeling revealed that both surface water transport and lateral flame spread rates are important when predicting fire-suppression behavior. Therefore, as the rack-storage array height increases, so does the water transport time, which results in the fire becoming more difficult to control. Likewise, as the lateral spread rate increases, e.g., as occurs in the absence of wood pallets, fire-suppression also becomes more difficult.

1. Introduction

Fire is the leading cause of industrial property loss. Understanding the fire spread and suppression mechanisms can help improve the performance of protection systems and reduce fire damage. Full-scale fire suppression tests are the basis of most industrial fire protection guidelines and standards. Due to the wide spectrum of real world fire scenarios, evaluating the fire protection performance with full-scale tests cannot be conducted for each case. One effective approach is to use a physics-based, computational fluid dynamics (CFD) model for assisting the design of full-scale tests and extrapolating test results to wider scenarios. In addition, CFD models can help gain insights into suppression physics, where full-scale tests cannot provide detailed information due to the challenges with instrumentation and high costs.

In fire protection engineering, commodity storage is classified into different categories according to their burning behavior. One of the simplest and most commonly used standard commodities is Class 2 [1], which represents a low-hazard category of cartoned commodities found in industrial storage facilities. The Class 2 commodity consists of three nested, double-wall, corrugated-cardboard boxes (1.07 m×1.07 m×1.07 m) surrounding a thin metal liner. The boxes are placed on top of a hardwood pallet. Other standard commodities include Cartoned Unexpanded Plastics (CUP), Cartoned Expanded Plastics (CEP), etc. [1]. All these standard fuels have similar physical geometry, use identical wood pallets for support, and have other materials packaged inside the cardboard boxes. The first surfaces involved during a fire would be the exposed hardwood pallet and cardboard surfaces. Therefore, developing a CFD fire-suppression model targeting Class 2 commodity would be precursory to developing a CFD model capable of predicting the fire suppression behavior of some of these more complex fuels.

Fire growth and suppression modeling of the Class 2 commodity requires accurate sub-models of the following key physics. The first one is the fire dynamics, which has been studied extensively [2,3]. Many CFD models, such as NIST's Fire Dynamics Simulator (FDS) [4] and FireFOAM [5], can model the gas phase combustion and fire induced flow with reasonable accuracy. The second set of required physics is the flame-to-wall heat transfer [6,7] including radiation and convection. Chatterjee et al. [8] and Chen et al. [9] developed soot/radiation models for radiative heat transfer. Ren et al. [10] quantified the radiative/convective heat flux components using wall-resolved Large

* Corresponding author.
E-mail address: ning.ren@fmglobal.com (N. Ren).
[1] Materials Science Division, Energetic Materials Center, Lawrence Livermore National Laboratory, 7000 East Avenue, P.O. Box 808, M/S L-288, Livermore, CA 94550-9234, United States.

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Nomenclature

A	pre-exponential factor (s^{-1})
C	coefficient; c-factor $(m/s)^{1/2}$
c_p	specific heat (J/kg K)
E_a	activation energy (J/mol)
ΔH_{py}	heat of pyrolysis (J/kg)
h	heat transfer coefficient (W/m^2 K); sensible enthalpy (J/kg)
I	absorbed radiant heat flux (kW/m^2)
k	thermal conductivity(W/m K); kinetic energy (m^2/s^2)
n	Reaction order
q	heat flux (W/m^2)
R	ideal gas constant (J/mol K)
RTI	thermal response index $(m\ s)^{1/2}$
r_s	stoichiometric ratio
S	strain rate (s^{-1})
s	length (m)
T	temperature (K)
T_{link}	sprinkler link temperature (K)
t	time (s)
u	velocity (m/s)
Y	species mass fraction

Greek

ε	emissivity; energy dissipation rate (m^2/s^3)
ρ	density (kg/m^3)
ω	reaction rate (kg/m^3 s)
ν	kinetic viscosity (m^2/s)
χ	radiant fraction
Δ	filter size (m)

subscripts

$_{sgs}$	subgrid quantity
$_{v}$	virgin material
$_{0}$	Initial value

Eddy Simulations (LES). An empirical convective heat transfer model for coarse-grained modeling has been applied by Wang et al. [11] for modeling rack-storage fires. The third key set of physics is the solid-phase pyrolysis. Chaos et al. [12,13] studied fire properties of corrugated cardboard and wood using data from a bench-scale Fire Propagation Apparatus (FPA) and a Shuffle Complex Evolution (SCE) optimization method [14]. The final component is the water-based suppression physics, which includes spray atomization, spray dispersion, and water film flow transport. Zhou et al. [15] characterized sprinkler sprays and provided information for spray dispersion modeling. Meredith et al. [16,18] developed models for thin-films on solid surfaces, which include interfacial heat transfer, evaporation, and surface tension effects.

Meredith et al. [19] and Wang et al. [11] conducted comprehensive, industrial-scale, fire-suppression modeling of a three-tier-high Class 2 commodity (without pallets). Their work demonstrated the capability of the model and established a fundamental approach for simulation of fire suppression of rack-stored commodities. The current study is an extension of this previous work [11,19] by including wood pallets and storage heights up to five tiers, to provide a more comprehensive evaluation of the model. Two free-burn configurations (wherein no water is applied) and two fire-suppression configurations using ceiling sprinklers were modeled in this study. The objective of the current work is to understand the fire spread mechanisms and identify key parameters for fire suppression evaluation.

2. Model description

2.1. Gas-phase model

This study used FireFOAM [3,5], a large-eddy-simulation (LES) fire modeling tool based on the OpenFOAM [20] toolbox. In the gas phase, FireFOAM solves filtered transport equations for sensible enthalpy, species mass fractions, and the fully-compressible Navier-Stokes Eq. (3). The sub-grid kinetic energy and dissipation rate are calculated using the k-equation turbulence model [21,22] given by

$$\frac{\partial(\overline{\rho}k_{sgs})}{\partial t}+\frac{\partial(\overline{\rho}k_{sgs}\tilde{u}_i)}{\partial x_i}-\frac{\partial}{\partial x_i}\left(\overline{\rho}(\nu+\nu_{sgs})\frac{\partial k_{sgs}}{\partial x_i}\right)=-\overline{\rho}\left(\frac{2}{3}\left(k_{sgs}+\nu_{sgs}\frac{\partial\tilde{u}_k}{\partial x_k}\right)\frac{\partial\tilde{u}_i}{\partial x_i}-2\nu_{sgs}\tilde{S}_{ij}\tilde{S}_{ij}\right)-\overline{\rho}\,\varepsilon_{sgs}, \tag{1}$$

where the strain rate is $\tilde{S}_{ij}=(\partial\tilde{u}_i/\partial x_j+\partial\tilde{u}_j/\partial x_i)/2$, the sub-grid turbulent kinetic energy dissipation rate is $\varepsilon_{sgs}=C_e k_{sgs}^{3/2}/\Delta$ with C_e=1.048, the sub-grid turbulent eddy viscosity is given by $\nu_{sgs}=C_k k_{sgs}^{1/2}\Delta$ with C_k=0.03, and the filter size is $\Delta=(\Delta x\Delta y\Delta z)^{1/3}$. The combustion model uses the Eddy Dissipation Concept (EDC) [23] assuming a single-step, infinitely-fast, non-reversible chemical reaction, which is

$$\overline{\dot{q}_F'''}=\frac{C_{EDC}\overline{\rho}\,\varepsilon_{sgs}}{k_{sgs}}\min\left(\tilde{Y}_F,\frac{\tilde{Y}_{O_2}}{r_s}\right), \tag{2}$$

where the modeling coefficient is C_{EDC}=4. For sprinkler sprays, the major suppression mechanism is surface wetting and cooling. Flame extinction is a secondary suppression mechanism, and is not included in the current version of the model. Flame extinction will be addressed in our follow-up fire-suppression modeling studies.

The radiative heat transfer equation was solved by a finite-volume implementation of the discrete ordinate method given by

$$\frac{dI}{ds}=\left(\frac{\chi_{rad}\ \overline{\dot{q}_F'''}}{4\pi}\right). \tag{3}$$

In the studied fire scenarios, flames were attached to the wall surface. Most of the wall radiative heat flux originated from the nearby flames in the wall-normal direction. In the simulations, only sixteen rays at different solid angles were used for radiation calculations. Using a limited number of rays reduced the numerical costs while preserving accurate radiative heat flux predictions at the wall.

The radiation emission source within the gas phase was assumed to originate solely from the flame reaction zone with a fixed radiant fraction of the local heat release rate. The absorption of the participating media was neglected considering the short mean beam length within a typical rack-storage flue space (15 cm). The radiant fractions of the pyrolysates from both cardboard and wood were assumed to be 22% [24]. In the flaming zone, the convective heat flux was reduced as the fuel release rate increased to account for the ‘blowing effect’ in the boundary layer [11].

2.2. Pyrolysis model and material properties

The thermal decomposition of solid fuels was treated via a one-dimensional pyrolysis model [12] with a single-step Arrhenius reaction. The reaction, energy and mass conservation equations are as follows:

$$Virgin\rightarrow\frac{\rho_c}{\rho_v}Char+\left(1-\frac{\rho_c}{\rho_v}\right)Pyrolysate, \tag{4}$$