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# Analysis of a semi-empirical sprinkler spray model

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ABSTRACT

Modelling the atomization process in fire sprinklers has remained a challenge mainly due to the complexity of sprinkler geometry. A review of existing fire sprinkler spray modelling approaches, including film flow and sheet tracking models, showed that they mainly assumed a constant sheet velocity and linear attenuation of the sheet thickness before its disintegration. In the present study, a liquid sheet trajectory sub-model based on the solution of stream-wise conservation equations has been used to predict both sheet thickness and velocity as it radially expands. This will also help to investigate the extent to which a change in the release angle can affect the sheet characteristics. The analysis carried out shows that the proposed approach improves the predictions of mean droplet diameter and initial droplet speed. A semi-empirical approach is further introduced in the study by using experimental volume fraction measurements to characterize sprinkler sprays in the near field. For a given direction predictions have been conducted for droplet volume median diameter, water volume flux and droplet average velocity at different elevation and azimuthal locations. A reasonably good agreement is found for the near field measurements.

## 1. Introduction

Modelling sprinkler atomization is a challenging task, due to the stochastic nature of the breakup process. This complexity is predominantly influenced by the sprinkler geometry. Predictive models are required to evaluate sprinkler spray characteristics for coupling with fire models to predict sprinkler suppression performance. Droplet dispersion models are available [1] for tracking droplets after the initial atomization process is completed, but there is no general atomization model to predict the initial spray characteristics for sprinklers and this is a critical missing link in the modelling of fire suppression with sprinklers.

Various experimental studies have been conducted to characterize droplet's size and velocity in sprinkler spray using methods such as photographic techniques [2], laser-light shadow imaging method [3–4], Phase Doppler Interferometer [5] and Particle Image Velocimetry [6]. These studies have provided valuable data for the development of atomization and spray models. One of the first correlations presented from droplet size measurements was suggested by Dundas [2], in the form $d_{V50}/D_0 = CWe_0^{-1/3}$. Measurements of spray undertaken by Yu [3] showed that any change in the injection orifice diameter and the deflector geometry in an upright sprinkler affects directly the coefficient of proportionality, *C*. The droplet size distributions of the experimentally studied sprinklers were expressed as an amalgamated form of log-normal and Rosin–Rammler distributions. Despite the insensitivity of these distributions and correlations to some key parameters relevant to the initial spray, they are still used as primitive predictive models. Yu [3] noticed a deviation from the $\Delta p^{-1/3}$ scaling law for droplet size at low pressures (around 69 kPa). The experiments of Sheppard [6] presented the variation of radial velocity with polar angle at various azimuthal angles, as well as a rough approximation of the radial velocity close to the sprinkler ($\sim 200$ mm), which is described by $0.6(\Delta p/\rho_f)^{1/2}$. Ren et al. [7] and Zhou and Yu [8] conducted series of experiments on simplified and commercial sprinklers, respectively. Both studies investigated the effect of sprinkler geometrical components on the spray formation process and provided more insight to some essential physics of the atomization process.

Research was also undertaken by many researchers on the modelling of sprinklers sprays. The underlying simplified atomization physics resulting from a jet impinging on an axisymmetric horizontal disc (deflector plate) are thoroughly discussed in the literature [1,9–10]. At the first stage the jet transforms into a film flow upon impact, moving radially outwards on the deflector surface. The film is transformed into an unconfined sheet as it expands beyond the deflector edge. A sinuous wave grows on the decaying thickness sheet due to existing inertia, surface tension, viscous force and the pressure difference between the sheet upper and lower surfaces. At critical wave amplitudes, the sheet either breaks up into cylindrical strands (ligaments) or disintegrates directly to droplet depending on the jet Weber number [9].

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**Nomenclature**

| | |
|---|---|
| $A$ | amplitude [m] |
| $C$ | coefficient of proportionality |
| $C_d$ | friction coefficient of the deflector surface |
| $D_o$ | sprinkler orifice diameter [m] |
| $d$ | diameter [m] |
| $d_{V50}$ | volume median diameter [m] |
| $f$ | dimensionless total growth of the wave |
| $g$ | gravitational acceleration [m/s$^2$] |
| $K$ | sprinkler *K*-factor [m$^3$/s kPa$^{-1/2}$] |
| $N$ | number of droplets per degree |
| $N'$ | number density [m$^{-3}$] |
| $n$ | wave number [m$^{-1}$] |
| $\Delta p$ | pressure difference at sprinkler orifice between water reservoir and atmosphere |
| $Q$ | volumetric discharge [m$^3$/s] |
| $\dot{q}$ | water volume flux [m$^3$/s/m$^2$] |
| $\mathrm{Re}_\xi$ | stream-wise Reynolds number: $\rho_g D_0 \lvert U_g - U_f \rvert / \mu_g$ |
| $\mathrm{Re}_\zeta$ | tangential direction Reynolds number: $\rho_g D_0 \lvert W_g - W_f \rvert / \mu_g$ |
| $r$ | radial location from sprinkler/radius [m] |
| $S_\xi$ | stream-wise viscous forces in $\rho_g/(2\delta)[0.79(1+150\delta/r)(\mathrm{Re}_\xi)^{-1/4}](U_g - U_f)\lvert U_g - U_f \rvert$ |
| $S_\zeta$ | tangential-wise viscous forces $\rho_g/(2\delta)[\,0.79(1+150\delta/r)(\mathrm{Re}_\zeta)^{-1/4}](\,Wg - W_f)\,\lvert W_g - W_f \rvert$ |
| $T$ | temperature [K] |
| $t$ | time [s] |
| $U$ | velocity [m/s] |
| $V$ | volume [m$^3$] |
| $W$ | swirl velocity [m/s] |
| We | Weber number $\rho U^2 D/\sigma$ |
| $z$ | vertical displacement below fire sprinkler angle [m] |

*Greek symbols*

| | |
|---|---|
| $\gamma$ | volume fraction |
| $\theta$ | elevation angle (Polar angle) |
| $\delta$ | film/sheet thickness [m] |
| $\nu$ | kinematic viscosity [m$^2$/s] |
| $\rho$ | density [kg/m$^3$] |
| $\phi$ | azimuthal angle |
| $\lambda$ | wave length [m] |
| $\mu$ | dynamic viscosity [Pa s] |
| $\psi$ | sheet deflection angle |
| $\sigma$ | surface tension [N/m] |

*Subscripts*

| | |
|---|---|
| 0 | jet |
| *bu* | break up |
| *d* | deflector |
| *Dr* | droplet |
| *f* | fluid |
| *g* | gas |
| *lig* | ligament |
| *s* | sheet |
| $\xi$ | stream-wise coordinate |
| $\zeta$ | tangential coordinate |

As the ligaments expand outwards, aerodynamic forces cause dilatational waves to grow along the ligament. When these dilatational waves reach their critical amplitude, the ligaments break into smaller fragments which contract to form drops due to surface tension.

The featured physics in atomization process have been investigated and reported in the literature. The film flow development over a flat plate is predicted by two main models. One of the approaches is an analytical model based on a free-surface similarity boundary layer concept developed by Watson [10]. This model has been a popular choice in numerous applications, hence is used in the present study. Another film model is the integral approach recently formulated by Zhou and Yu [8] where the sheet thickness can be calculated for different degrees of viscous effects. To track the trajectory of the water sheet emerging from a deflector plate, the most widely used and simplest approach assumes an inversely linear decay of sheet thickness and constant velocity of the radially expanding sheet prior to its breakup point known as the Taylor hypothesis [11]. An alternative more rigorous model and detailed sheet tracking approach consists in solving a set of stream-wise continuity equation to resolve the sheet trajectory characteristics as derived by Ibrahim and McKinney [12] and mentioned in [13]. The work presented in the present study builds on this latter model which is referred to as “Detailed Trajectory Model” (DTM) throughout this paper. The aerodynamic instability and disintegration of viscous and inviscid liquid sheets to ligaments and droplets have been studied and reported in the literature [14,15].

The overall goal of the present study is to develop and thoroughly investigate a methodology that is more accurate with further capabilities to predict the near-field initial sprinkler atomization building on and extending some existing models. To achieve this target, two liquid sheet tracking sub-models have been implemented and their accuracy is investigated to shed more light on their capability for the sprinkler initial spray prediction. The present work also further introduces and explores the concept of a semi-empirical approach which is capable of predicting the volume median diameter, average droplet velocity and volume flux of the spray at different elevation and azimuthal locations under the sprinkler with a relatively good degree of fidelity.

## 2. Mathematical modelling

The atomization process relevant to fire sprinklers starts from the moment the liquid jet exits the orifice of the sprinkler and ends when the droplets are formed. This could be categorized as film flow formation, sheet trajectory and growth of instability on sheet's surface toward its breakup, ligament formation and finally droplet formation. Fig. 1 summarises the atomization physics and associated sub-models. Throughout the modelling process, the liquid's temperature and release pressure and the ambient air temperature are required as initial condition as well as the sprinkler's *K*-factor and its orifice and deflector diameter. The mathematical sub-models are briefly discussed in this section with the modifications and extensions introduced by the present authors.

### 2.1. Film formation

In order to calculate the thickness and speed of the sheet leaving the sprinkler's deflector, tines and slots, the film formation over the deflector should be modelled. Film formation comprises of regions such as stagnation point formation, boundary layer formation and developed boundary layer. The detailed characteristics of each of