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Review Article

A review on fire suppression by fire sprinklers

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Shehu A Abdulrahman[1], Khaled Chetehouna[1], Axel Cablé[1,2], Øyvind Skreiberg[3] and Maurice Kadoche[2]

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Abstract
Water spray remains the most effective, environment-friendly and economical way of fighting accidental or unwanted fires, and this is largely due to its thermal characteristics. The mechanism of fire suppression by sprinkler water sprays is influenced by numerous factors, which have been the focus of years'-long and on-going research studies to improve its extinguishing performances. A comprehensive review study was carried out in this study to assess the level of technological know-how and current state of research in the field. A total of 2473 published articles spanning 50 years (i.e. 1970–2020) were systematically collected and analysed, whereby more than 100 relevant articles were selected and integrated in the discussion. In particular, the review focuses on research relating to the interactions of sprinkler sprays with flame, fire plume and hot surfaces, aiming to provide a better understanding of the phenomena involved in fire suppression.

Keywords
Fire safety, protective systems, sprinkler systems, fire suppression

Introduction

Fire sprinklers have played a tremendous role in the protection of life and properties. The first installation of sprinklers for fire protection dated back to 1874 by Henry S. Parmalee of New Haven, Connecticut, USA. Further improvement on his invention followed with the installation of the first automatic fire sprinkler system for the protection of his piano factory.[1] Subsequently, several researchers and inventors of fire sprinklers have contributed to the successes of what it is today. Fire sprinkler systems has evolved from the conventional

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[1]INSA Centre Val de Loire, Université d'Orléans, Bourges, France
[2]EXEC SAS, Goussainville, France
[3]SINTEF Energy Research, Trondheim, Norway

Corresponding author:
Khaled Chetehouna, INSA Centre Val de Loire, Université d'Orléans, PRISME EA 4229, 18020 Bourges, France.
Email: khaled.chetehouna@insa-cvl.fr

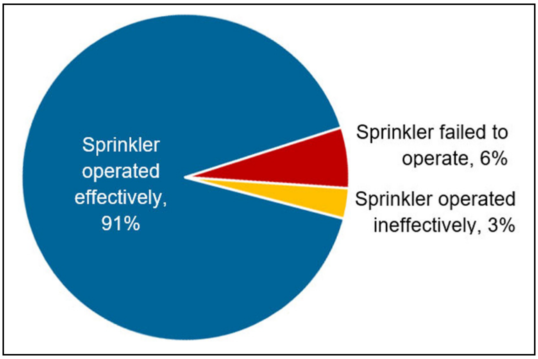

Figure 1. Sprinkler operation and effectiveness in home fires, modified after the study by Ahrens.[2]

sprinklers to automatic sprinklers system and SMART sprinkler systems, which continuously gather information, such as pressure, temperature and water presence, to measure the overall health of the sprinkler system. Accordingly, the report of the National Fire Protection Association (NFPA) attributed to Ahrens,[2] with an installed fire sprinkler system, 96% of fire spread was confined to the room against 71% of fires without any form of Automatic Extinguishing Systems (AESs). Automatic fire sprinkler is one type of AES and mainly uses water as the extinguishing medium.

Automatic fire sprinkler system comprises of several components in addition to the sprinkler head, which optimizes and atomize water droplet sprays and is capable of automatically releasing a measurable quantity of water when it detects presence of fire.[3] The overall purpose of any AES is to control a fire until firefighters arrive on the scene.[2,4,5] Beyond this objective, researchers have also reported remarkable improvements in fire sprinklers operation such as its effectiveness in smoke scrubbing, thermal radiation attenuation and complete extinguishing of fire.[5–7] Available statistics yet attributed to Ahrens and reported by the NFPA indicate that for 2010 to 2014 structure fires, sprinklers are present in an estimated average of 49,840 (10%) cases.[2] The report further reveals an overall effectiveness of 91% for sprinklers, which operated in fires large enough to activate them, as presented in Figure 1.

The NFPA provides regularly updated national standards for sprinklers design, installation, operation and maintenance; thus, supported by NFPA13, 14, NFPA750 codes and so on, fire sprinkler protection systems are continually being improved through further research and may, therefore, be preferred over the other AESs.[8] Although, experimental research in this field is greatly affected by repetition considering risk and cost involved,[9] the need to improve on fire protection systems design has been the focus of many researchers. However, the central focus of current research has been the interactions between the sprinkler sprays and fire. This will be discussed further in the subsequent sections of this article.

A number of research–reviews on fire suppression using water sprays have been reported; for instance, effectiveness studies (survey on potentials of automatic fire sprinkler systems in fire protection) was conducted as per literature[5,10] while, fundamental and applicative studies are reviewed in the literature[11–13] with extensive report on innovations (new fire protection technologies including hybrid systems, which use a combination of atomized water and inert gas to extinguish fires) and fire codes applications were presented in the literature[14–17] and modelling of fire suppression by sprinkler water sprays,[18,19] among many other approaches. While each respective article has uniquely attempted to discuss certain aspects of sprinkler development, to the best of this author's knowledge, none has treated the interactions of sprinkler water sprays and fire in compact form. Moreover, most of the available research–reviews deal with fire suppression by water mist systems. These systems use a mist of water, with droplets of lower diameters than sprinkler systems, typically of 50–300 μm, and are based mostly on fire suppression by oxygen displacement, and are mostly not considered in the present review, which is devoted to sprinkler systems.

In order to identify future developmental area and performance improvement for sprinkler fire suppression system, there is a need to review the progress that has been made on fire sprinkler technology over the last few decades. Essentially, it is recognized that one area that needed more understanding and has been gaining research attention includes the in-depth understanding of the interactions of sprinkler sprays with flame, fire plume and hot surfaces, allowing to better evaluate the conditions for swift fire suppression. In recent studies, both numerical and experimental approaches have been used to investigate this problem. Additional efforts by way of large-scale and small-scale sprinkler system fire suppression test have also been carried out. As a first approach, this review article is intended to highlight areas of improvement and research gaps in this field of study of fire suppression by sprinklers.

Fire protection, otherwise also known as fire 'suppression' or 'extinguishing', refers to the means by which the elements of fire (mainly, fuel, oxygen and heat) are removed and fire can be controlled. In order to evaluates and analyse the extent to which this topic is addressed by research literatures, research publications were searched and obtained on databases online using the keywords: sprinkler AND 'fire suppression' and sprinkler AND 'fire extinguishing'. The choice of keywords for the database search were made based on preliminary test of other keywords that have been used and which produced an inadequate number of articles, and in some cases articles irrelevant to the topic of this review. Articles were selected from the top five science publishers (Elsevier, Springer, Taylor & Francis, Sage, Wiley) based on the number of journals published.[20] After analysis of the publication years of the obtained articles, Figure 2 shows the resulting trends in the number of available articles on the topic for the past 50 years (i.e. 1970–2020). A total of 2473 articles were found for the period 1970–2020 (50 years). Using the keywords sprinkler AND 'fire suppression' in the search engines, 1531 articles were obtained over the full period, while 942 articles were obtained using sprinkler AND 'fire extinguishing' as second keywords. Observing the trends in publications by year from Figure 2, we can observe that the subject has been receiving adequate and continuous attention from researchers, implying that scientific challenges remain and that progressive development is being observed.

The publications were then read through in order to pinpoint relevant articles in the scope of this study, and discarding all other studies. The considered publications were selected according to the following criteria:

- Written in English to retain only articles of international impact;
- Specifically addressing sprinkler fire suppression systems;
- Non-peer-reviewed literature (e.g. technical reports, book chapter) were included only when rich in relevant and innovative content.

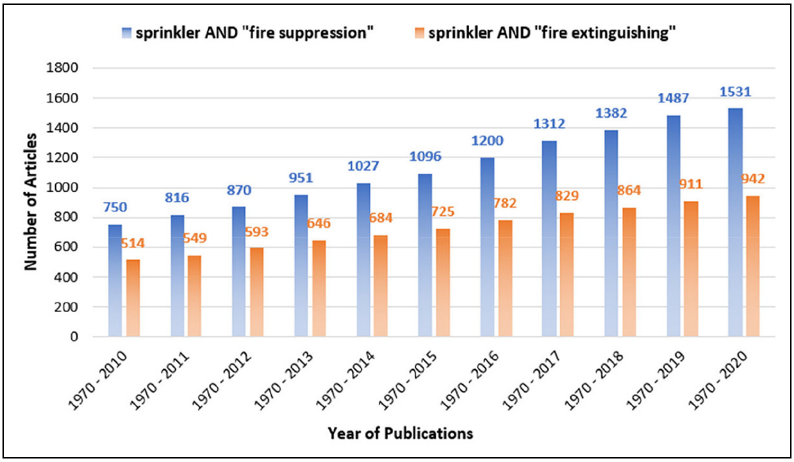

Figure 2. Progress of available articles by keywords for the period 1970–2020.

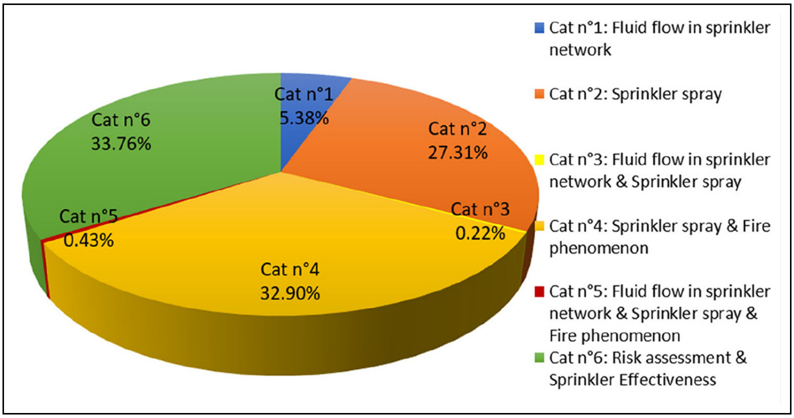

Figure 3. Classification of the number of selected articles related to the study of sprinkler spray and fire for 1970–2020.

The resulting relevant articles represents 22.1% of the total, and their distribution by research topics is shown in Figure 3, classified into six different categories: (1) the study on the fluid flow inside of fire sprinkler piping, which represented 5.38% of the available articles; (2) the analysis and characterization of fire sprinkler sprays representing 27% of the selected articles; (3) studies considering, in a combined manner, the impact of the flow in the piping and the sprinkler spray, representing only 0.22%; (4) literature works considering the interaction between sprinkler sprays and fire, accounting for 32.9% of the selected papers; (5) studies considering, in a combined way, the influence of the flow in the pipes, sprinkler spray and the fire phenomenon with 0.43%; and (6) risk assessment and general sprinkler activation and effectiveness studies, being the largest represented category with 34% of selected papers.

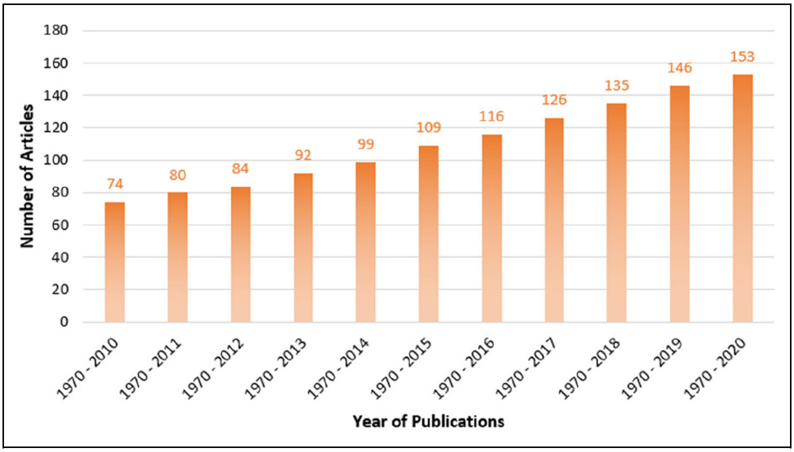

Figure 4. Number of relevant articles corresponding to the study of the interactions between sprinkler sprays and fire.

The advantages of using fire sprinklers over other firefighting techniques has been discussed in detail by many researchers;[1,2] however, more technical effort and scientific research in this field are required to utilize it optimally for the protection of buildings against unintentional fires. In the present study, the choice was taken to further focus the review on the research works related to the interaction of sprinkler sprays and fire, that is, category 4 in Figure 3. In fact, the phenomena related to this category incidentally play a vital role in fire suppression. Available literature comprised of reports, which studied the interactions of sprinkler spray and fire phenomenon and with emphasis on compartment fire, also providing information on the scale and type of experiment, spray characteristics, fuel configurations and size, enclosure (including ventilation) conditions and applicative case studies of real event and scenario. This category accounted to a total of 153 relevant articles. The distribution of these studies by year spans for the period 1970–2020 is depicted in Figure 4.

Generally, fire sprinkler systems are classified as either wet system or dry system based on their installation configurations. While sprinklers technology has evolved over years as conventional sprinkler, automatic sprinkler systems, early suppression-fast response (ESFR), SMART and so on and although sprinklers assessments studies (in the form of effectiveness study) have been well discussed and published,[5,14,16] there remains scientific challenges. These challenges concern, in particular, the understanding of the physical and chemical phenomena involved in the interaction between sprinkler sprays and fires, the respective contributions of these phenomena, and the evaluation and prediction of fire suppression.

Hence, in the present review article, phenomena involved in fire suppression by sprinkler are first presented (section ‘Sprinkler suppression phenomena’), and special focus is then given on studies related to the interaction of sprinkler sprays and fire plumes (section ‘Interaction of sprinkler spray and stratified hot air layer (fire plume)’), interaction of sprinkler sprays and flames (section ‘Interaction of sprinkler spray and flame’) and interaction of sprinkler sprays and hot solid surfaces (section ‘Interaction of sprinkler spray and hot solid surfaces’).

Sprinkler suppression phenomena

A fire practically goes through stages of growth; at the initial stage after ignition, a coherent buoyant gas stream rises above a localized zone: above the combustions zone and into surrounding uncontaminated air. Depending on the fire characteristics and the enclosure geometry, the buoyant gas stream becomes turbulent, subsequently flashover occurs. In the attempt to explain how sprinkler spray interacts with fire (in relation to the interactions with flame, fire plume and hot surfaces) and how these phenomena affect sprinkler fire suppression performance, remarkable contributions have been made on this subject, which are referenced accordingly in the subsequent sections, with particular emphasis on compartment fire.

Sprinkler sprays are characterized by several factors which dictates spray dynamics and penetration, droplets size distribution, spray flux density, spray angle and spray momentum[3,21,22] during fire suppression process. On the contrary, a fire can be described as involving a column of hot gases and combustion products which rises upwards above the flame zone. The buoyancy of the combustion products and hot gases decreases as the plume rises further away from the flame boundary, mainly due to the cooling effects of entrainment of surrounding air. This phenomenon has been the subject of many researches as will be reviewed in the current article. The plume (gradually, depending on the surrounding factors) losses its buoyancy when the plume temperature equals the surrounding air temperature. Interestingly, researchers have focused on developing a common method for the determination of the general fire plume characteristics, including geometry, temperature, gas flow speed and smoke quantity[19,23,24] as these factors greatly influence the understanding of fire behaviour and their interaction with water spray. However, four mechanisms have been identified as responsible for the interaction of sprinkler water sprays and fire, which are direct cooling (heat extraction) mechanism of burning material has an effect on both pyrolysis reaction, which produces flammable volatiles, and the diffusion flame reaction in the gas phase. Cooling of the smoke layer by thermal radiation attenuation is due to the presence of water droplets, and vapour reduces thermal feedback to the fuel and, therefore, decreases the burning rates and prevents ignition of the unburned fuel. While oxygen displacement mechanism affects mainly gas phase combustion reaction due to mixture dilution with water vapour.

For example, the heat transfer mechanism of fire suppression by the application of water sprays has been discussed in several studies. Droplet atomization and spray dispersion play an important role in the effective delivery of sprinkler water spray during fire suppression and extraction of heat from burning fuel. The dynamics of water droplet interactions with convective flow, drop evaporation and attenuation of thermal radiation was expressed by Heskestad[25] using the physical relations as follows

$$\frac{d^2\left(x_p/L\right)}{d(t/t_0)} = \left(\frac{t_0^2}{L}\right)g - \left(\frac{3B\rho v^{\frac{1}{2}}}{4\rho_w}\right)\left(\frac{3\beta\rho v^{\frac{1}{2}}}{4\rho_w}\right) \times \left|\frac{L}{t_0 u_0}\frac{d(x_p/L)}{d(t/t_0)} - \frac{u}{u_0}\right|^{\frac{1}{2}}\left(\frac{L}{t_0 u_0}\frac{d(x_p/L)}{d(t/t_0)} - \frac{u}{u_0}\right) \tag{1}$$

where x_p is the drop position coordinates, L is the characteristics length (m) of the enclosure, t is time (s), t_0 is the reference value of t (s), g is the acceleration due to gravity (m/s^2), B is a numerical constant, ρ is the gas density (kg/m^3), ρ_w is the water density (kg/m^3), v is the kinematic viscosity (m^2/s), u is the gas velocity (m/s) and u_0 is the reference value of u (m/s). The expression accordingly indicates that drop sizes, drop velocities and flux densities affects the pressure gradients, which in turn affect the convective flows of the fire.

Hence, an expression for the relative drop trajectories in relation to compartment sizes when $t^2{}_0/L$ is constant, L/t_0u_0 is constant and u_0/d is constant, is related to the drop sizes by the expression

$$d \propto u_0 \propto L^{1/2} \tag{2}$$

where d is the drop diameter (m).

The drop mass loss rate was then expressed as a function of the gas velocity and drop diameter, in the range of Reynolds number of interest

$$\dot{m} \propto \left| u_p - u \right|^{1/2} d^{3/2} \tag{3}$$

where u_p and d are the drop velocity (m/s) and drop diameter (m). It is assumed that gas and water temperatures are conserved. Thus

$$\dot{m} \propto {u_0}^{1/2} d^{3/2} \tag{4}$$

Similarly, the rate of evaporation of a droplet is dependent upon its surface area, the characteristic heat transfer coefficient and the relative velocity between droplet and the surrounding gas.[26] Hence, for spherical droplet in a quiescent atmosphere, the heat transfer may be written as

$$\alpha = \text{constant} \times \frac{k}{d} \quad \left(\mathrm{W/m^2/K}\right) \tag{5}$$

where α is the heat transfer coefficient, k is the thermal conductivity of the surrounding gas (W/m^2/K). The measurements of droplet evaporation in moving airstreams have been studied using well-related diverse and ingenious techniques to establish the non-dimensional heat transfer and fluid flow parameters

$$Nu = \frac{\alpha d}{k} \ \text{(Nusselt number)} \tag{6}$$

$$Sc = \frac{v}{D} \ \text{(Schmidt number)} \tag{7}$$

$$Pr = \frac{c\eta}{k} \ \text{(Prandtl number)} \tag{8}$$

$$Re = \frac{ud}{v} \ \text{(Reynolds number)} \tag{9}$$

where d and k are the diameter of the droplet and thermal conductivity, respectively; while v, η and c are the kinematic viscosity, dynamic viscosity and specific heat capacity of air at constant pressure, respectively; and D represents the mass diffusivity of water in air (m^2/s).

In expressing the evaporative cooling phase of fire suppression, Santangelo and Tartarini[27] state that an increase in evaporative effectiveness is expected with decreasing droplet diameter and increasing droplet velocity as a result of rapid convective heating. Thus; the convective heat transfer coefficient h and the mass transfer coefficient h_m were evaluated using the dimensionless quantities of Nusselt, Nu, and Sherwood, Sh, as follows

$$Nu = \frac{hd}{k} = 2.0 + 0.6Re^{1/2}Pr^{1/3} \tag{10}$$

$$Sh = \frac{h_m d}{D} = 2.0 + 0.6Re^{1/2}\left(\frac{v_g}{D}\right)^{1/3} \tag{11}$$

where k is the thermal conductivity of gas phase, D is the mass diffusivity, Re is a 'relative' Reynolds number that is based on relative velocity between droplet and gas phase, Pr is the Prandtl number and v_g is kinematic viscosity of the gas phase. Regarding the oxygen displacement mechanism of fire suppression by water sprays, the Arrhenius finite reaction rate model was used to evaluate combustion rate of fire, R as a function of temp and mass fraction of the reactants, thus

$$R_f = -A\rho^{\alpha+\beta} m_f^{\alpha} m_{ox}^{\beta} e^{-E/RT} \tag{12}$$

where A, α and β are empirical constants, ρ is the fluid density; m_f and m_{ox} are mass fractions of the fuel and oxygen, respectively; while E represents the activation energy of the chemical reaction, R and T are the ideal gas constant and temperature of the droplet, respectively.

The radiative blocking of heat transfer was expressed as a function of the fraction of total heat flux, r, transmitted through water spray as the share represented by the total transmitted flux q_{tr}

$$r = \frac{q_{tr}}{E_T} \tag{13}$$

where r represents the fraction of the total heat flux, E_T is the emissivity power of the black body and q_{tr} is the total transmitted flux obtained by integrating q_λ, the transmitted flux, over the whole range of wavelength, as follows

$$q_{tr} = \int_0^\infty q_\lambda d\lambda \tag{14}$$

However, maximum blocking of thermal radiation is achieved if droplet diameter has the same order of magnitude as the maximum emission wavelength of the fire source. Reports on fire suppression processes using water sprays are presented by Mawhinney and Richardson,[11,15,28] among many other authors. The characteristics of the fire as well as the design of the installed sprinkler system played a key role in the understanding of this phenomenon. A fire is characterized by three zones, namely, flame zone, transition zone and smoke zone (see Figure 5).

In the proceeding sections, available literatures as related to interaction between sprinkler water spray and fire plume are discussed and research gaps are identified accordingly.

Interaction of sprinkler spray and stratified hot air layer (fire plume)

Effective fire suppression by sprinkler spray depends largely on the delivery of water to burning surfaces to overcome the suppression mechanisms (discussed above), which is, in turn, dependent on the spray characteristics, (this will be discussed in the second article of this report) to overcome buoyancy action of the opposing drag force of the stratified hot air

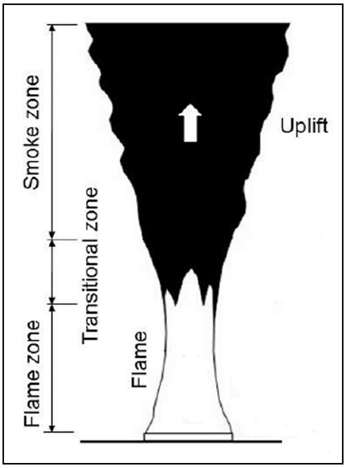

Figure 5. Fire plume zones and description.[23,24]

layer, which tends to deflect it away (vaporize, decreasing plume penetration) from reaching the target fire source. The interactions between sprinkler spray and stratified hot air layer, sprinkler spray and flame are reviewed accordingly.

Fire sprinklers are normally installed at ceiling height, which facilitates the discharge of water spray directly above the fire source. Several models aimed at the understanding of the suppression phenomenon and the improvement of sprinkler spray design have been developed. The smoke layer is the uppermost part of the fire plume zones and incidentally the closest to the installed sprinklers, hence the importance of understanding this interaction cannot be overemphasized. The interaction of sprinkler water sprays with hot combustion gases, fire-induced hot-air flows and stability of the smoke layer are discussed.

One of the earlier pioneer studies on the interaction of sprinkler spray and fire plume was reported by Alpert.[29] The author applied field-modelling approach to investigate sprinkler-induced air flow carried out using particle-tracking method while the fire plume was simulated via a distributed volumetric release of energy (hot, buoyant jet delivered) from floor level and discrete droplet trajectories at the ceiling level was used to simulate the sprinkler spray for two maximum spray angles (57.3 degrees and 90 degrees, cases) and for a range of water injection velocities. The cooling effect of the spray was calculated, and the results on the influence of spray angle on spray cooling and surface cooling was also reported. The study described an increasing level of penetration as the velocities increased for both cases of spray angles, whereas plume temperature reduces to about 70% for the wide-angle spray, in contrast to the narrow-angle spray. This significance of the numerical approach offered by this study had furnished other researchers with significant data, hence subsequent studies have been reported based on this approach for the investigations of other parameters as it relates to the interactions of water spray and fire plume. However, the buoyancy effect approach on plume reaction to water sprays had previously been applied by Morgan and Baines[30] and Bullen[31] to calculate the drag to buoyancy ratio of the stratified hot air layer and to predict the stability analysis of the smoke layer. Utilizing the combine effect of cooling and air-drag, the stability of the entire smoke layer was calculated using a macroscopic parameter known as the drag to buoyancy ratio, but in this case a smoke layer of constant thickness and droplets size of constant diameter were applied. This approach was also later used by Morgan who reported the concept of 'smoke logging' as a result of the smoke layer losing buoyancy and falling to a lower level. These research works paved the way for more investigations in this field, while also relying on the works of Morton et al.[32] on fluid motion in buoyant plumes, which serves to provide the basic by which researchers can investigate on this very important subject.

The buoyant smoke layer generated by an enclosure fire can be cooled down significantly by the water spray thereby losing their buoyancy and fall to lower level. However, this situation impedes smoke extraction (through vents) and the majority of fire deaths of occupants trapped within building enclosure was as a result of inhalation attributed to smoke; Gann et al.[33] reported that two-thirds of these deaths occurred outside the room of origin. There are several studies, which attest to the fact that ventilation systems are also affected by the buoyant smoke layer. Thus, the cooling of the smoke layer using sprinkler water spray is an important mechanism in the study of the interaction between sprinkler spray and fire plume.

The effect of the drag to buoyancy (D/B) ratio and convective cooling of the smoke layer was further investigated by Tang and Fong.[34] This was based on the approach of Alpert from their previous work, which was also extended to a three-dimensional simulation and the cooling effect of sprinkler water droplets against the fire induced hot air flow was studied. The model utilized was based partly on the particle-source-in-cell method and the finite difference method and the advantage of this method had been demonstrated by the application in the interaction between the water droplets and hot air.[29] They stated that the resultant air flow and temperature field predictions indicate how the hot air layer is affected by sprinkler spray. However, water droplets are treated only as a hollow cone and no attempt was made to compute the droplets trajectories; momentum and heat coupling effect between hot air and water droplets are uniquely considered. While smoke movement field model was treated primarily as convective problem, the authors are quick to point out the need to validate this model, providing measurement on the heat release rate (HRR) of the fire, air flow and temperature fields, smoke concentration, sprinkler water droplet sizes and velocities. Subsequently,[35] using a two-dimensional approach, they developed a model that described how the smoke layer–induced fire is affected by sprinklers (sprinklers are described by an imposed envelope with the shape obtained from the water droplet trajectories), and parameters such as drag to buoyancy ratio, air entrainment rate and convective cooling were quantified. It was observed that when D/B is greater than one, the stratified smoke layer is disturbed in all cases, hence, the predicted drag to buoyancy ratio indicates the stability of the stratified air layer. The authors, therefore, concluded that if natural venting is present, smoke extraction will not be effective, and the developed model can provide predictions for smoke clogging in a confined sprinkler process. It is also worthy to note here that, the mean fluid level at most times is also governed by the dynamic pressure caused by the presence of waves due to thermal instabilities in this case and both played a critical role in understanding buoyancy of smoke flow; without the integration of the critical velocities to the impending pressure, an understanding of the phenomenon still will not be fully understood. Using field modelling approach, Hoffman and Galea[28] developed a three-dimensional, transient Eulerian–Eulerian model based on the volume fraction approach. This model was used to describe the interaction of water droplets with the hot turbulent atmosphere of the fire compartment. The model was modified in a study, and the computing power of code Parabolic Hyperbolic Or Elliptic Numerical Integrated Code Series (PHOENICS) was utilized to solve the large-scale flow field induced by water droplets spray. The article concluded that the numerical procedure described using particle tracking and volume fraction methods and in conjunction with a computing technology promises improved understanding of the interaction of sprinkler water sprays and fire-induced hot air flow.

Chow and Cheung, in separate reports[36–38] using field modelling technique, carried out simulation of the sprinkler water spray with fire induced hot air for the purposes of validating their previous work. The study was considered by dividing the problem into a gas phase and a liquid phase and several parameters were evaluated. The smoke layer stability was evaluated by calculating the average smoke layer temperature and the smoke layer height, also considering the effect of these parameters on the mean droplet size. The authors further extend the approach by adding the component of sprinklers water sprays as a liquid phase and solved using a Lagrangian approach.[36] Droplet trajectories were evaluated from the air drag and convective cooling. By varying the droplet diameter size, different cases of hot air flow patterns, water trajectories, temperature profiles, convective cooling and D/B ratio were evaluated. However, validation with experimental results agreed partially, and not for tests in which the fire location was far away from the boundary. The model did not consider droplets vaporization, which affects the thermal stability of the hot gases and stability of the smoke layer; in addition, the effect of the depth of the smoke layer was also not reported. This implies that, for a mean velocity of droplets, the smoke layer analysis should indicate clearly the effect on the fire induced air flow as well as the severity of smoke production. Similarly, using the two-zone modelling approach, the stability of the smoke layer and heat transfer between hot gases and water droplet was investigated by Tang and Fang.[39] They varied the input parameters of water flow rate, orifice diameter, droplet diameter, spray angles, ambient air temperature, as well as the initial smoke layer thickness and temperature. They found that the mean droplets diameter and spray angles strongly influences the stability of the smoke layer, while the sudden strong downward smoke layer displacement was attributed to the entrainment of cool air into the water spray envelop when the smoke layer is below critical thickness and water spray is high enough. The heat transfer model developed was also reported to be satisfactory when compared with experimental data. A model developed by Forney and McGrattan,[40] had earlier demonstrated that air entrainment and gas cooling in a compartmental fire investigation greatly influences sprinkler actuations and movement of the smoke layer, as well as thermal stability within the enclosure. The model was based on large Eddy simulation (LES) technique. In addition, the National Institute of Standards and Technology (NIST) team also initiated the development of a sub-model for sprinkler–hot layer interaction designed to be incorporated into two-layer zone models of compartment fires.

Using LES and Reynolds-averaged Navier-Stokes (RANS), computational fluid dynamics (CFD) approaches, O'Grady and Novozhilov[41] investigated the interaction between a water sprinkler spray and fire ceiling jet. The model depicted a scenario based on an experimental setup as shown in Figure 6, and the model predictions considered the droplet vaporization. In addition to other parametric measurements, gas temperature and tangential velocity in the ceiling jet were evaluated, and a difference of 12% and 6%, respectively, in comparison with the experimental results was observed, which indicates the sensitivity of the model used. The combined effects of two sprinkler sprays have been shown to have significant effects on the drag effect and on the evaporative cooling of the layer, the combination of which may cause smoke logging. Recommendation for future work on this approach is to consider parameters such as entrainment into the fire plume to provide a cushioning effect against smoke logging.

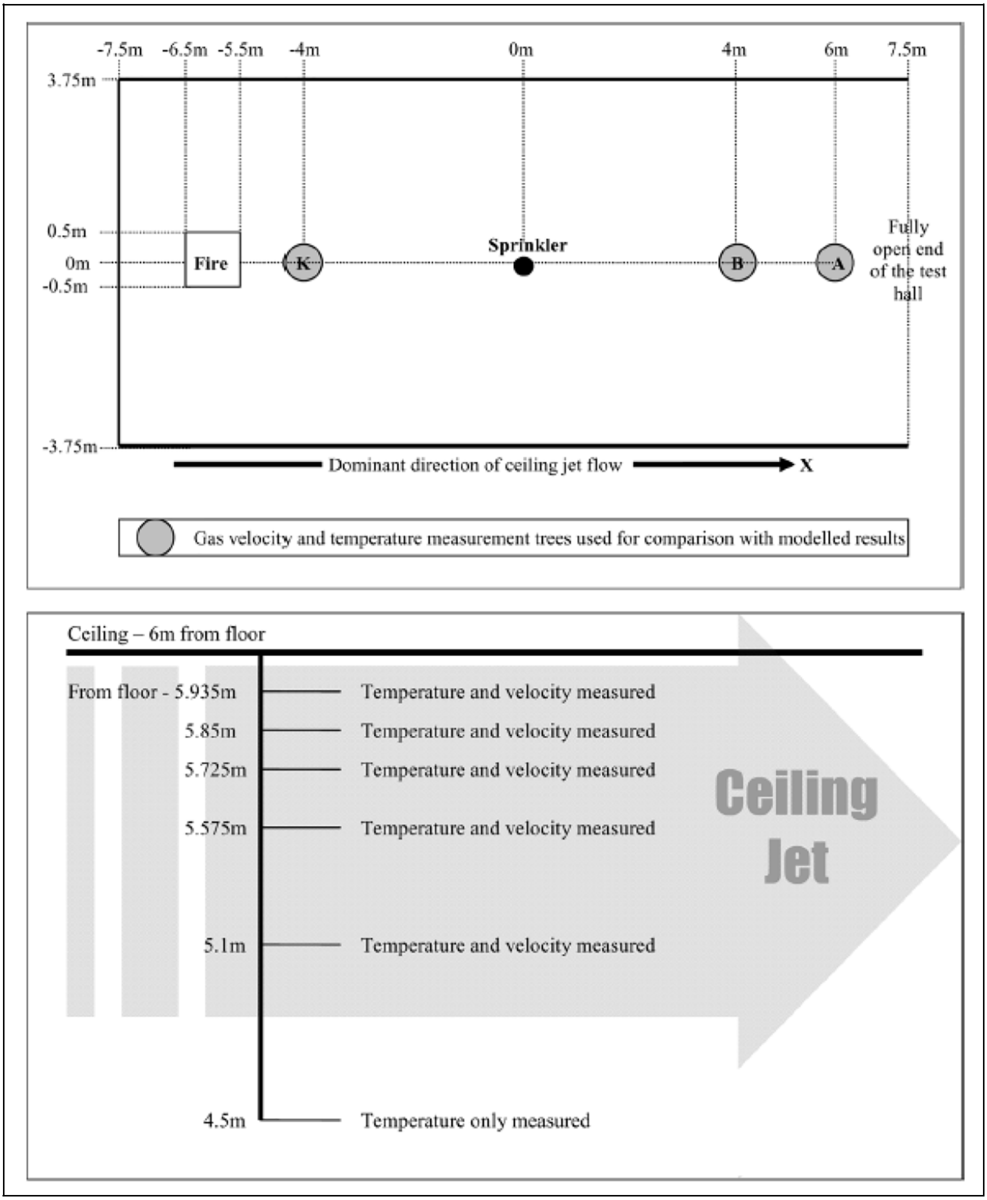

Figure 6. Experimental small-scale model showing the layout of the test room and the typical measurement tree used.[41]

The maximum entrainment will occur at the interface between the upper and lower layer[40,42] when the plume enters the smoke layer. Average temperature and mass flow measurements were, however, cleared except for the effect of smoke layer height.

However, Hua et al.[21] adopted a different approach, using the Eulerian–Lagrangian approach to simulate the interaction between fire plumes and water sprays. Water droplets

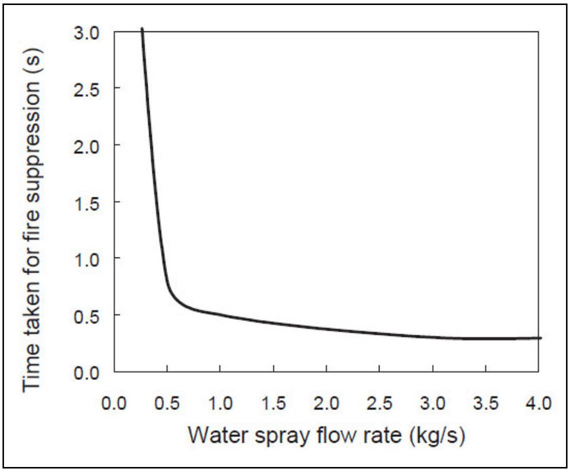

Figure 7. Variation of the fire suppression time against water flow rate. From the study by Hua et al.[21]

are tracked using the concept of droplet group, which target similar characteristics and traced movement of this finite group. The physical model described that a 0.25 m^2 methane burner was used and water spray nozzle was located directly above the burner at a height of 1.8 m, while the water spray characteristics (spray pattern, droplet sizes and flow rate) varied. The effective time for fire suppression under various water application rates was also evaluated as seen in Figure 7. A higher fire suppression time implies that the flow rate is low, a similar analysis of which was reported by Hamins and McGrattan. In their case, the propane flow through the igniter was approximately 0.5 L/s, yielding a 40 kW fire that was almost 50 cm in height. The study concluded from its findings that a solid cone water spray pattern and fine water droplet sizes increase the suppression efficiency, while emphasizing that high flow rates will only lead to more expensive operating costs. A modified buoyancy equation model of Morton's was proposed by Schwille and Lueptow[43] to include a fire sprinkler spray, and by adding a term in the momentum equation to reflect the momentum of a uniform-disperse droplet field of a sprinkler spray, the adjusted momentum equation was obtained. This was done by including the effect of homogeneous, uniform velocity droplet field on the momentum of the field. The model demonstrated that the interaction between the upward momentum of the plume and the downward momentum of the droplet spray played a critical role in effective fire suppression. On the other hand, an experimental investigation on the first direct measurements of the general structure of fire plume using infrared intensity as it interacts with a suppression spray was investigated by Schwille and Lueptow.[44] For a variety of fire sizes and spray strengths from methane fuel burner, they observed that the effective width of the fire plume increases with increasing spray strength. However, this increase in effective width is not a result of an increase in projected area of the fire without suppression. They also observed that while larger droplets may penetrate through a fire plume, a spray at the same mass flow rate that consists of a greater number of smaller droplets has greater effects on the buoyant plume because of its higher drag force, hence the reduction of the vertical momentum of the plume.

However, using LES approach, Xia et al.[45] conducted a numerical study to investigate the thermal and dynamic effects of three water droplet sizes (780, 390 and 195 mm) on buoyant reacting plumes, while also varying the volumetric flow rate and droplets speed. It was found that effect of droplets arising from both the interphase drag and evaporation tends to decrease the grid-scale kinetic energy, except in regions close to the spray nozzle. Smaller droplets are subjected to evaporation because of their small total surface area and short interaction time with the plume, while larger droplets can penetrate whole plumes to reach the hot surface. In addition, Nam[46] also investigated the influence of an increasing water discharge rate for the different fire sizes and found that progressive plume–dominated flow region occurs, while decreasing fire sizes shows a water spray–dominated plume flow. The location of the interaction boundary of the hot air plumes to that of the water spray for sprinkler protection through combined gas–liquid velocity and droplet size measurements was experimentally investigated by Zhou.[47] In this work, the momentum of the hot air plume without spray was calculated directly from the velocity and temperature measurement near the exit of the nozzle. A constant discharge rate of water spray was used to interact with hot air plumes of varying HRR. At peak of the hot air plume, they found that the velocity near ceiling height has reduced by 50% while layer thickness increases fourfold. In addition, peak velocity had moved towards the outer boundary. The study identifies the momentum ratio of hot air to spray, droplet size variation and volume flux due to water evaporation as key parameters that define plume–spray interaction. Similarly, Beji et al.[48] also reported a reduction in the maximum ceiling jet velocity by 50%, while increase in ceiling layer thickness observed was also four times for the vertical jet–dominated spray regimes. The three regimes of spray–jet interaction (i.e. water spray dominated, vertical jet dominated or equal influence of the spray and the vertical jet) were well captured by the numerical simulations. Link et al.[49] developed a numerical model using FireFOAM for the prediction of spray dispersion and plume penetration. To generate spray measurements for the numerical model, data were obtained from an experimental test facility. Four flow conditions were investigated for close and far sprinkler spacing, each against quiescent air and strong jet (i.e. 0–3.7 m/s) conditions. They found that the strong jet was able to overcome the smallest drops within the spray, reversing their direction and reducing the volume of flux at the floor. In their conclusion, they observed that the non-uniformity of sprinkler spray conditions means that small changes in location can also lead to large changes in volume flux.

Furthermore, a simplified model for smoke-filling time under the influence of sprinkler activation was theoretically and experimentally investigated by Chung and Tung.[50] They studied the variations of HRR (identified as an important parameter for calculating the smoke rate) of complex geometrical structures. They also recommended and used a model for analysis based on the division of HRR curve, before sprinkler activation and after sprinkler activation. The report confirmed that the smoke layer descend was very fast in the case of sprinkler activation in a small compartment, and that a controlled low-level smoke temperature was observed at the location of fire source. The experimental results show that the smoke-filling time of a sprinklered fire test may have a 10%–20% faster smoke-filling time than a non-sprinklered fire test in a confined space. Hence, the report concluded that smoke layer descend for a sprinklered case is 17% faster than for a non-sprinklered case, given the conditions under which the study was undertaken. An experimental investigation was carried out by Pretel[51] to study the effect of water spray and smoke for a confined and mechanically ventilated enclosure. Observing the effect of water spray on vertical stratification, it was found that more the droplets, better is the mixing; the gas phase is fully mixed and concentration of stratification vanishes at water flow rate of 100 L/min. It was further observed that gas concentration in the enclosure had become identical in the upper and lower parts of the

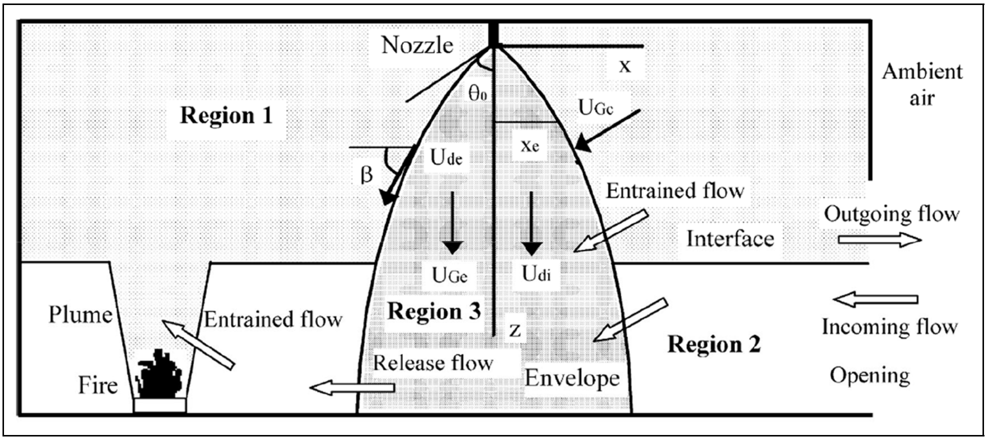

Figure 8. Physical structure of the compartment fire environment.[53]

room. Similarly, Zhang and Chow[52] also investigated the stability of the smoke layer and the mass flow rate using fire dynamics simulator (FDS) code, based on the LES approach. The cooling effect of water spray was analysed and it was found that temperature decreases was almost linear with respect to the working pressure of the sprinkler system. This investigation has also demonstrated the great effect of water spray on the movement of smoke in the compartment.

Yao and Chow[53] developed a mathematical model for simulating the fire environment of a compartment under the action of a solid cone water spray. The researchers observed that problems can occur when using zone models to simulate the sprinklered-fire environment in a compartment when the stability of smoke layer is lost. Thus, compartment dimensions to droplet ratio was used to overcome the identified problem. Using a Lagrangian approach on the basis of macroscopic balances for single droplets, the global evolution of spray was modelled. Stable smoke layer was defined as a situation whereby spray dimensions is relatively smaller compared to the compartment dimension, which assured of thermally stable hot and thick layer in the compartment. The compartment was divided into three regions on the basis of smoke stability analysis (as seen in Figure 8). The HRRs and water application rates were varied, and volume mean diameters of the solid-cone spray, smoke layer interface height, smoke temperature and air temperature, smoke flow rate through the opening and oxygen concentration in the air layer were evaluated. The study concluded that for an effective control of compartment fire through hot gas entrainment and water vapour production, a water spray containing a variety of droplet sizes should be utilized. However, in the experimental test reported by Zhang et al.,[54] the smoke was generated from a pool fire (HRR was 200–810 kW) in an adjacent room and was then collected in the sprinklered test room, thus certain thickness of a smoke sheet layer was measured at the smoke layer interface. Referenced to the sheet layer height, the ratio of the drag at the sheet layer to the layer sheet buoyancy was used to calculate the smoke layer stability, by a modified Bullen approach. Based on their analysis of the results, they concluded that the stability of the smoke layer depends only on the orientation of the sprinklers and the working pressure. The working pressure is 0.05–

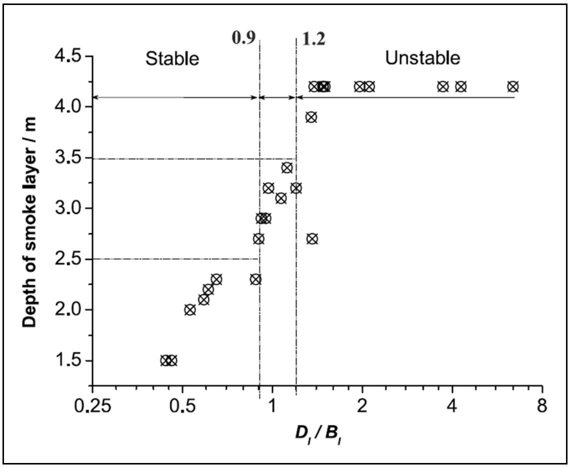

Figure 9. Typical smoke layer thickness after sprinkler operation, after the study by Zhang et al.[54]

0.15 MPa. It is also worthy to note from Figure 9 that the critical stage for smoke layer stability is at 0.9–1.2, as concluded by the authors.

Building upon the outcomes from their previous experimental work on the influence of the water spray characteristics on the downward smoke displacement due to drag and cooling, Tang et al.[55] emphasized the measurement of smoke layer temperature distribution vertically along the centre of the spray region and radially at 0.5 m from the same location. The objective was to measure air entrainment effect. Water spray characteristics and operating pressure are adopted from Mawhinney et al.[8] As a result of the entrainment of cool air rather than surrounding hot air layer, temperature within the smoke envelope region decreases significantly, and continues to decrease with increase in water pressure, while the absolute value of downward smoke layer displacement also increased. To quantitatively illustrate the overall agreement for temperature inside and outside the water spray region, Tang et al.[56] applied CFD simulations to investigate the impact of a water spray on the fire smoke layer inside a hood, and the influence of the water spray characteristics on the downward smoke displacement due to drag and cooling was extensively provided. It was further confirmed that droplet size parameter played a key role when simulating downward smoke displacement caused by spray angle (related to vertical water flux). Also, using the CFD code FDS, the smoke stable-stratification-length was reported to increase with increasing HRR, but decreases with increasing longitudinal ventilation, for a rectangular tunnel section study conducted by Zeng et al.[57] They further confirmed that smoke stable-stratification occurs at the downstream and will not move towards the upstream. A comparison of typical smoke layer temperature for 1.0–1.5 MW compartment fire suppression is presented in Table 1.

The collection halls are similar in dimensions and a single nozzle point was considered in the test. From the outcome of the table, it can be seen that the smoke layer height values to the smoke layer height after its loss of stability played a critical role in the study of the interaction of water spray with smoke layer stratification for compartment fire. Due to the cooling effect, the smoke layer decreased and, in most of the cases, the temperature decrease was almost linear to the working pressure as reported in literature.[52,54,55]

Table 1. Comparison of smoke layer temperature for compartment fire.

HRR (MW)	Sprinkler pressure (bar)	Smoke layer temperature	Smoke layer temperature (after cooling)	Smoke layer thickness (mm)	Smoke layer thickness (mm; after cooling)	Flow rate	Ventilation	Reference
1.0–1.5	0.5–0.75, 1.5	103.9°C	103.8°C	2000		56.7–97.98 L/min	Yes	Zhang and Chow[52]
1.0–1.5	0.03–0.09	311 K	298 K	2000		0.73–1.26 kg/s	No	Tang, et al.[55]
1.0	0.6	12.3–3.2 K	11.2–3.0 K	2500–3500	1200	–	No	Zhang et al.[54]

HRR: heat release rate.

Interaction of sprinkler spray and flame

Research works on the interaction of water spray and flame zone are reviewed in this section for an enclosure geometry of compartment fire. The visible flames of a fire represent the region where combustion is occurring. Thus, for effective fire suppression, sprinkler spray design must be able to achieve a length of travel corresponding to the mean flame height of the source fire.[58] The mean flame height is defined as the elevation above the source of the fire on the central axis, where the flames appear 50% of the time.[43]

A series of tests was carried out to investigate the influence of sprinkler actuation times in preventing flame spread for varied fire sizes in a tunnel fire test by Marke.[59] They observed that as fire size increases, the chances of preventing flame spread (and extinction of ignition source) decrease. At maximum fire size (90 kW), they were able to determine an effective actuation time of 30 s to prevent flame spread to target object (cables) and subsequently for fire extinction to take place. However, they also found that the size of the target object (cables) matters during the test, which implies that for smaller fires and larger target object, the max pre-burn time increases marginally. A single nozzle type discharging 8.9 L/s at 100 kPa was used throughout the experiments, which gives room for alternative investigation; moreover, for the tunnel profile dimensions indicated, the maximum fire size of 90 kW could have provided false peak value considering that petrol fuel was used, since it has the tendencies for turbulent reaction in excess vents condition. Similarly, a series of full-scale experiments were conducted by Xie et al.,[60] to investigate the effect of different water application times 20–45 s after ignition on a burning upholstery chair. They examined and compared the results for the burning test with water spray and without water spray. However, they observed that peak values of temperature obtained at 45 s was 507.1°C, against 900°C for burning tests without water spray. They further stated that there is a near exponential relationship between the peak HRRs and the relative application times of water spray.

In a series of 12 required delivery density (RDD) tests, Bill et al.[61] investigated the RDD of a residential and quick response sprinkler. Fire growth, HRR and RDD test measurement were described for a vinyl-covered reclining chair. The report indicated that the variations in RDD measurement is a function of the variation in fire spread and shielding at the time of water application and the RDD was not influenced by the HRR, rather by the fire spread and shielding. It is reported that a nominal RDD of 5 mm/min over a convective HRR of 100–450 kW.

A series of full-scale experiments was performed by Bennetts et al.[62] for the standardization of normal and fast response sprinklers involved in a pressurized and non-pressurized small- and open-plan office areas and fire tests with estimated HRR between 35 and 85 kW. They evaluated sprinklers performance for different fire sizes and parametric measurements, such as the activation time response of the sprinklers. The efficacy of the extinguishment times was faster for small office fire than the open-plan area office by a difference of 3 min. However, the efficacy of extinguishment for pressurized lobby was better than non-pressurized in terms of smoke restriction and build-up. It is also the observation from this report that relatively larger fire size up to 1 MW is required to cause sprinkler activation, even though the ratio of the room dimensions was seen to be a factor. Thus, extinction time is faster for the smaller office on the basis of convective HRR at the time of sprinkler activation. However, Vincent et al.[63] also investigated the influence of sprinkler configurations as well as the fuel configuration for the protection of rack storage and to palletize storage configurations. Thus, in this case, for both cartoned and un-cartoned (heptane fuel) containers, the combination of ESFR ceiling sprinklers and quick-response, large-orifice in-rack sprinklers installed within the longitudinal flue space of the rack storage arrangements provides the most effective protection.

Similarly, Xia et al.[64] investigated the effectiveness of changing spray angles on combustion suppression using an LES approach. They reported that the drag effects of droplets caused significant changes to the flow and flame structures, identifying in particular that dense droplets can cut through the reaction zones, causing flame extinction. The high temperature regions associated with reaction zones were suppressed by the spray droplets in all cases. The report[64] further revealed that, for a 15-degree discharge angle, the concentrated droplets were able to suppress the buoyant flame effectively, through intense thermal and dynamic effects in the central region. Meanwhile, significance of droplet sizes in flame suppression was investigated by Sarkar et al.[65] with emphasis on the characterization of droplets size. They discussed its effects for both premixed and non-premixed combustion. In their conclusion, it was observed that droplet inertia and evaporation are the two phenomena which govern flame suppression for both cases. For the premixed flame, flame speed was influenced by the presence of water spray.

A mathematical approach was developed by Trapp and Rangwala[66] to assess the location and number of sprinklers required for optimum design and containment of fire. Based on a previously developed fire model, a revised HRR approach was used to estimate the temperature at the target array through computing the flames radiative heat flux. In addition to modelling the existence of ceiling and in-rack sprinklers, the HRR, flame height, temperature and velocity in the plume and ceiling jet, sprinkler activation and ignition of the target array and fire suppression criteria were also investigated. A CFD model calibrated based on large-scale test results was developed by Yuan and Smith.[67] The study considered the effects of sprinkler location, water flow rate and sprinkler activation temperature on the suppression of conveyor belt fires to investigate the interactions of ventilation airflow, belt flame spread and the water spray system of a mine entry. While, flame spread was a model using FDS, kinetic properties of pyrolysis of the conveyor belt burning were determined from data given by a thermogravimetric analysis (TGA). Similarly, FDS was used to model the water spray suppression of belt fires, and conveyor belt fire suppression was conducted based on a fire suppression facility. The report observed that the sprinkler location was found to significantly affect the conveyor belt fire suppression and development; however, it was also noted that at 25 L/min, water flow rate was found to have little effect on conveyor belt fire suppression. The effectiveness of side wall sprinklers to prevent the spread of undercarriage fire was investigated using CFD/FDS code by Ge et al.[68] The study examined three different cases of sprinklers installations such as overhead sprinklers only; sidewall sprinklers on one side of the trains only and sidewall sprinklers on both sides of the trains for a suppression test of an estimated fire size of 7 MW under free burning condition. Evaluation of flame cooling/inerting effects was observed using the flame temperature limiting concept of FDS tool. Maximum heat flux was observed to progressively decline from 39.2 to 8.72 kW/m^2 (critical heat flux was reported to be 18.7 kW/m^2 at ignition temperature of 400°C) for case 1–case 3 especially in the case of connected train-car.

Fire suppression modelling on a large scale of corrugated cardboard boxes on wood pallets with storage height of up to five tiers was conducted by Ren et al.[69] using the OpenFoam CFD code. Simulation for two free burn tests without water spray application and two fire suppression configuration using ceiling-type sprinkler systems was evaluated. They observed that exfoliation largely contributes to fire spread with increased burning area and HRR. In addition, the report also confirmed a faster lateral spread rate than on the vertical side surfaces due to flame impinging on the bottom surfaces (in the case of test without pallet). Hence, flame impingement on the bottom surfaces largely determines the lateral flame spread rate. Furthermore, as storage height increases, the suppression effectiveness reduces as the surface film flow transport time increases. On the contrary, as lateral flame spread rate increases, the suppression effectiveness also reduces.

Furthermore, the design of sprinkler fire protection of highly challenging fires was experimentally investigated by Xin et al.[70] Configuration at component level was tested for fire detection, fire location and sprinkler activation under various experimental conditions. The setup comprised of movable ceiling positioned 3.4 m above the fire source sand burner, and SMART sprinklers spaced at 0.76 m directly above the fire source. Three fire sizes were evaluated and the variability in detector performance, impact of ambient conditions on fire detection and system performance under non-flat ceilings were reported. In a study conducted by Noaki et al.,[71] a series of burning experiments for different layers wood crib were carried out to characterize the maximum value of HRR of wood cribs. Varying the delivered water density and water activation time, the respective HRR was evaluated. They found that regardless of the number of layers of wood cribs, the reduction of the maximum HRR was proportional to water flow rate. Furthermore, it was revealed that as long as the wood crib burning is not ventilation controlled, the area wetted and hence the reduction in peak HRR is independent of the number of layers.

Furthermore, the influence of water droplet sizes on the fire suppression mechanisms of sprinklers and water mist was investigated by Liu et al.[72] using a CFD approach. Fixed typical droplet diameters (based on the experiment of Zhoh and Yu) and spray angle were maintained for both water mist and sprinkler systems with different operating conditions throughout the test. The report further confirms that latent cooling, volumetric displacement and dilution of oxygen and fuel were the main suppression mechanisms for water mist systems while heat extraction by water droplets from the fire was found to be the main suppression mechanism for sprinkler systems.

A different approach to the study of water spray and flame interaction was reported by Heskestad.[73] Therein, extinction conditions for flames interacting with water sprays in open space/large space was experimentally investigated for circular pool fires from gas and liquid fuels in the form of methane and heptane, respectively. The water spray was applied centrally from a spray nozzle directly above the fire point, and the experiments were conducted in three scales. The results from this study were reported to be consistent with an engineering relation showing extinction water flow rate approximately proportional to an effective nozzle diameter, and to the 0.4-power of both nozzle height and free-burn HRR. Another experimental study on the interaction of a fine water spray with liquid pool fires was performed by Liao et al.[74] Two pool fires of 50 mm diameter and 100×100 mm^2 dimensions, containing 34 and 100 g of fuel was used. The water spray characteristics of droplet size, velocity distributions and volume flux of the fine water spray are in accordance with the one reported by Noaki et al.[71] The researchers observed among other outcomes that the water spray suppressed the gas phase combustion through cooling, oxygen displacement and the attenuation of heat radiation. Qing et al.[75] developed a model for effective control of fire source HRR. The researchers sought to provide an improved method (other than the normalized thermal programme calculation method) by which the rise in temperature can be effectively evaluated and which can be used to describe effect of sprinkler system in the control of nuclear power plant (NPP) fire. Using FDS to simulate the process of turbulence flowing in fires based on LES, the computational domain of $10 \times 8 \times 4$ m^3 building structure was utilized, with a fuel diesel tank of dimensions $8 \times 2 \times 2$ m^3. Based on the findings from the report, the researchers observed that the CFD model was able to predict close to the real fire scenario the temperature rising and also demonstrated the effect of sprinkler system on the fire.

Nmira et al.[76] investigated the full polydisperse nature of the water spray using a droplet size method, to foster understanding of the interaction between a fire induced by the thermal degradation of poly-methyl-methacrylate (PMMA) and a polydisperse water spray that was located from above the fire. A parametric study was carried out to study the effects of droplet sizes with reference to the mean Sauter radius used, and water flow rate on the fire suppression of the system. Based on the prediction of the model developed, the researchers concluded that the time for fire suppression using polydisperse sprays decreases as the water flow rate increases, but with an asymptotic behaviour.

An experimental study conducted by Novozhilov et al.[77] on wood slats fire suppression for varying water flow rate, droplets sizes and velocity distributions indicated that extinguishment happens mainly due to fuel cooling due to the long extinguishing times of magnitude larger than that for plastic materials. Subsequently, the CFD fire model of the fire suppression was carried out. Comparing between the extinguishment times at an average of critical burning rate of 0.5 g/(m^{2}s) for experimental and numerical results, they found that the thermal time constant of the fuel load used, influences the extinguishment process rather than the water application rate. The understanding of this aspect is well-related in (Figure 10) the data provided by Hamins and McGrattan;[78] as it is the case here, complete water evaporation may have taken place as a result of the dissipation of energy by the droplet. In addition, the CFD kinetic parameters describing the wood pyrolysis rate was found to have predicted heat transfer effectiveness. In this context, the work of Marshall and Marzo[79] provides a mathematical model describing the important physical processes for sprinkler fire suppression. The study provides information on the behaviour of sprinkler sprays on fire by examining key processes of activation, atomization, spray dispersion and droplet surface cooling. A model for each of the processes was developed, which was described as critical for the development of the understanding of fire suppression.

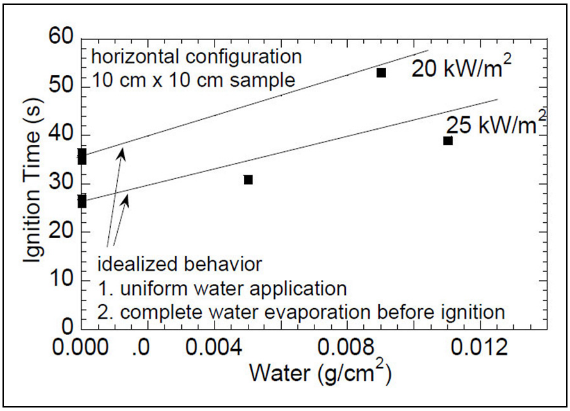

Figure 10. Flame ignition time as a function of water applied per unit area. After the study by Hamins and McGrattan.[78]

Interaction of sprinkler spray and hot solid surfaces

The interactions of water spray and hot solid surfaces in fire suppression occur in the form of cooling and pre-wetting (in the case of fire sprinkler). Several research studies have demonstrated that this is attributed to the large droplet size of water, which can penetrate the fire plume and reach the burning surfaces.[80] The hot surfaces (solid) represent the potential fire load that must be controlled and prevented from further spread/growth of fire. The interactions of a droplet on the hot surface are very important to the understanding of the suppression mechanism by sprinkler spray. Due to the complexity of this phenomenon, both numerical and experimental approaches have been used to investigate this study.

The deformation behaviour of droplets impinging on hot solid surface was investigated by Fujimoto.[22] Small (0.6 mm) and large (2.5 mm) droplets under same weber number are subjected to hot solid surface and the boiling deformation behaviour phenomena of the interaction was studied. The temperature of the hot surface and pre-impact velocities were varied, between 170°C–500°C, and 1.7–4.1 m/s, respectively. It was reported that at the lower temperature, droplet boiling was observed, and at intermediate temperature, a simultaneous splitting and vaporizing effect was observed. However, at the higher temperature of the hot surface, no droplet splitting was reported, and droplets simply roll as it vaporized. Pre-impact velocities were not reported to have influenced the process. However, it is not clear if the surrounding condition (thermal radiation) could have influenced the pre-impact conditions/behaviour of the droplets. This study provides the understanding of the boiling behaviour associated with droplets impacting on hot solid surface during fire suppression. Similarly, a single suspended water droplet lifetime and droplet saturation rate was investigated by Beji et al.[81] The study was conducted based on a previous experiment by Volkov et al.[82] using a CFD code, FDS. Water droplet diameter of 2.6–3.4 mm and convective hot air flows at 100°C–800°C were varied according to the experimental setup. The comparison between CFD predicted results and measured results indicates better accuracy for the range 300°C–800°C. However, at lower temperatures between 100°C and 200°C, it shows stronger deviation. This is attributed to an underestimation of the mass transfer rate by the model.

Furthermore, they reported a strong deviation for the droplet saturation rate, which was more significant especially at higher temperatures of 800°C by an increase of up to 30°C.

Marshall and Marzo,[79] applied the ceiling jet expression of Alpert (1972) together with the lumped mass analysis to study the thermal responses of sprinkler heads. Once the water droplets reached solid surfaces exposed to the thermal radiation from the fire and to the hot gases convective heat transfer, they provided evaporative cooling, which resulted in the reduction of the average surface temperature. The report provided relevant results for some challenges to the mechanics of fire suppression; however, there exists important differences between the heat transfer systems occurring in metallurgical applications and those which operate during the extinguishment of burning solid fuels that needs to be considered. Meredith et al.[80] developed a model using OpenFOAM to solve for fundamental equations of continuity, momentum and energy. Subsequently, they validated the radiation heat transfer with a unique experimental setup of a vertical panel with water flowing down the surface. They reported that for a cellulosic-based fuel, as long as a surface is covered by water, pyrolysis occurring at around 700 K will be suppressed due to the large convective cooling of water. Similarly, the report points out that thermocapillary instabilities, vaporization and conjugate heat transfer play a dominant role for fire suppression behaviour of solid fuel. However, in the experiment conducted by Xin et al.[83] to evaluate the absorptivity effect and water application rate on the burning surfaces of two roll papers, the authors made the following observations: (1) the evaluation of burning surfaces on water transport patterns indicated that it is sensitive to the surface conditions and (2) when the outer layer exfoliates, wet paper detaches from the roll so that further wetting is terminated on the exfoliated paper, but continues onto the underlying layer. The authors concluded on this study by stating that surface delamination and exfoliation are crucial to the growth of roll paper fires and also noted that high water rate application and application times were observed to have slight significant effect on the suppression. Furthermore, the impact of water spray on temperature and flame behaviour of vertical wall PMMA slab was experimentally and numerically investigated by Zhao et al.[84] The effect of heat flux (6.03–33.2 kW/m^2) distribution and flame height (at 50 and 100 s), for varied water application rate (0.0002–0.002 kg/s) are reported. They found that the water spray is capable of strengthening the fire resistance of combustible materials even under high heat flux radiation, which is attributed mainly to external heat flux and combustion property of the material. Milke et al.[85] expands the study of Dawson's on the cooling of a solid surface. In the experimental study conducted, de-ionized water droplets were delivered on a hot surface at mass flux of 0.24–1.6 $\text{g/m}^2\text{s}$. To facilitate non-flooding conditions, a much lower than usual sprinkler characteristics were utilized and the surface was subjected to radiant heat between 110°C and 180°C. Spatial distributions of the surface temperature at a specific time were obtained by considering each pixel individually in a digitized frame. It is reported that localized cooling was measured around the droplets initially. Subsequently, they attributed the cooling effect to the tendency for several individual droplets to merge due to the longer evaporation times associated with the decreasing solid surface temperature. Typical HRR of different fuel configurations as a function of the surface area indicated that for large scale fire suppression testing, the burner had made strong impact but could not sustain it as observed for solid combustibles, largely wood cribs in the form of slates. A comparison of the HRRs as made for different fuel configurations and based on the wetted surface area (Figure 11).

On the contrary, the impact of droplets on hot liquid surface relate to the regimes of droplets life time considering the drops velocity and fall height. The drops behaviour is,

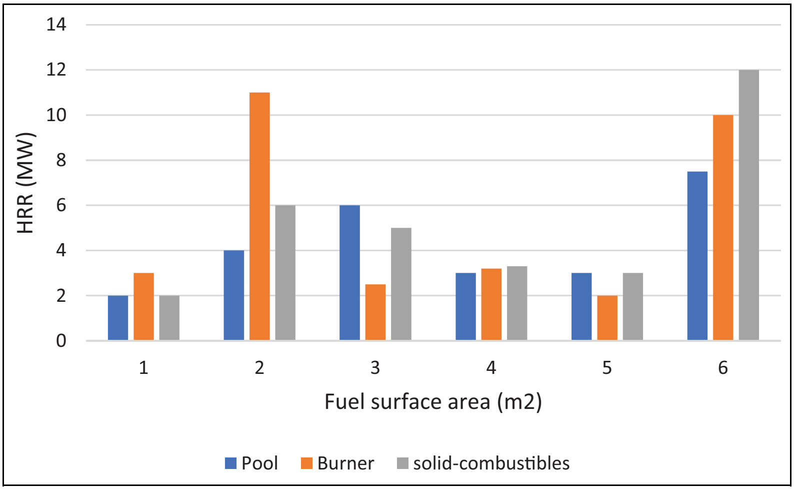

Figure 11. Comparison of the heat release rate of fuel configuration as a function of fuel surface area.

therefore, a key to understanding its interaction with hot surface. An experimental study was carried out by Jenft et al.[86] involving round pools of 25–35 cm diameter from both diesel and fuel oil. The flow rate and mean diameter of the injected droplets were 25 L/min and 112 μm, respectively. They evaluated the fuel surface temperature and the pyrolysis rate during water application and until fire suppression. The authors faulted prescribing evolution of HRR or pyrolysis rate as this leads to discrepancies on fuel temperature, stating that energy removed by vaporization is decoupled from the heat flux into the pool surface and the heat conduction through the pool. However, Xu et al.[87] carried out an experimental investigation on water droplet impacting on a burning fuel liquid surface. Three different impact regimes were discovered and analysis was carried out by using several important parameters, that is, maximum crater depth and width and maximum jet crown height. It is reported that all three parameters increased when the impact of velocity was increased. However, as velocity impact was increased beyond 3.513 m/s, a sharp decline was observed in the maximum crater depth and width, as well as the maximum jet crown height. The report, thus, concluded that fire plume has an evidence influence on the loss rate of the impact velocity of water droplet.

Discussion

Based on the available literatures that were reviewed so far, empirical and numerical studies are the dominant topics of the research articles in fire suppression sprinkler systems and they have provided valuable information on current development of fire sprinkler systems in use today. Experimental and CFD approaches on the contrary, provide real data that are applicable by virtue of being validated. For instance, CFD research offered the advantages of dealing with too many interacting variables and tendencies for repeatability. However, experimental investigations offered more realistic results, which are applicable and verifiable. Although the more recent of the research articles contributed by demonstrating an application of good innovation to the sprinkler systems operation for improved performance, yet several points remain unanswered. There are a number of areas of investigation, which could broaden the understanding of the subject matter based on the literatures that have been reviewed. Thus, a summary of small- and full-scale research in the interaction of water spray with fire plume are presented in Tables 2 and 3.

The tendencies for smoke to cool and loss of buoyancy, thereby falling to the lower level leading to smoke clogging has been an on-going challenge; while most reports mainly focused on the effect of drag to buoyancy ratio between water sprays and smoke layer, some discussed the effect of air entrainment to understand this situation. The changes in the ventilation conditions is another variable to consider as it strongly influences spray penetration and spray dispersion, especially for wide-angle sprinkler application. Spray angles and injection velocities as well as spray volume flux have extensively been used in most research; however, further application in experimentation could explain underestimation of mass transfer rate especially for ceiling jet flows and doorway flows (subsequent article is underway in which the authors will review extensively the aspects of spray characterization in relation to fire suppression). A key factor in developing improved fire suppression investigation so as to obtain reliable data, is to examine the time to flaming ignition of the respective fuel used. This parameter is often ignored or not properly assigned for the combustion process. Fewer research studies have considered it; however there should be an archive of data for different fuel configurations, which will be readily available to complement existing data and for improving fire codes. Similarly, experiments involving single suspended droplets to investigate the droplet lifetime could be improved by the CFD application whereby several other variables (droplets characteristics) could be used to explain relative extinguishing time and vapour accumulation. This can be done both experimentally and numerically, with the greatest benefit from a combination of the two approaches. The numerical modelling could be usefully employed simply to examine the fluid mechanical aspects of the interaction (as demonstrated by some of the reports) and could be further developed to include the extinction process itself. Another aspect that requires improvement is the effect of ceiling vents on air entrainment of compartment fire, whereby the fuel location and initial ceiling level are investigated. For instance, a discharge by an isolated sprinkler in the region of the upper hot layer of fire gases will cause the sprinkler to not perform very well owing to venting condition but this is not the case as discussed earlier in the report. Empirical investigations have been able to develop a model for hydrodynamics and the boiling phenomena of droplets, including studies on smoke layer stability; however, comparison between the results obtained and measured values from experimental study shows varied deviations. Improving accuracy in parameters of experimental investigation is encouraging.

Finally, this review has identified a number of areas by which fire suppression by sprinkler water spray can be understood with great benefit towards the improvement of sprinkler system performance. In addition to the areas of improvement mentioned, test rigs (full-scale models) for sprinkler suppression investigation of practical fire scenario, also falls short in the number of available literatures found in this review. This approach is encouraged especially in the interaction of sprinkler spray and hot surfaces whereby subjective units are studied individually.

Conclusion

In the present work, more than 100 research articles related to the study of fire suppression by automatic sprinkler systems were selected, based on the available literature from the last

Table 2. Summary of small-scale studies on enclosure fire sprinkler system.

References	Description	Enclosure dimensions	Fuel type	HRR, peak	M	Measurements	No. and type of sprinkler head(s)
Marke[59]	Time to flame spread for tunnel fire on different actuation time of water	NS	Petrol pool	90 kW	E	Temperature, HRR, CO	Single point nozzle, flow rate 8.9 L/min, discharge at 100 KPa
Zhang, et al.[54]	Investigates on the ratio of the spray drag to smoke buoyancy to determine smoke stability	Fire chamber: 4 × 2 × 2.4 m^3 and Hall: for smoke collection: 4.0 × 4.2 × 4.0 m^3	Diesel pool fire	200–810 kW	E	Temperature, HRR, plume height, visibility	Two upright, one pendant sprinklers. Orifice sizes and k-factor are 12.7 mm, K80. Orifice size and k-factor for nozzle A is 13.5 mm, K120
Vincent et al.[63]	Investigate the effectiveness of early suppression-fast response (ESFR) sprinklers in warehouse rack storage configuration	7.6 m metal containers in 6.1 m, 7.6 m and 9.1 m high building	Heptane pool	NS	E	Plume velocity, temperature,	49 ESFR pendant sprinklers, K-factor of 20 L/min/bar$^{1/2}$, RTI of 28 (ms)$^{1/2}$
Xu et al.[87]	Single droplet impingement on a burning fuel liquid surface	Liquid container0.075 × 0.075 × 0.08	Alcohol pool	NS	E	Impact velocities	Impact droplet diameter of 2.2 mm
Noaki et al.[71]	The study identifies correlations for maximum value of HRR for a given combustible material at varying water application conditions	Experimental test bench	n-heptane, wood cribs	6–12. 8 kW	E	Temperature, HRR	1.89–7.56 mm per min

(continued)

Table 2. Continued

References	Description	Enclosure dimensions	Fuel type	HRR, peak	M	Measurements	No. and type of sprinkler head(s)
Tang et al.[88]	Effects of spray angle and vertical water flux distributionon the downward smoke displacement was studied. Using FDS, v6, LES approach	The dimensions of the smoke hood are 2 m × 2 m × 1.2 m.	Diesel pool simulated fire; size:0.3 m × 0.3 m × 0.07 m^3	NS	N	Gas flows, temperature, HRR	The nozzle is set centrally in the smoke hood, at height 2.6 m fromthe floor, with orifice diameter equal to 1.5 mm
Xin et al.[83]	Fire detection, sprinkler activation and fire suppression of a 25.6 m high roll papers storage warehouse.	NS	Gasoline pool, three rolled paper fires	320, 160, 80 kW	E	Firm rate, exfoliation layer & time	Single point nozzle, flow ratesbetween 0.8 and 2.3 L/min
Schwille and Lueptow[43]	Studied the effect of suppression on the fire plume and analysis how the interaction boundary depends on the fire and the spray	Test bench	Methane gas burners, with 10, 18 and 25 cm diameters	5, 15, 50 kW	E	Temperature, plume height,velocity	Nozzle types: orifice size 3.97, 3.57 mm; K-factor 0.76, 0.73 L/minKPa$^{1/2}$; spray angle 120°, 50°F980 sprinkler (orifice size 12.2 mm, K-factor 8.07 L/minKPa$^{1/2}$).
Yu, 2012	Froude-modelling-based scaling relationships for spray–plume interaction	1.22 m × 1.22 m × 1.22 m	Propane burner	10–50 kW	E	Gas temperature, HRR	9 nozzles, 0.18 L/min with a volume-median droplet diameter of62 mm
Meredith et al.[80]	Radiation heattransfer is applied to a vertical panel with water flowing down the surface for model validation	NS	NS	5–33 kW	N	Temperature	Water flow rates range from 2 to 52 g/m/s

(continued)

Table 2. Continued

References	Description	Enclosure dimensions	Fuel type	HRR, peak	M	Measurements	No. and type of sprinkler head(s)
Crocker et al., 2010	Twenty-four full-scale fire tests were conducted to determine a simple method for accounting the impact of a single residential sprinkler on fire-induced doorway flows	Compartment size 9.75 × 4.88 × 2.44 m^3 fire test room	Premixed air-propane burner, 0.46 m^2	31.6,62.9, 105.3, 158 kW	E, N	Plume height, velocity, CO, CO_2, NOx, O_2, HRR	2, Tyco LFII is a pendent sprinkler with a 4.9 K-factor, water flow rate of 49.2 L/min
Hua, et al.[20]	Effect of water spray characteristics on fire suppression mechanism and efficiency was studied. Using SIMPLEscheme, Eulerian–Lagrangian approach	An open quiescent environment	Methane burner, 0.25 × 0.25 m^2	53 kW	N	Temperature, velocities, mass flows	Water spray nozzle is located 1.8 m directly above the centre of the burner surface, droplets sizes range from 100 to 270 mm in diameter
Li et al., 2014	Scaling of internal walltemperatures in enclosurefires: scale 1, 1/2 and 1/35	2.4 m × 2.4 m × 3.6 m,1.2 m × 1.2 m × 1.8 m,0.69 m × 0.69 m × 1.03 m	Propane burners	4.4–1200 kW	E	Temperature, HRR,	NA
Hamins and McGrattan[78]	Investigate the effect of entrainment hot gases (air and smoke) on sprinkler, vent and draft curtains	Test facility of dimensions 37 m × 37 m and 8.2 m high	Propane burner & 125 cartons of rack storage boxes	NS	E	Gas temperature, HRR, actuation time, etc.	Upright sprinklers with orifice size 15 mm. Actuation temperature 74°C. RTI and C-factor are 148 $(ms)^{1/2}$ and 0.7 $(m/s)^{1/2}$

(continued)

Table 2. Continued

References	Description	Enclosure dimensions	Fuel type	HRR, peak	M	Measurements	No. and type of sprinkler head(s)
Xiao, 2012	A model which predicts vent flows along room was developed. Using FDS, LES approach	Computational domain, based on physical dimensions: 9.75 m length, × 4.88 m width, 2.44 m height. Cell sizes 0.1 m^3	0.46 m^2 burner with premixed air/propane	45–100 kW	N	Temperature, HRR, velocities, CO, CO_2	Tyco LFII pendent sprinkler (residential sprinkler) with 4.9 K-factor
Antonov et al., 2016	The effects of collision of two water droplets on a flow of high temperature gases was investigated	Experimental test bench	Kerosene burner	*1100 K	E	Temperature, velocity of gases	Droplet radii 0.025–0.25 mm
Volkov et al.[82]	Investigate the characteristics distances travelled by single droplet in opposing flow of high temperature gases	Test bench	Kerosene burner	NS	E	Impact velocities	Droplet initial diameter, 2.6–3.4 mm
Xie et al.[60]	Investigates the effects of water application times 20–45s on the HRR of burning upholstery chair	Fire test room, 3.6 m × 2.4 m × 2.4 m high	Upholstery chair	1246.6 kW	E	Temperature, HRR, CO, CO_2	Single point nozzle, orifice diameter 2 mm, flow rate 50.6 L/min
Bill et al.[61]	Investigate the required delivery density (RDD), for a residential quick response sprinkler	NS	Reclining chair	1500 kW	E	Temperature, HRR	12 sprinklers of 2.3–8.6 mm/min, C factor 0.52 $(m/s)^{0.5}$
Yao, 1998	ESFR sprinkler tests, measurements of RTI, ADD and RDD	3 m × 3 m × 3.5 m	2 × 2 × 4 array of rack storage of plastic commodities	1231 kW	E	Temperature, ADD, RDD, CO, O_2	1 sprinklerK-factor = 14US

(continued)

Table 2. Continued

References	Description	Enclosure dimensions	Fuel type	HRR, peak	M	Measurements	No. and type of sprinkler head(s)
Lin and Huang, 2020	Fire suppression of peat smouldering fire	Cylindrical steel mesh reactor with diameter of 10 cm and height 15 cm	Wood crib fire	NS	E	Temperature	Sprinkler nozzle, with orifice diameter of 15 mm, operating pressure of 500 KPa
Zhao et al., 2015 (Invalid source specified)	The effect of water spray fluxes from 0, 30°C spray angles on suppression of wind-aided vertical RPU (rigid polyurethane) fire was investigated	Standard combustion chamber: 10 m × 7 m × 4 m (height)	Heptane pool, RPU (rigid polyurethane) material	NS	E	Temperature, rad flux, CO, smoke density, extinguishing time	Single (improvised) spray nozzle, flow rate is 0.084 L/min
Trapp and Rangwala[66]	Engineering correlations for optimization of the effect of various configuration of in-rack warehouse storage fire was investigated. Using MATLAB algorithm approach	NA	Group A plastic (based on NFPA13, for commodity classification)	1055 kW	T	Temperature, HRR, velocities	N-number, in-rack and ceiling sprinklers
Hoffman and Galea, 1991	An empirical relationship to evaluate heat transfer between the water sprays and flames from different fire scenarios was investigated. Using SIMPLEST code and IPSA; PISO; algorithm. Turbulence, K-e	Office scenario 2.44 m × 3.66 m and 2.44 m in height (1848 grid cells), and hospital scenario 7.32 m × 7.85 m × 2.7 m (2310 grid cells)	Simulated fire: typical of office and hospital scenario	Office fire and 50 kW heat source. Hospital fire and 6 kW heat source	T, N	Temperature	A single centrally positioned sprinkler located 1.8 m from the fire and 0.1 m below the ceiling. Water flow rate 0.596×10^{-3} m^3/s

(continued)

Table 2. Continued

References	Description	Enclosure dimensions	Fuel type	HRR, peak	M	Measurements	No. and type of sprinkler head(s)
Liu, et al.[72]	The study investigated the effect droplet sizes on the fire suppression efficiency for sprinkler and water–mist systems for fully ventilated compartment. Using FDS, EL approach	Dimensions of computation domain: 4 m × 4 m × 3 m room, with centrally located ventilation 0.38 × 0.38 m^2	Simulated fire: 1 m^2 size methane pool	200 kW	N	Temperature, HRR, velocities, mass fractions, relative humidity	A single standard quick response sprinkler type: 8.2–13.0 mm orifice size, K factor 43.2, 83.5 and operating pressure of 0.48, 0.53 bar. droplet diameter is 1–2 mm
Beji et al.[81]	Study of heating and evaporation ofa single water droplet for validation of numerical models	NA	Simulated fire of 100–800°C convective hot air flow	NS	N	Temperature	Single suspended water droplet source of initial diameter between 2.6 and 3.4 mm
Link et al.[49]	Quantify spray dispersion and spray–plume interactions for FireFOAM model validation	1.87 m × 1.87 m × 1.5 m	NA, plume modelled as forced air jet	NS	N	Temperature, plume velocities	4 K 33.1 L/min/bar$^{1/2}$ sprinklers

HRR: heat release rate; M: methodology; NS: not specified; E: experimental; RTI: response time index; FDS: fire dynamics simulator; LES: large Eddy simulation; N: numerical/computational fluid dynamics (CFD); NA: not applicable; CO: carbon monoxide; CO_2: carbon dioxide; ADD: actual delivered density; T: theoretical analysis; m: mass loss rate.

*Heat release rate per unit area.

Table 3. Summary of full-scale studies on enclosure fire sprinkler system.

References	Description	Enclosure dimensions	Fuel type	HRR	M	Measurements	No. and type of sprinkler head(s)
Alpert[29]	Investigate how pressure, flow rate, drop size spray angle, influences degree of water penetration, 2D simulation using TEACH-T elliptic & Lagrangian approach	An impermeable ceiling boundary is located at a vertical distance of 2.4 m above the floor	Simulated fire (propane burner)	606, 677 kW	N	Ceiling jet temperature, gas velocities	A nozzle point located at ceiling level with water flow rate is 4.6 kg/s
Bennets et al.[62]	Performance of sprinklers and detectors in real office fire situations	3 × 3 × 2.75 m^3 (1)4.85 × 4.25 × 2.75 m^3 (2)	Typical office setup	Up to 2 MW	E	Temperature, HRR	Numerous K6 L/min/(bar)1/2 sprinklers, flowrate 66–46 L/min,
McGrattan and Sheppard[42]	Thirty-four large scale fire tests were conducted to investigate sprinkler performances as influenced by roof vents and draft curtains on large building	Large-scale fire test facility, 37 × 37 × 30 m	Heptane burner, 125 cartons of polystyrene cups rack storage configuration as fire sources.	NS	E	Temperature	49 upright sprinklers, orifice size 15 mm. Actuation temperature 74°C. RTI and C-factor are 148 $(ms)^{1/2}$ and 0.7 $(m/s)^{1/2}$
Nam, 1996 [46]	Drop size, mass flow rate, discharge velocities and angle, for ESFR sprinkler spray characterization was model using PHOENICS code, PSI-CELL method.	Computation was done over two areas, 1.49 and 5.23 m^2 circles	Heptane spray fire	0.5, 1.0, 1.5 MW	N	Temperature, velocities	1.88, 3.15, 4.42, 6.23 L/s water flow rate, assigned to a single sprinkler head installed horizontally 0.23 m below the ceiling

(continued)

Table 3. Continued

References	Description	Enclosure dimensions	Fuel type	HRR	M	Measurements	No. and type of sprinkler head(s)
O'Grady and Novozhilo[41]	Investigates the effects of sprinkler spray on a ceiling jet fire. Using FDS, LES approach	15 m × 7.5 m × 6 m high, fire test room. Computational domain with cell size of 7.5 cm (1,600,000 cells)	Propane gas burner, 1 m^2 simulated fire	1.5 MW	N	Temperature, velocities (gas)	A single Wormald A CU/P K-80 sprinkler head. flow rate 80, 101 L/min, operating pressure 1.0, 1.6 bar
Ingason and Li, 2019	Investigates the importance of early activation of FFFS in reduction of the maximum HRR of fire	1600 m long, 6 m high and 9 m wide Runehamar tunnel with a cross-section of approximately 47 m^2	Heptane pool, wood crib	80–100 MW	E	Temperature, HRR, CO, CO_2, NO*x*, O_2,	K-360 (L/min/bar1/2) yields a water flow rate of 375 L/min
Chow and Fong[35]	The transient 3D air flow, temperature and pressure fields induced by a volumetric heat source was investigated, using a SIMPLER scheme and k-e for turbulence Mod	9 m × 6 m × 3 m had been considered, divided into 5491 grid points	Simulated wood crib fire source	NS	T	Temperature	14 sprinkler heads, and water flow rate 20–217 dm^3/min
Chow and Fong[35]	Air drag and cooling effects of sprinkler water spray on fire induced hot air was studied. 2D Mod approach using PISO algorithm	9 m × 6 m × 3 m had been considered, divided into 5491 grid points	Simulated wood crib fire source	NS	T	Temperature, HRR	16 sprinkler head (common type, FOC rules): 590 KPa pressure, 1.17 kg/s,

(continued)

Table 3. Continued

References	Description	Enclosure dimensions	Fuel type	HRR	M	Measurements	No. and type of sprinkler head(s)
Chow and Cheung[36]	Investigate the effects of gas flow, temperature and smoke concentration field. 2D Mod approach using PISO algorithm and k-e turbulence approach	Compartment dimensions of 15 m long, 7.5 m width, 6 m height	Simulated fire-induced hot air from a gas burner	1.0–1.5 MW	T, N	Temperature, velocities (mass flows) and so on	6 sprinkler heads with nozzle diameter of 12.7 mm and water flow rate 80–100 L/min used
Novozhilov,et al.[77]	The mechanism of wood fire extinguishment was investigated. Using FIRE code and turbulence k-e	A 7 m long section × 5.4 m and height of 2.4 m	Wood crib fire (slats)	NS	N	Temperature, HRR, CO, CO_2	Wormald type 'A' 15 mm diameterpendant nozzle, maximum droplet diameter was 1.5 mm and pressure 350 KPa
Schwille and Lueptow[44]	A model for the effect of droplet spray for equation of buoyant plume developed. Using modified Morton's buoyant plume eqn.	An open quiescent environment	Simulated fire	500–1500 kW	T	HRR, temperature, velocities (plume)	A single sprinkler head 0.94 m above the fire, sprinkler orifice and flow rate 19 mm and 6.23–8 L/s
Chow and Cheung[37]	Air drag and cooling effects of sprinkler water spray on fire-induced hot air was studied. 2D PISO algorithm. Turbulence, k-e	length 3.8 m, width 2.4 m and height 2.4 m, (grid cells 4116)	simulated fire: typical of office	NS	T	Temperature, HRR, velocities, mass flows	A single centrally positioned sprinkler head with actuation temperature of 74°C and 12.7 mm nozzle diameter

(continued)

Table 3. Continued

References	Description	Enclosure dimensions	Fuel type	HRR	M	Measurements	No. and type of sprinkler head(s)
McGrattan, et al. 2000	Investigate the effect of water application rate to ignition and HRR of a group of plastic commodities. Using FDS, LES approach	Computational domain is 50 m × 50 m × 20 m. Grid cells of 10 × 20 cm	Simulated fire: rack storage configuration of Group A commodity plastics in cartons of corrugated paper	NS	N	Gas flows, temperature, HRR and actuation time	Upright sprinklers with orifice size 15 mm. Actuation temperature 74°C. RTI and C-factor are 148 $(ms)^{1/2}$ and 0.7 $(m/s)^{1/2}$
Lai et al., 2010	The influence of fire source location on the actuation of both smoke detector and sprinklers system was investigated	Interior dimensions of compartment 5.7 m × 4.7 m × 3.3 height	Movable and fixed fire load(s) of office equipment	10 MW	E	Temperature, CO, CO_2, NO*x*, O_2, HRR, actuation time	4 sprinkler heads with K-factors of 80 $L/min/(bar)^{1/2}$
Pasandideh-Fard et al., 2001	Investigates the heat transfer as a result of water droplet impinging on hot surface	NA	Simulated fire, 50 mm square stainless-steel plate,	NS	N	Temperature, impact velocity	0.5–4.0 m/s water drops velocity and droplet diameter is 2 mm
Ren, et al.[69]	Study investigate fire spread mechanisms rack-stored commodities and identify key parameters for fire suppression evaluation. Using FireFOAM, LES approach	The domain was 17.88 m long, 13 m wide and 10.16, 14.25 m high. Grid cell is 2.54 cm, 4.64 cm	Simulated fire: wood pallet and corrugated cardboard box (class 2, commodity)	22–30 MW	N	Temperature, HRR, velocities, CO, CO_2, time	15, standard-response upright ceiling sprinklers (K-factor of 160 $L/min/bar^{1/2}$)

(continued)

Table 3. Continued

References	Description	Enclosure dimensions	Fuel type	HRR	M	Measurements	No. and type of sprinkler head(s)
Ge, et al.[68]	Effectiveness of side wall sprinklers to suppress fire in train stabling yard on the typical combustible material of MRT train was investigated. Using FDS, v5, LES approach	Large area typical stabling yard of 300 m long, 210 m wide and 14 m high	Simulated fire source: typical MRT trains of dimensions 24 m × 3 m × 3.4 m	7 MW	N	Temperature, HRR, velocities, CO, CO_2	Fast response sprinklers: orifice diameter, 16 mm, flow rate, 90 L/min volumetric droplet size, 1000 μm, RTI is 50 $(ms)^{1/2}$, activation temperature 68°C, and 12.7 m above floor level and 3 m apart
Qiang, et al.[75]	The influence of discharge pressure, spray distance on the effectiveness of controlling the fire source heat release rate was studied. Using FDS, LES approach of UBS Fuel Tank Room scenario	8 m × 2 m × 2 m is located in the 10 m × 8 m × 4 m high concrete building structure and 8 m × 2 m × 2 m fuel tank room	Simulated fire source: diesel	*2060 kW/m^2	N	HRR, gas flows velocities, temperature	A single water spray point, specifications are: operating pressure, 0–2.0 bar; K-factor is 40 $L/min/bar^{1/2}$ and activation temperature is 74°C.

HRR: heat release rate; M: methodology; 2D: two dimensional; N: numerical/computational fluid dynamics (CFD); NS: not specified; E: experimental; RTI: response time index; ESFR: early suppression-fast response; FDS: fire dynamics simulator; LES: large Eddy simulation; FFFS: fixed fire-fighting system; 3D: three-dimensional; T: theoretical analysis; FOC: Fire Offices Committee; NA: not applicable; CO: carbon monoxide; CO_2: carbon dioxide; m: mass loss rate.

*Heat release rate per unit area.

50 years (1970–2020). The selected articles were classified and reviewed according to the physical phenomena involved in the interaction between fire sprinkler water sprays and fire, that is, sprinkler spray with flame, fire plume and hot solid surfaces. It was found that extensive research effort has been carried out concerning the study of the interactions of sprinkler water sprays with flame and fire plume, while study of the interaction of sprinkler spray and hot surfaces has received less attention. A summary of sprinkler design parameters and variables from selected experimental and numerical research studies, are provided in compacted form to serve as references, particularly for comparative study of both large-scale and reduced-scale sprinkler fire suppression investigation. The evolution of the trends of research over the last 50 years with respect to the interactions of sprinkler water spray and fire has been addressed, also sighting scientific challenges. However, the authors recognized that new pathways for research in fire suppression systems, which also promises novel technological alternatives exist, such as hybrid fire suppression systems, SMART sprinkler technology and vacuum sprinkler systems application, are gradually taking the lead of research in fire protection.

In conclusion, this present review work was able to establish that

1. Six categories of studies were identified from the 153 available relevant literatures, which are fluid flow in sprinkler network with 5.3% of articles; sprinkler spray (27.3%); fluid flow in sprinkler network and sprinkler spray (0.2%); sprinkler spray and fire phenomenon (33.0%); fluid flow in sprinkler network and sprinkler spray and fire phenomenon (0.4%); and risk assessment and sprinkler effectiveness studies (34.0%).
2. Publications were reviewed for sections such as sprinkler spray and fire plume; sprinkler spray and flame; and sprinkler spray and hot solid surfaces.
3. Several key parameters relevant to fire suppression were highlighted including plume penetration and spray dispersion, spray momentum and water flux distribution. While varied operating parameters include spray angles and injection velocities, spray volume flux, spray drop size, drop velocity, spray droplets size, HRR and so on.
4. The reviewed literature also provided information on parameters that have been studied such as the scale (full/reduced scale) and type of research (experiment/numerical), sprinkler characteristics, fuel configuration and size, ventilation/enclosure conditions and varied case studies of real events and scenarios.

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ORCID iD

Khaled Chetehouna https://orcid.org/0000-0003-2850-5521

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Author Biographies

Shehu A Abdulrahman received his master degree in Energy and Environmental engineering in 2017 from the University of Maiduguri, Maiduguri, Nigeria. He is now a PhD student at the Permeation, Pyrolysis, Combustion and Fire (P2CF) research team, in the Combustion and Explosion axis of the PRISME Laboratory, National Institute of Applied Sciences (INSA Centre Val de Loire), Bourges, France. His research interests focus on the fire behaviour and suppression of compartment fires, and on the study and development of innovative fire sprinkler systems.

Khaled Chetehouna is Full Professor in Fire and Energy Sciences and Vice-Chairman for Research at the National Institute of Applied Sciences (INSA) of the Centre Val de Loire region, France. He is head of the P2CF (Permeation Pyrolysis Combustion and Fire) team at the PRISME Laboratory (EA 4229). His research activities are devoted to Fire Sciences and Fire Safety, and in particular: the characterization of Fire Degradation of Composites Materials for Aerospace and Automotive applications, the study of Flame propagation in buildings, and the Evaluation of the performance of Fire Suppression systems for the protection of Industrial buildings and Cultural Heritage, including innovative environmentally friendly sprinkler systems. He has also worked many years (1997-2015) in the field of Wildland fires for which he has developed different experimental approaches and new metrologic tools. Prof. Chetehouna is a member of the strategic board of the CNRS French Research Group in Fire Sciences GDR “Feux” n°2864 since 2010. He is the author of 109 documents including more than 78 papers in international peer-reviewed journals, 779 citations by 580 documents, with h-index of 16 (25 May 2021).

Axel Cablé is an independent expert accredited by the French Ministry of Higher Education, Research and Innovation for R&D operations in the fields of Fire and Industrial Safety, Energy Efficient Buildings and Composite Materials. A. Cablé holds a PhD in Fluid Mechanics and an Engineering degree in Energy Sciences. He has 12 years of experience in leading research institutes in France and Norway (UMR CNRS, CEA, INSA, SINTEF), and is specialized in the development, numerical modelling, experimental testing, and certification of innovative technologies. He is currently General Manager of the SME EXEC (Paris Area, France) which developed and patented the novel Vacuum Sprinkler system, and head of the company IBS-Conseil (Lyon Area, France) which specializes in Regional, National and European funding of R&D projects and innovative technologies.

Øyvind Skreiberg is Chief Scientist of Stationary Bioenergy at SINTEF in Trondheim, Norway and holds a doctoral degree in thermal conversion of biomass from the Norwegian University of Science and Technology (NTNU) in Trondheim. He has more than 25 years' experience in the field and has worked and published (more than 600 publications and presentations in total) on a number of bioenergy topics, e.g. renewable heat production, BtE, WtE, combustion, gasification, pyrolysis, torrefaction, carbonization, CHP, ash-related challenges, wood stoves - and their building integration, emissions in general and especially NOx. He has been active in many projects focusing on thermal decomposition of wood under various conditions. He has led and worked in a variety of national and international projects at SINTEF for the last 13 years, and earlier at NTNU, and is active in international networks as IEA Bioenergy, EERA Bioenergy and RHC-ETIP as well as biocarbon/biochar networks. Øyvind Skreiberg chairs the RHC-ETIP horizontal working group on 100% RE Buildings. Dr. Skreiberg is author of 154 publications indexed by Scopus with an h index of 32 based on 3267 citations (26 May 2021).

Maurice Kadoche is the CEO of the SME EXEC (Paris Area, France) and inventor of the Vacuum Sprinkler system technology. Mr. Kadoche is among the most recognised industry experts in fire protection in France, with more than 45 years of experience in the field. He has an Engineering Diploma from Technion Institute of Technology & from Neguev University (Israel), and a wide expertise in Fire Protection of critical risks and infrastructures, including military and nuclear sites, and 25 years as R&D and Technical Director in large European and international companies.