FIRE SUPPRESSION PHYSICS FOR SPRINKLER PROTECTION

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ABSTRACT

Fire protection using sprinklers is one of the most cost-effective and reliable technologies available for fire safety and property protection design. Given the complexity associated with sprinkler protection, codes and standards have mostly been developed by conducting large-scale tests that are costly and often difficult to generalize. Numerical modeling has long been pursued as a cost-effective method that can supplement large-scale testing and give valuable physical insights when interpreting test data. Therefore, there is a strong and continued interest in the fire community regarding the development of predictive fire modeling capabilities. For large-scale fires with sprinkler protection, the interest appears to be focusing on a new-generation computational fluid dynamics (CFD) tools. The key issue in achieving this objective is to understand and model the most important physical phenomena associated with sprinkler protection. To address this issue, FM Global initiated a sprinkler technology program, focusing on the study of fire suppression physics for sprinkler protection. This program is part of a large effort toward developing a CDF code - FireFOAM (http://www.fmglobal.com/modeling), aiming at predicting fire growth and suppression with sprinkler protection. The present paper discusses exploratory work in this program, including measurements of sprinkler spray properties and spray penetration, water absorption by porous fuels, surface and corner water flows, water transport in rack storage, and water evaporation and fire suppression experiments in single-wall and parallel panel configurations. This paper will also introduce ongoing experimental studies and future plans to guide model development and to validate modeling results, with the ultimate goal of simulating sprinkler protection of commodities in the real world.

INTRODUCTION

For fire safety and property protection design, sprinkler protection has long been recognized as one of the most cost-effective and reliable technologies available. When adequate sprinkler protection is provided, property losses in commercial and industrial facilities due to fires can often be greatly reduced. This can be seen from Figure 1, which shows the averaged US dollars per reported fire loss based on FM Global's experiences. With proper maintenance, a sprinkler system can be used for many decades, resulting in a desirable solution for fire protection with a high level of reliability.[1] A recent study further shows that sprinkler protection can help improve the sustainability of buildings.[2]

Given its importance to property loss prevention, research and development of sprinkler technology has been carried out for more than half a century. Due to the complexity associated with sprinkler protection, requirements and standards have mostly been developed by conducting large-scale tests that are costly and often difficult to generalize. Past work on sprinkler technology was reviewed by Chen[3] and recently by Kung[4]. In brief, early work on sprinkler technology has largely relied on full-scale tests to evaluate the effectiveness of sprinkler systems to protect against fire hazards. Since the 1980s, the development of Early Suppression Fast Response (ESFR) sprinklers promoted the invention of key concepts of sprinkler technology and research, e.g. Response Time Index (RTI), Actual Delivered Density (ADD) and Required Delivered Density (RDD). The result of this development and the wide usage of ESFR sprinklers greatly expanded the scope of sprinkler protection in commercial and industrial facilities. In the new millennium, however, a rapid change of industrial technologies and practice, especially in storage facilities such as warehouses, has created new challenges to current sprinkler technology. First, with increasing applications of sprinkler protection, demand has grown tremendously for evaluating sprinkler system performance for specific fire scenarios. Second, many evaluations appear to be parametric studies of protection scenarios similar to others tested in the past. Third, ever increasing storage height and fire hazard level challenge the capabilities of modern fire testing facilities worldwide. Therefore, new methodologies are needed to study sprinkler protection systems, besides traditional full-scale testing.

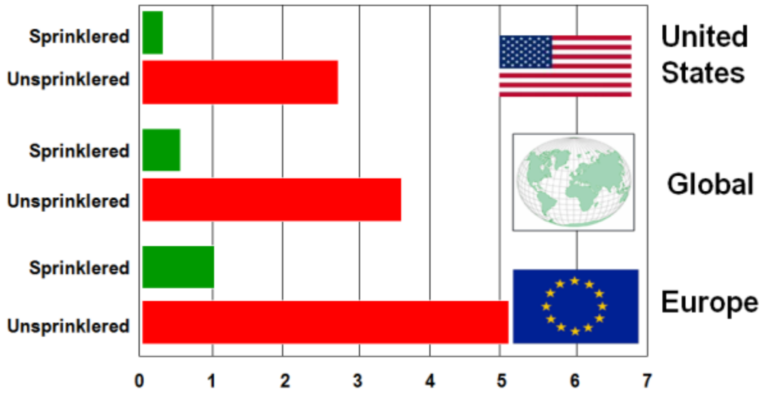

Figure 1 FM Global Loss Experience (US $ millions, average per reported fire loss).

A possible method to address this problem is to conduct tests at reduced scales, i.e., scale modeling. However, this solution is challenging in practice due to difficulties of scaling down both fuel and sprinkler, while maintaining the controlling physics of fire growth and suppression processes. A variation of rigorous scale modeling is the methodology of commodity classification, i.e., testing suppression behavior using a small module of the fuel array compared to the real fire scenario, in order to obtain classification of the fuel (commodity) of interest. This type of method was first developed by Chicarello and Troup[5] in 1990, and recently revisited by Xin and Tamanini[6] where a new scheme was proposed. The commodity classification method is essentially a compromise between the rigor of the scale modeling technique and the accuracy of the test results, which can be useful within its scope of applications. There are also small-scale experimental studies[7,8] based on B-number theories that try to address the commodity classification problem. However, it appears that further development of this theory for practical applications depends on incorporating important physics and practical geometries, such as flame radiation and water transport in rack storage configuration, when aimed at commodity classification for sprinkler protection.

Parallel to experimental methods, numerical modeling has long been pursued as a cost-effective approach that can supplement large-scale testing and give valuable physical insights when interpreting test data. For example, the Fire Dynamics Simulator (FDS) developed by National Institute of Standards and Technology (http://fire.nist.gov/fds/) and FireFOAM being developed by FM Global (http://www.fmglobal.com/modeling). Therefore, there is a strong and continued interest in the fire community on the development of predictive fire modeling capabilities of large-scale fires with sprinkler protection through the use of new-generation computational fluid dynamics (CFD) tools. Past work in numerical modeling of fires has laid the foundation of addressing the suppression problem, e.g., investigations of sprinkler spray interactions with fire plumes[9,10,11] simulations of steady-state buoyant plumes[12,13,14,15,16] and modeling of heat and smoke transport in enclosure fires.[17,18]

However, in the most widely used numerical fire code – FDS,[19] the developers implemented a global quantity based suppression model even though local variables such as heat and water fluxes are available from numerical simulations. This suggests that the lack of knowledge in basic understanding of fire suppression physics for sprinkler protection is common to the entire fire community. Therefore, a technical approach is needed to address this important issue for both fire safety and property protection purposes, given the increasing applications of sprinkler protection in various buildings.

TECHNICAL APPROACH

The key issue in numerical modeling of sprinkler suppression is to understand and model the most important physical phenomena. As shown in Figure 2, the key phenomena include sprinkler spray formation and characterization of initial spray conditions; spray and fire plume interactions and spray and ceiling flow interactions; water transport on solid commodities and interactions among water flow, solid fuel and flames. Based on a review of past work, it appears that water transport and interactions with flames and solid fuels as well as characterization of sprinkler sprays have higher priorities than others, since we have the least amount of knowledge for these phenomena.

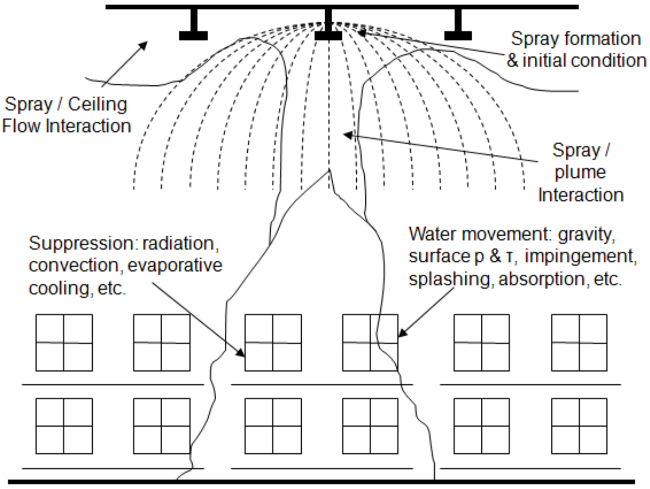

Figure 2 Key phenomena in fire suppression using sprinklers.

In order to understand the key suppression physics for model development, FM Global initiated a sprinkler technology program, focusing on the study of fire suppression physics for sprinkler protection. The basic technical approach is to study each of the key phenomena mentioned above through experimental studies, and develop a numerical model to include these key physics. The sprinkler technology program has focused on experimental work assisting model development as well as providing data for model validation. The present paper discusses exploratory work in the sprinkler technology program, including measurements of sprinkler spray properties and spray penetration, water absorption by porous fuels, surface and corner water flows, water transport in rack storage, and water evaporation and fire suppression experiments in single-wall and parallel panel configurations. This paper will also introduce ongoing experimental studies and future plans to guide model development and validate modeling results, with the ultimate goal of simulating sprinkler protection of commodities in the real world.

NUMERICAL MODELS

The framework of FireFOAM is based on an open source code OpenFOAM (http://www.openfoam.org). FireFOAM integrates the governing equations for gas, liquid and solid phases that are solved numerically on non-structured grids using parallel computation. The basic governing equations for the gas phase include mass, energy and momentum transport as well as the ideal gas law.[16] For the solid phase, a single-step pyrolysis model provides mass conversion from solid fuel to gaseous fuel, while a one-dimensional heat transfer equation keeps track of the energy flux in the solid fuel.[20] At this moment, geometry changes such as fuel burnout and collapse have not been included. For the liquid phase, the droplet transport of sprinkler spray is described in a Lagrangian scheme, while the film transport of water surface flows on solid fuels includes mass, energy and momentum balances.[21,22] As illustrated in Figure 3, the surface water flow can be either a continuous film or discrete rivulets. However, given the range of the water film/rivulet thickness for sprinkler applications, which is often less than 1 mm, both films and rivulets can be described by thin-film transport equations, with special treatment along rivulet contact lines.[21,22]

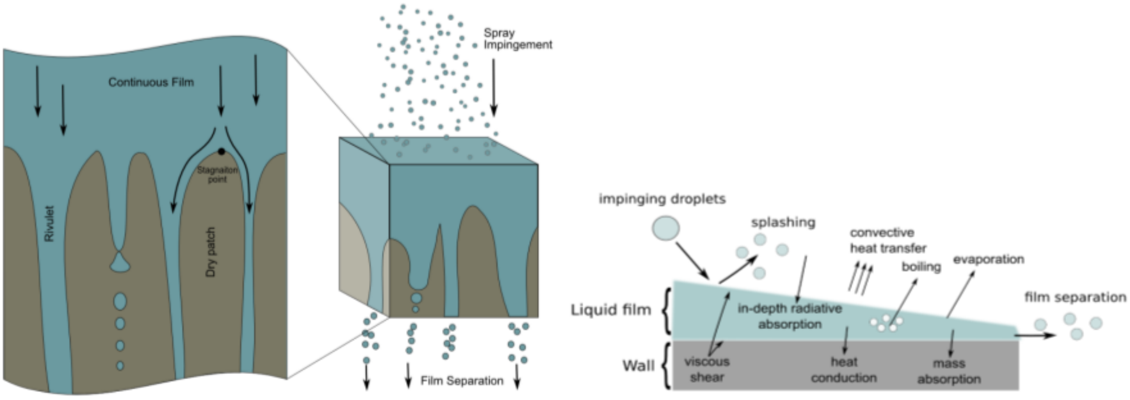

Figure 3 Illustration of numerical modeling framework for water transport and interactions.

The key physics for sprinkler suppression are described in the source terms of the film transport equations. For the mass balance, the key source terms include droplet impingement, water splashing, evaporation, film separation and water absorption by porous fuels. For the energy balance, the dominant source terms are incident radiation from the flame and heat conduction to the fuel in addition to all sensible heat associated with the source terms in mass transport. For the momentum balance, shear stress terms on the liquid and solid interface as well as all the source terms in the mass balance are important, while the shear stress on the liquid and air interface is often negligible in buoyancy-dominated gas flows.

In order to model these source terms, experimental investigations are needed to help understand the controlling physics, as well as providing model validation data. These experiments were designed with increasing complexity so that separate phenomena and integrated effects can be evaluated.

EXPERIMENTAL STUDIES

The experimental studies can be categorized into three groups: water transport on fuel surface under no-fire conditions; water, flame and fuel interactions under simple geometries; and water-based fire suppression in complex geometries. More details of the experiments discussed here can be found in Refs. 23, 24, 25 and 26.

Characterization and simulation of initial sprinkler sprays

Figure 4 shows the measurements of sprinkler spray fluxes (left) and corresponding FireFOAM simulations with given initial conditions based on experiments. The spray initial conditions were measured using shadow imaging in the near field (~ 0.6 m) where the water jets from the sprinkler orifice have just broken into discernable droplets. In the far field, e.g., 3.05 m below the sprinkler, the water fluxes were measured using a line of containers under steady-state conditions. The water flux simulation using FireFOAM (right panel in Figure 4) was conducted for a K-205 sprinkler under 3 bar operating pressure. It appears that the simulation provides reasonable predictions under no-fire conditions. Further evaluation of interactions between spray and fire plume will be carried out using ADD test data discussed later in this work, and a series of dedicated laboratory-scale experiments using a hot air plume simulating the fire source.

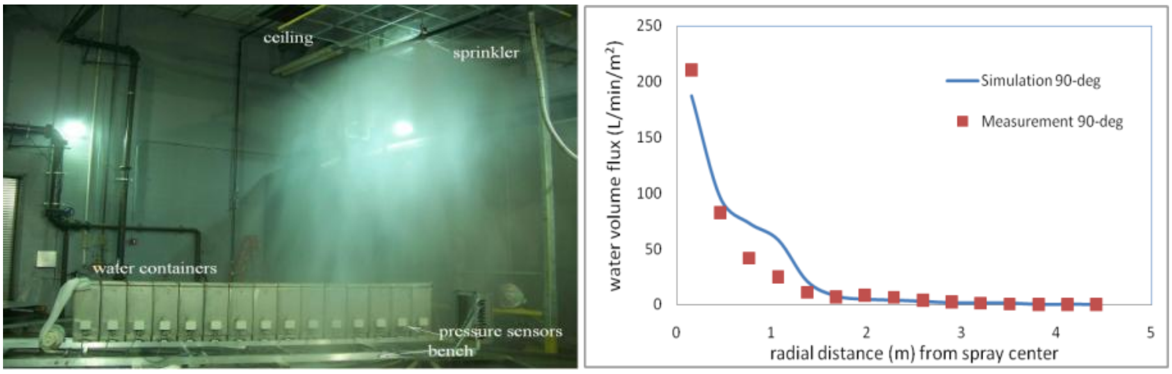

Figure 4 Measurements and simulations of initial sprinkler spray conditions.

Water transport on fuel surface under no-fire conditions

When there is no fire, water can flow on solid fuel surfaces in the form of films or rivulets, can be absorbed by porous fuels and can separate from fuel surfaces around corners before reentering the gas phase as droplets. Of course, these phenomena can also happen in the presence of fires. However, it is convenient to obtain a basic understanding of these phenomena under no-fire conditions.

Water absorption by solid fuel can occur for porous/cellulosic fuels such as corrugated paper board. Figure 5 shows measurements of water absorption under different water temperatures. The amount of water being absorbed increase with time as ~ $t^{1/2}$, as well as with water temperature. The scaling law of $t^{1/2}$ is consistent with previous work by Jayaweera and Yu.[27] However, a simple analysis shows that the increase of absorption with temperature can not be explained by the change of material properties such as water viscosity and surface tension. Regardless of the impact of water temperature, the majority of surface water flow runs over the surface of corrugated cardboard, and the absorbed portion is relatively small.

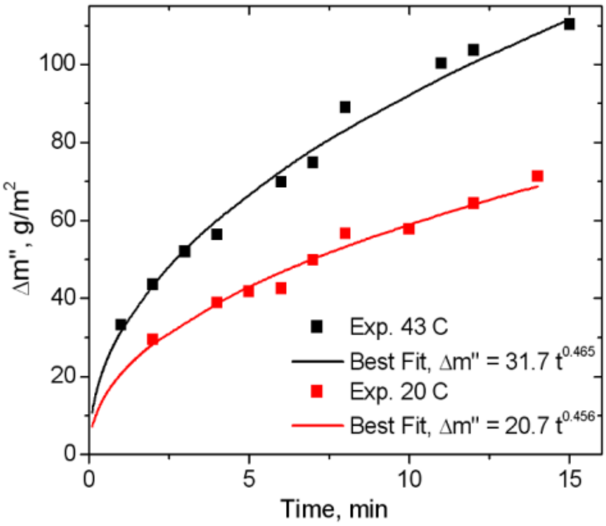

Figure 5 Water absorption by corrugated cardboard under different temperatures.

For water running over the fuel surface, one of the basic flow scenarios is vertical surface flow. The film thickness of vertical surface flow can be measured using a triangulation method on laser-reflection signals.[23] This technique can also be applied with two probes at a fixed separation distance to yield velocity measurements. The results show that the film flows are basically laminar within the range of water flow rates relevant to sprinkler applications. The measurements also suggest that the film velocities at the free surface as well as averaged across the film agree reasonably well with calculations based on Nusselt's classic theory, as shown in Figure 6.

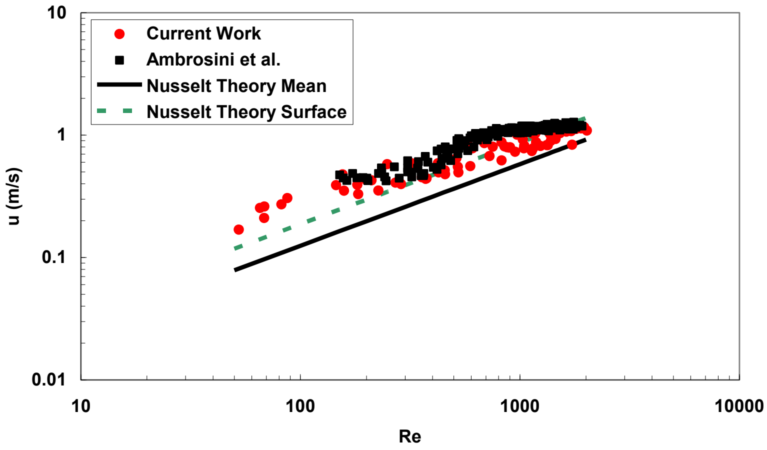

Figure 6 Film flow velocities on a vertical wall.

The thin-film flow can separate from the surface of a corrugated cardboard box upon rounding the bottom corner. This is a main transport mechanism in complex geometries for many engineering applications such as warehouse rack storage. Figure 7 shows that under different film Reynolds numbers, the location and trajectory of water separation can vary greatly, resulting in drastically different flow patterns.[23] Further analysis shows that a modified force ratio of inertia and gravity vs. surface tension can help determine the critical separation condition at the corner.[23]

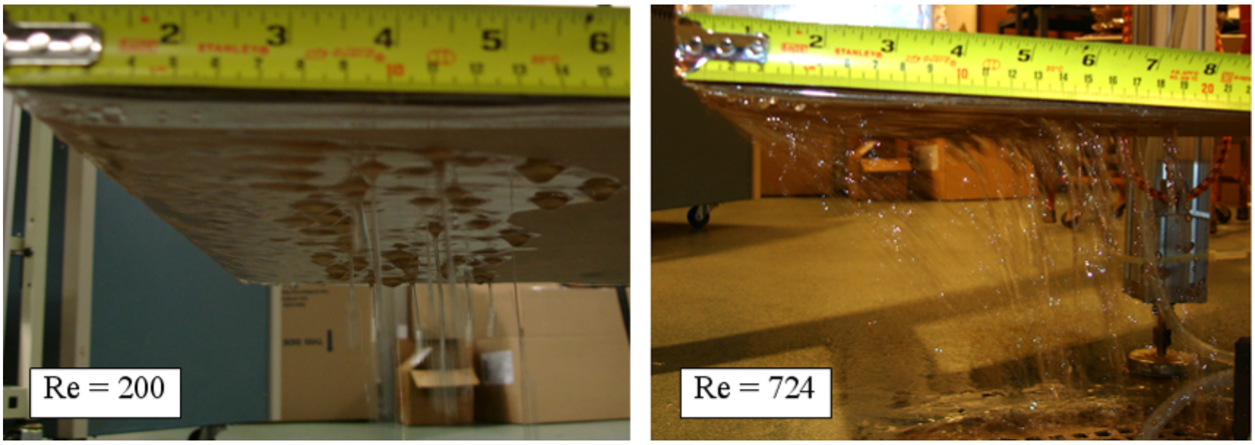

Figure 7 Flow patterns around a corner of corrugated cardboard.

The separate effects of water absorption, surface flow and corner flow are all important processes in the water transport of rack storage on solid fuels. Figure 8 shows that, under different water fluxes, the wetted-area fraction of the fuel surfaces can change significantly.[24] Considering the amount of water flowing over the fuel surface and the amount of energy required to evaporate the surface water, it appears that sprinklers control fire spread mainly through surface water flows, which can prevent the solid fuel from heating up. In contrast, control of fire by sprinklers has been traditionally thought to be the results of water absorption in the commodity adjacent to the burning zone.

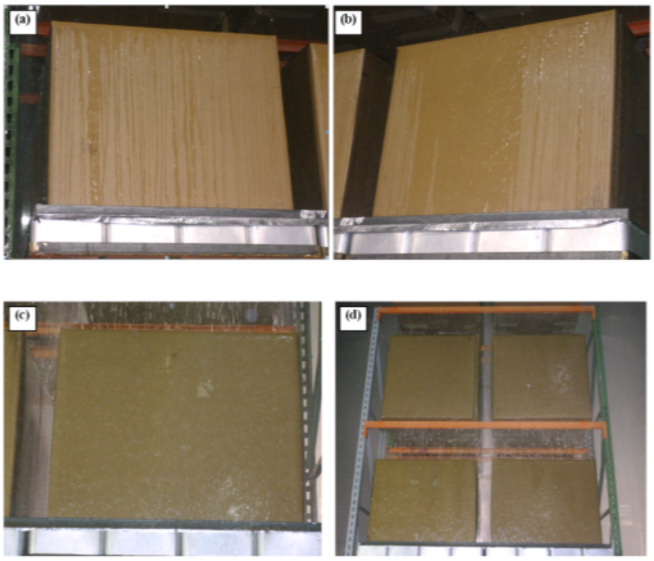

Figure 8 Water transport in rack storage under different flow rates: (a) 4 mm/min; (b) 12 mm/min; (c-d) 24 mm/min.

Water, flame and fuel interactions in simple geometries

Beyond a basic knowledge of water flow and transport under no-fire conditions, one needs to understand how flame heat transfer interacts with the surface flow of water and the pyrolysis and heat transfer in the solid fuel. These phenomena are complex in and of themselves. As a result, the experimental investigations need to be conducted under simple geometries to make the complexity of the problem manageable. Figure 9 illustrates the setup of single, vertical wall experiments for water evaporation and suppression.[23] Since it has been long established that flame radiation is the dominant mechanism for large fire propagation,[28] the flame heat flux is simulated using a radiant panel in the present work.

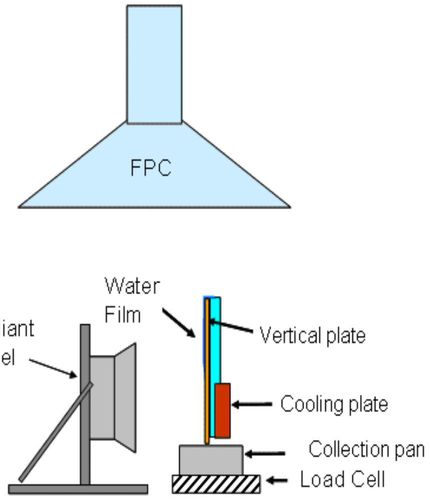

Figure 9 Single-wall experiments under constant radiation fluxes.

Both evaporation and suppression experiments can be conducted using the test setup shown in Figure 9. Some representative results are given in Figure 10. On the left are evaporation rates measured on vertical surfaces subject to different radiative heat fluxes. It appears that the evaporation requires a minimum amount of energy, equivalent to approximately 8% of the latent heat of inflow water. As the heat flux increases, the evaporation process becomes more efficient with the slope of the curve trending upward. On the right is the critical incident heat flux at which the vertical film flow changes into rivulets on a 41 cm × 46 cm area of Aluminum panel with insulated back surface. Such results provide the data needed to evaluate numerical models so that the surface flow pattern can be simulated properly. Note that, the results in Figure 10 are specifically applicable to the experimental conditions in this work, and should not be generalized to arbitrary vertical surfaces.

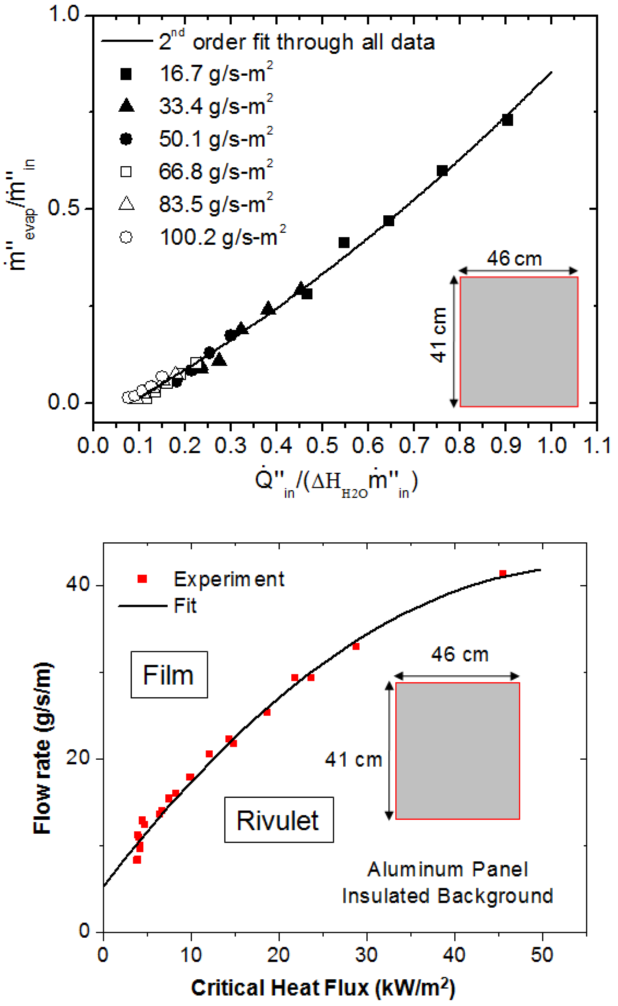

Figure 10 Results of single-wall experiments: evaporation rate (left) and flow transition (right).

In the single-wall experiments, the flame heat transfer from fires is simplified as a constant heat flux. Consequently, these experiments can assist validating interactions of the water flow and the solid fuel. In order to include flame heat transfer into the model validation, we selected parallel panel fires subject to water surface flow. This geometry is still quite simple compared to many engineering applications such as rack storage. Figure 11 illustrates the fire burning behaviors with water applied on both panels prior to ignition. Panel (a) and (b) show the early stage and a full-developed fire, respectively; panel (c) and (d) show that the fire can become quite non-symmetric occasionally due to small ambient drafts in the laboratory. As a result, global quantities such chemical heat release rate should be used for analysis, instead of point measurements from thermocouples and heat flux gauges. Exploratory tests using parallel panels show that this type of experiment can provide appropriate data for validating sub-models dealing with flame, water and fuel interactions in simple geometries.[24]

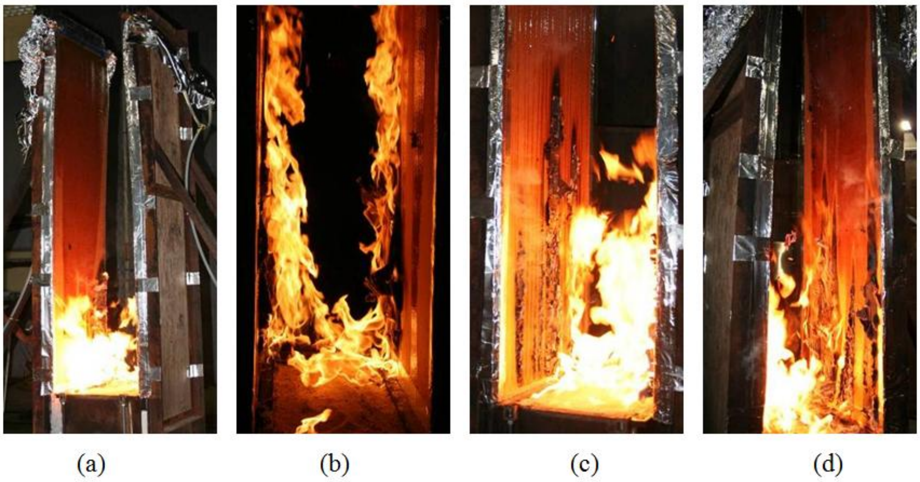
(a) (b) (c) (d)

Figure 11 Parallel panel suppression experiments.

Water-based fire suppression in complex geometries

Further validations of integrated effects for the model can be achieved by the use of ADD and Water Application Apparatus (WAA) tests. The ADD tests help evaluate model performance in calculating sprinkler spray penetration through the fire plume, while the WAA tests focus on fire suppression of rack storage with given water flux uniformly applied just on top of the fuel. Figure 12 shows these tests under a 20 MW calorimeter. On the left is a newly designed ADD apparatus that can produce up to 8 MW fires under sprinkler sprays; on the right is the test setup of 4×2, 3-tier rack storage of idealized Class 2 commodity. A pallet load of the idealized Class 2 commodity consists of a 3 layers of double-wall corrugated cardboard boxes with a metal linear inside. The boxes of the second column from the right in the fuel array were instrumented with thermocouples and plate thermometers. Some repeated measurements of heat release rates in the WAA tests are plotted in Figure 13, which suggests that this type of experiment can generate a variety of fire suppression scenarios, e.g., controlled and out-of-control, and provide quite repeatable data for model validation purposes.

Figure 12 ADD and WAA tests under 20-MW calorimeter.

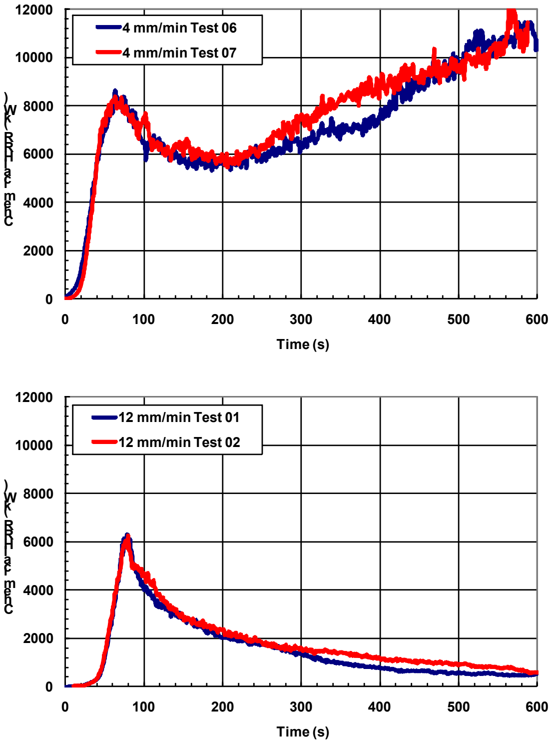

Figure 13 Heat release rates under different water fluxes for rack storage fires.

SUMMARY AND FUTURE WORK

The physics associated with fire suppression using sprinklers were investigated experimentally. A framework for numerical modeling of sprinkler suppression was presented and the key physics for model development were identified. Preliminary experimental studies were carried out, with an emphasis on evaluating the experimental methods. The key physics considered in this work include initial sprinkler spray characterization, water absorption by porous fuels, water transport in rack storage configurations, water evaporation on vertical walls with external radiation, and water suppression on vertical walls and parallel panels, as well as ADD measurements of spray penetration and WAA suppression tests of rack storage fires.

Overall, the experimental results showed that the measurement techniques examined in the present work are adequate to investigate the phenomena related to sprinkler-based fire suppression, and confirmed that qualitatively, the key physics considered in the modeling framework are appropriate to simulate fire suppression using sprinklers.

Based on this experimental study, future work will focus on detailed investigations of key suppression physics and repeated measurements for model validation. The key physics that require further study include film-to-rivulet transition, statistical characteristics of rivulets, water splashing in the vicinity of box edges and water flow over single and multiple corrugated cardboard boxes. To validate the suppression model, measurements are needed for water evaporation rates on vertical walls subject to external radiation, and heat release rates in parallel panel tests with pre-wetted fuels. Results from the suppression physics studies will be incorporated in the basic water transport model that has been integrated with the rest of the FireFOAM code. Validation of the integrated model will be then conducted using the single-wall and parallel panel experiments, and finally WAA tests and full-scale sprinkler tests using idealized Class 2 commodities in rack storage.

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