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An experimental study of complex fuel burning behavior with water application

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ABSTRACT

This work reports a series of small-scale experiments conducted to characterize the burning behavior of selected complex fuels with water application. The main objective of this work is to provide suitable data for the development and validation of fire suppression sub-models for commodities with multiple fuels and complex geometry (complex fuels). The water transport process and burning behavior of two representative complex fuels are examined using three fuel surface conditions including a regular-closed face (CF), a side-open face (SF) and a top-side-open surface (TF). The fuels are exposed to two water application rates at three different water application times with respect to ignition. The results of water collection rates under no fire condition show that the water transport is delayed in the open surface cases (SF and TF). In the free-burn experiments, the surface conditions are shown to have little impact on the fire growth rates. The results of the fire suppression experiments show that the water application time has the most significant impact on controlling the fire, and that the open-surface conditions tend to adversely affect the suppression outcome.

1. Introduction

A computational code, FireFOAM [1], based on the OpenFOAM framework has been developed recently at FM Global to model fire growth and suppression in large industrial scale fires. Such modeling effort has been aimed at helping reduce the number of expensive large-scale tests and generalize the test results. While good progress has been made in modeling simple commodities, such as Standard Class 2 [2], most fuels of interest in industrial fires are complex fuels. A complex fuel is defined here as a solid commodity that has multiple combustible materials and an intricate geometry with multiple surfaces that can be potentially exposed to fire and water [3]. Such complicated composition and geometry, which can change in the course of the fire, present a severe challenge for numerical models.

One difficulty arises because of the limited spatial resolution made possible by current computer capabilities, especially for modeling large-scale fire tests. Therefore, the multi-component nature and varying geometry of complex fuels cannot be resolved in detail by the computational grid. Sub-models are required to describe the chemical and physical processes that occur at sub-grid scales and cannot be modeled directly. Another challenge is that some underlying physics such as complex fuel pyrolysis with water application are not well understood, so that suitable numerical models become difficult to develop. Therefore, experimental studies are needed to guide the model development and to provide data for their validation.

Numerous experimental studies have reported fire growth and suppression behavior of complex fuels. Yu and Kung [4] developed velocity and temperature correlations for growing fire plumes in a rack storage configuration. Gollner et al. [5] examined a B-number based theory to predict burning rate of a single fuel load of standard plastic commodity. Xin et al. [3] conducted single pallet load characteristic-fuel-unit tests to gain insight into the burning behavior of complex fuels. In the studies with water application, Lee [6] reported extensive suppression tests of corrugated carton fires. Yu et al. [7] established empirical suppression correlations based on the results of Lee [6]. Hamins and McGrattan [8] conducted a series of experiments to characterize the suppression of rack-storage commodity fires involving a plastic commodity. Xin and Tamanini [9] quantified the critical delivered flux that can prevent fire growth for different fuels arranged in open frame double row rack storage configurations.

A multi-layer pyrolysis model has been developed in FireFOAM [10] to effectively simulate the global burning behavior of a complex fuel in free-burn fires. The current suppression model in FireFOAM [1] describes the process by accounting for: cooling of unburned surfaces by water; reduction in the surface heat transfer computed through coupling with the gas phase combustion model; water transport over flat fuel surfaces; and in-depth pyrolysis coupling heat transfer in the solid fuel with a thermal decomposition reaction. In the case of a cartoned plastic commodity, for example, this suppression model can represent the governing physical phenomena up to the point when the outer surface of the cardboard packaging is breached exposing the inner structure of the commodity, which, under water application, cannot be treated as a plane fuel surface. At this point one needs to describe the complicated interaction between the burning inner

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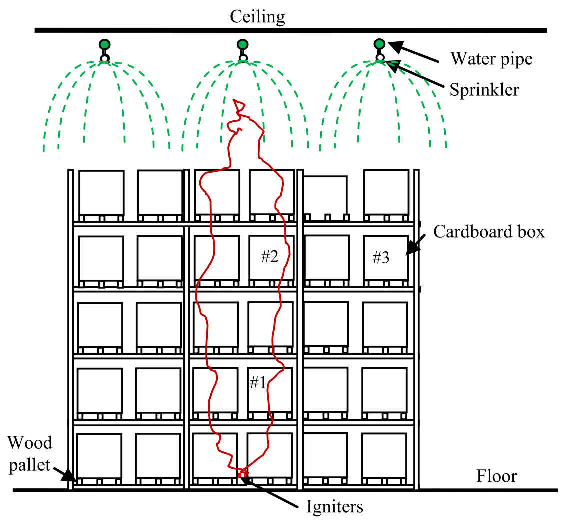

Fig. 1. Schematic of a typical 5-tier high rack storage fire.

structure of the commodity and water transport and cooling.

The objective of this study is to provide suitable data of water transport, fire growth and fire suppression with water application to the development of such a model. Following the free-burn test setup [3], the present work characterizes the burning behavior of a Characteristic Fuel Unit (CFU), e.g., a pallet load of a given complex fuel with water application. The basic design idea of the experimental setup is to reproduce a fuel structure similar to that of a rack storage assembly, while providing favorable conditions for quantitative measurements of heat transfer and water transport parameters.

2. Experimental setup

Fig. 1 shows a schematic of a large-scale, 5-tier high rack storage fire for illustrating the relative effect of fire heat transfer and water cooling on a pallet load of a cartoned commodity. The fire is assumed to be ignited in the center at the bottom of the fuel array. When the fire reaches a certain size, the ceiling sprinklers activate and deliver water to the top surface of the burning fuel. Most of the water delivered by ceiling sprinklers is expected to cascade downward along the exposed fuel surfaces. Due to the different distances of the different cardboard boxes from the fire plume and the sprinkler spray axis, each box can be exposed to various heating and cooling conditions. For example, Box #1, which is close to the fire origin, may receive higher heat fluxes than Box #2; however, Box #2 may get more water cascading down from the top of the fuel array; furthermore, Box #3 may experience very little heating and only get pre-wetted until the fire spreads to its location. With time, the external cardboard surface can burn out and the inside fuel can be exposed to fire. The sprinkler water can then flow into the box through the opened surface. The fire suppression process is expected to be dependent on the result of the complicated interactions of the flame heat transfer and the water flow through the exposed fuel surface.

To provide a controlled environment, the experimental design in this work employs a constant ignition source, several different water flow rates, as well as varied application times with respect to ignition. Cartoned Unexpanded Plastic (CUP) [2] and Standard Class 3 [2] commodities were selected as representative complex fuels. A pallet load of CUP has nominal dimensions of 1.07 m×1.07 m ×1.07 m and consists of eight cardboard cartons. Each carton is made of single-wall corrugated cardboard, and is filled with 125 polystyrene cups arranged in a 5×5×5 matrix separated by single-wall corrugated cardboard dividers. A Standard Class 3 commodity has the same geometry as the CUP, except that the polystyrene cups are replaced by paper cups. Subsequent descriptions of the test setup will only use the CUP commodity as an example. In the previous free-burning study [3], one test condition was to expose one surface of CUP to the fire and shield the other five surfaces using 13 mm thick Gypsum board. The HRR of CUP under this condition exhibited a steady-state burning period of nearly 450 s. The present work used the same fuel setup with one exposed fuel surface.

Fig. 2 shows a schematic of the experimental setup for the complex fuel burning with water application and a photo taken during a test. To model a constant ignition condition, a propane-fueled sand burner was placed below the exposed surface of the fuel assembly and was kept on burning throughout the experiment. The propane flow rate to the burner was 93 Lpm and the chemical HRR was measured to be 130 ± 5 kW. A flow meter was used to monitor the flow rate of propane to the burner. The effective length of the sand burner was 1.07 m to cover the width of the fuel assembly. To model the water delivery, a tube water applicator was placed above the fuel assembly. The applicator was made from a copper tube (13 mm diameter) with 119 small holes (1.2 mm diameter) distributed evenly along the tube length. The effective length of the water applicator was also 1.07 m. Water was supplied to the tube applicator from both ends. Two water flow rates of

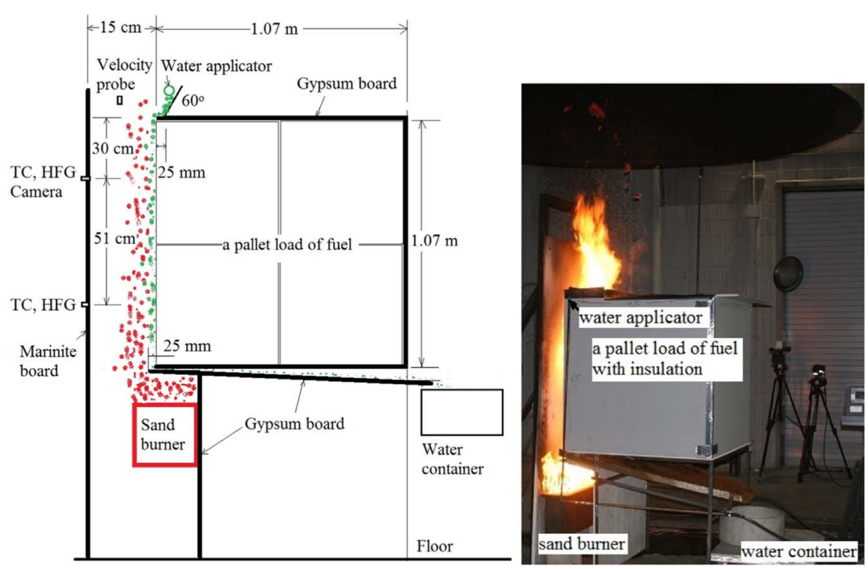

Fig. 2. The side view of a conceptual design and a photo of the test setup under the 1 MW calorimeter.