Fire Safety Journal 68 (2014) 30–40

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

An experimental study on the spray characteristics of residential sprinklers under low-flow and low-pressure conditions

Ljiljana Zlatanovic [a,*], Jan Vreeburg [b], Jan Peter van der Hoek [c], Ivars Poznakovs [d]

[a] *Delft University of Technology, Department of Water Management, Delft, The Netherlands*
[b] *Wageningen University, Sub-department of Environmental Technology, Wageningen, The Netherlands*
[c] *Delft University of Technology, Department of Water Management, Delft, The Netherlands*
[d] *Riga Technical University, Water Engineering and Technology, Latvia*

ARTICLE INFO

Article history:
Received 17 June 2013
Received in revised form
2 May 2014
Accepted 31 May 2014
Available online 3 July 2014

Keywords:
Domestic fire sprinkler
Spray characteristics
Theoretical heat capacity
Evaporative heat capacity

ABSTRACT

An experimental investigation to explore the characteristics of the initial drop screen which was formed by sprinkler heads at low water pressures was carried out. Two commercially available sprinkler heads (with thin and massive frame arms) were modified, not only in terms of deflector plate design, but also with respect to the orifice diameter, in order to decrease the flow and study the effect on liquid sheet thickness, initial sheet angle, sheet breakup distance and drop size distributions and their correspondence with the existing mathematical models. It was found that the addition of a boss in the sprinkler design had little impact on the average drop size and sheet breakup distance. The presence of the boss was found to influence the initial angle of the liquid sheet, which was in line with findings of previous researches. Longer slots on the deflector plate did not change the initial angle of the sheet considerably, but did result in an earlier sheet breakup and smaller median drop diameter.

A drop combustion sub-model was built, introducing two novel parameters: theoretical heat capacity (THC) and evaporate heat capacity (EHC), which could be used for estimating the actual heat capacity of the spray. In combination with the calculated drop size distribution in a spray screen, the combustion sub-model confirmed that sprinkler performance does not depend merely on provided flow, but rather on the drop size and the number of drops in a drop screen.

1. Introduction

Worldwide, fires cause more than 10,000 deaths per year [1], while home fires account for over 75% of all fire fatalities [2]. Among various technologies for reducing the burden of domestic fires, residential fire sprinklers have proven to prevent more than 80% of residential fire fatalities and around 70% of property damage per fire [3]. Moreover, according to a recent study, fires in sprinklered dwellings have less negative environmental impact compared to non-sprinklered dwellings, as greenhouse gases released by burning dwellings could be significantly reduced when automatic sprinklers are activated [4].

The history of automatic fire sprinklers started with Philip W. Pratt's patent in 1872, while the first automatic sprinklers system was applied in practice in a piano factory in 1874 [5]. Since then, automatic fire sprinkler has been defined as a device which is automatically activated when heated to a predetermined point, i.e. in case of a fire. Once the sprinkler is activated, a water stream is discharged through the sprinkler orifice. The water stream then strikes the sprinkler deflector, forming a spray which is delivered to a fire hazard area. To accomplish the goal of extinguishing or controlling a fire, not only must the formed sprinkler have sufficient momentum to penetrate the fire plume and reach the burning area, but it also must have adequate evaporative heat capacity (EHC) to adsorb heat from the fire plume and cool the surrounding environment. Therefore, the initial drop screen must consist of both large and small drops, since larger drops are better at penetrating fire plume and reaching more distant locations, while smaller drops have high heat adsorption capacity, and hence are more efficient in cooling the surrounding air [6,7].

Even though the sprinkles have been widely used for more than a century, their application in Europe is mostly restricted to industrial purposes. Wide application in residential environments is still limited due to both technical and emotional issues [8]. The emotional issue of fire sprinkler restriction is the result of the so-called "Smoke detector" and "Hollywood" syndrome. "Smoke detector" syndrome is associated with an alarm going off once in a while for no obvious reason, while "Hollywood" syndrome implies that if one of the fire sprinklers goes off, all of them will go off as

---

[*] Corresponding author.
E-mail addresses: l.zlatanovic@tudelft.nl (L. Zlatanovic), jan.vreeburg@wur.nl (J. Vreeburg), j.p.vanderhoek@tudelft.nl (J.P. van der Hoek), ivars.poznakovs@inbox.lv (I. Poznakovs).

http://dx.doi.org/10.1016/j.firesaf.2014.05.018

well. However, in reality, only the sprinkler closest to the fire source will be heated and activated. The technical problem of wide spreading domestic fire sprinkler system implementation is more challenging. The core of the problem is the required water flow and injection pressure for conventional fire sprinklers, which is from 50 to 80 l/min and 0.7 to 1.6 bar, respectively. In the Netherlands, water flow and pressure at a household level are considerably lower (approximately 30 l/min and 0.5 bar, respectively, at the most distant location in a household). The required flow for a sprinkler system can never be supplied by a standard drinking water connection [9]. Installation of a conventional sprinkler system would require a separate reservoir and a pump. Such a system should be maintained and tested regularly, which makes it very expensive and non-applicable on a large scale.

In the past five decades significant efforts have been made to experimentally and theoretically establish a correlation between design parameters of fire sprinkler systems and initial spray characteristics. Scaling laws Eq. (1) for the sheet breakup locations and Eq. (2) for the median drop diameter were firstly proposed by Huang [10]:

$$2r_{bu,sh}/d_0 = CWe^{-1/3} \tag{1}$$

$$d_{50}/d_0 = CWe^{-1/3} \tag{2}$$

where $r_{bu,sh}$ is the location at which the sheet is broken into ligaments and drops [m], d_{50} is the median drop size [m], d_0 is the orifice diameter [m], C is an experimentally found constant and We is the Weber number [−] ($We = \rho U^2 d_0/\sigma$, where ρ is water density [kg/m^3], U is velocity of water flow at the sprinkler orifice [m/s], d_0 is diameter of the injection orifice [m] and σ is surface tension of water–air interface [kg/s^2]).

In order to evaluate the scaling laws, Dundas [11] used 6 sprinkler heads which were geometrically similar, but had different nozzle orifice diameters ranging from 3.1 to 25.4 mm and, with pressures ranging from 0.345 to 5.25 bar. Utilizing the high speed photographic technique, counting and measuring the size of drops by electronic scanner, he concluded that his experimental results were in line with the proposed $We^{-1/3}$ law.

Drop size measuring experiments were also performed by Yu [12], but this time with a more sophisticated laser-based imaging technique. In this research, three upright sprinkler heads with different orifice diameters were used for measuring drop characteristics at two different locations, at 3 m and 6 m below the sprinkler heads. The results were also very much in line with $We^{-1/3}$ scaling law.

Widmann [13] and Sheppard [6] employed the Phase Doppler Interferometry (PDI) technique for measuring the spray characteristics of various sprinkler heads. Despite high accuracy of the PDI method, measurements could only be done at a single point and just a small sample volume was subjected to the analysis. When operating under pressures in the range from 0.93 to 2.0 bar, Widmann confirmed the scaling law of the previous researchers. However, at a low pressure of 0.69 bar, the local mean volume drop size was found to be considerably smaller than the one predicted by the scaling law. The influence of a much wider pressure range, from 0.345 to 5.52 bar, on drop characteristics was examined by Sheppard. Spray characteristics for 16 different sprinkler heads with different orifice diameters were measured by PDI technique at radial distance of 0.38 m from the sprinkler head. He stated that the correlation of the drop size to the Weber number was not applicable, most likely due to the limitations associated with the utilized PDI method.

Planar Laser Induced Fluorescence (PLIF) techniques were employed in Blum's study [14] and the obtained results showed that the sheet breakup location for sprinklers with different types of deflector shape also followed $We^{-1/3}$ scaling law. It was also noticed that incorporation of the boss into the sprinkler design apparently increased sheet instability, and consequently the sheet breakup distance became significantly shorter.

Ren continued Blum's research [15] and reported that the sheets formed by the sprinkler with a commercially available deflector broke up earlier than the sheets generated by the flat deflected sprinkler at a comparable orifice diameter. The detected behavior was most likely a result of geometrical features which had been added to the flat deflector. This may have resulted in formation of the considerably thinner sheet at the edge of deflector, and hence smaller drop sizes.

Based on the free surface boundary layer [16] and wave dispersion theories [17], a deterministic model of the atomization process was developed by Wu [18]. Assuming a flat deflector plate, the sprinkler was modeled as an axisymmetric impinging jet. At high injection pressure ranges, the agreement between the modeled and measured data was found to be outstanding. However, at low pressure conditions (below 0.69 bar) large discrepancies were found between the modeled outputs and experimental data.

Liquid sheet thickness in the deterministic model, developed by Wu [18], was calculated using the Eq. (3) derived by Watson [16]:

$$\delta = \frac{d_0^2}{8r} + 0.0166\left(\frac{7\vartheta}{U_0}\right)^{1/5} r^{4/5} \tag{3}$$

where d_0 is the orifice diameter [m], r is the radius of the deflector plate [m], ν is water kinematic viscosity [m^2/s] and U_0 is the average jet speed from the orifice [m/s].

In a recent study [7], an integrated model has been developed so that the sheet thickness could be determined for different degrees of viscous interaction with the deflector. In this model, both sheet thickness (∂) and velocity of the water sheet at the deflector edge (U) can be numerically solved using Eqs. (4) and (5) with unknown starting thickness and sheet velocity:

$$\delta\frac{dU}{dr} + U\frac{d\delta}{dr} + \frac{\delta}{r}U = 0 \tag{4}$$

$$2U\delta r\frac{dU}{dr} + U^2\delta = -rg\delta\frac{dU}{dr} - \frac{1}{2}C_d r U^2 \tag{5}$$

where g is the acceleration of gravity [m/s^2] and C_d is the average friction coefficient of the deflector plate [−].

The results of the sheet thickness were found to correspond well with the data obtained experimentally under very low pressures (0.034 bar and 0.069 bar). Additionally, in this study the medium drop sizes were experimentally derived under low injection pressures (0.34 bar and 0.68 bar). However, the drop diameters were measured only at horizontal distances from the edge of the disk of 0.3 and 0.6 m, which were not necessarily areas of the initial sprinkler spray formations.

These experimental studies were mostly conducted under higher pressure ranges. These pressures made widespread application in domestic applications impossible. In the study described in this paper, an experimental study was carried out at low injection pressures, which were available in drinking water installation at household level in the Netherlands at the most distant location in a house. In order to assess the influence that the sprinkler geometry, under these circumstances, had on the key parameters of the atomization process, detailed measurements of sheet thickness, initial angle of the liquid sheet, sheet breakup distances and drop size distributions were performed.

Even though the Fire Dynamics Simulator (FDS), a computational fluid dynamics model of fire-driven fluid flow, is becoming increasingly popular lately [15], this research has developed two novel parameters based on the characteristics of a spray. In a combustion sub-model built based on [19] these two parameters, theoretical heat capacity (THC) and evaporate heat capacity (EHC),