Nuclear Engineering and Design 324 (2017) 67–77

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Numerical method for determining water droplets size distributions of spray nozzles using a two-zone model

W. Plumecocq*, L. Audouin, J.P. Joret, H. Pretrel

Institut de Radioprotection et de Sûreté Nucléaire (IRSN), PSN-RES, SA2I, LEF, Cadarache, St Paul-Lez-Durance Cedex 13115, France

ARTICLE INFO

Keywords:
SYLVIA
Fire modeling
Spray modeling
Water droplets size distribution

ABSTRACT

The water spray systems are widely used for fire safety area and is a well-established technique for providing safety and protection of nuclear installations and also industrial facilities. One major challenge is to be able to properly determine the technical features of the water spray system that are required for predictive simulations. For that, a Phase Doppler Interferometer (PDI) device, that is a complex and challenging laser technique, is often used to measure the water droplets size distributions and the water droplets velocities. However, some usual water spray models can require as input parameters only an overall water droplets size distribution and water droplets initial velocity and some statistical methods are needed to determine them from local accurate measurements. In this paper, it is addressed a new calibration approach for assessing the input parameters of this modeling by using large-scale and well-controlled fire tests. Then, by introducing some correlations to take into account different operating conditions of the pressure at the spray nozzle head, this technique is validated on other large-scale fire tests. After discussing thoroughly the results, this new method shows that it can be a valuable and efficient tool for determining the overall features of water spray systems linked with the modeling of water spray system used in this study.

1. Introduction

Water spray systems used for fire safety area are a well-established technique for providing safety and protection of industrial and nuclear installations. The research in the domain of water spray systems remains important due to the complexity involved in predicting the interaction between the water sprays and the fire environment. Indeed, a continuous research activity is underway to improve the capability of modeling and predicting tools (Plumecocq, 1997; Ranz and Marshall, 1952; Dundas, 1974; Grant et al., 2000; Wu et al., 2007; Nichols and Gregory, 1986), to measure accurately the characteristics of water spray systems (Sheppard, 2002; Malet and Parduba, 2016; Ren et al., 2011; Myers and Marshall, 2016) and to investigate the efficiency of such systems (Pretrel et al., 2016; Beyler and Cooper, 2001; Cooper, 1995) depending on the technique of water spraying of interest and on the objectives sought (for instance, fire extinction by flame cooling and oxygen concentration reduction through an increase of water vapor content, reduction of the aggressive features of hot smoke by gas cooling and soot removal by water spray droplets, protection of structural elements by direct or indirect cooling or fire radiation attenuation by water droplets and gas mixing).

The main advantages of sprinkler or deluge water spray systems are the wide availability, the relative low cost, the low level of operating pressure (< 5 bar except for water mist system) and a good efficiency in fire suppression if enough large amounts of water are supplied in relevant location and early time. An accurate experimental characterization of the water spray nozzle in terms of water droplets size distribution at injection and water droplets initial velocity is required as input data for predicting tools since water droplet evaporation kinetics is highly dependent on water droplet size and droplet fall time. Nevertheless, determining the water spray characteristics could be very challenging due to the design of spray nozzles (i.e. the geometric features of sprinkler head) mainly made for practical engineering goals involving often the complexity of water spray behavior (especially the breakup process of water jet inducing large variations of water droplets size and water droplets velocities close to the nozzle, and various spray diameter). In order to determine the main technical features of a water spray system, a Phase Doppler Interferometer (PDI) device is generally used to measure the water droplets size distributions and the water droplets velocities allowing to perform accurate local measurements. Nevertheless, some usual water spray models (Plumecocq, 1997; Nichols and Gregory, 1986) can require as input parameters only an overall water droplets size distribution and water droplets initial velocity. Thus it is needed to process some statistical methods over these

---

* Corresponding author.
E-mail address: william.plumecocq@irsn.fr (W. Plumecocq).

http://dx.doi.org/10.1016/j.nucengdes.2017.08.031
Received 9 March 2017; Received in revised form 24 August 2017; Accepted 28 August 2017

Nomenclature

Acronyms

ODE	Ordinary Differential Equation
PDI	Phase Doppler Interferometer
PID	Proportional–Integral–Derivative

Symbols

A	Cross-section area of the branch $[\mathrm{m}^2]$
B_M	Spalding number for the mass $[-]$
$\bar{c}$	Average molar concentration $[\mathrm{mol\ m}^{-3}]$
C_D	Drag coefficient $[-]$
CMD	Count median diameter [m]
d	Diameter [m]
D_A	Spray nozzle orifice size [m]
$\overline{D}$	Average diffusion coefficient $[\mathrm{m}^2\ \mathrm{s}^{-1}]$
f	Distribution function of water droplets $[\mathrm{m}^{-1}]$
g	Gravity acceleration $[\mathrm{m\ s}^{-2}]$
h	Branch's characteristic function [Pa]
H	Specific enthalpy $[\mathrm{J\ kg}^{-1}]$
HRR	Heat release rate [W]
k	Orifice flow coefficient $[\mathrm{m}^3\ \mathrm{s}^{-1}\ \mathrm{Pa}^{-0.5}]$
L	Length of a branch [m]
m	Mass [kg]
MMD	Mass median diameter [m]
M	Molar mass [kg mol]
Nu	Nusselt number $[-]$
n_0	Number concentration of droplets $[\mathrm{m}^{-3}]$
P	Total pressure [Pa]
Pr	Prandtl Number $[-]$
Q	Volumetric flow-rate $[\mathrm{m}^3\ \mathrm{s}^{-1}]$
Q_m	Mass flow-rate $[\mathrm{kg\ s}^{-1}]$
Re	Reynolds number $[-]$
R_{lin}	Aeraulic resistance (linear part) of a resistive element $[\mathrm{kg\ s}^{-1}\ \mathrm{m}^{-4}]$
R_{quad}	Aeraulic resistance (quadratic part) of a resistive element $[\mathrm{m}^{-4}]$
RH	Relative humidity [%]
S_l	Source term l of the ODE system $[-]$
Sc	Schmidt number $[-]$
Sh	Sherwood number $[-]$
sgn	Sign $[-]$
t	Time [s]
T	Temperature [K]
U	Internal energy per unit volume $[\mathrm{J\ m}^{-3}]$
v	Velocity $[\mathrm{m\ s}^{-1}]$
X	Molar fraction $[-]$
We	Weber number $[-]$
z	Height [m]

Greek letters

α	Spray nozzle coefficient $[-]$
γ	Specific coefficient depending on the conservation equation $[-]$
ε	Emissivity $[-]$
λ	Thermal conductivity $[\mathrm{W\ m}^{-1}\ \mathrm{K}^{-1}]$
$\varnothing$	Physical quantity of interest (mass, enthalpy, mass fraction…) $[-]$
μ	Dynamic viscosity [Pa s]
ρ	Density $[\mathrm{kg\ m}^{-3}]$
σ	Stephan-Boltzmann constant $[\mathrm{W\ m}^{-2}\ \mathrm{K}^{-4}]$
σ_g	Geometric standard deviation $[-]$
σ_w	Surface tension of water droplet $[\mathrm{N\ m}^{-1}]$

Subscripts

dn	Downstream
g	Gas
i	Interface
l	Index of the source term in the ODE system
lin	Linear
low	Lower layer (2-zone modeling)
quad	Quadratique
s	Water vapor
up	Upstream or upper layer (2-zone modeling)
w	Water droplet
∞	Bulk

experimental data to determine them. A second difficulty is linked to the high sensibility of water droplets size distribution and water droplets initial velocity due to the pressure effect at nozzle head. Indeed, an initial characterization of a water spray system is performed at a given pressure for the nozzle head before using in fire scenario. However, a slight change of water flow-rate (i.e. pressure head) can lead to significant variations of water droplets size distribution and water droplets initial velocity. Thus, an adjustment on both water droplets size distribution and on water droplets initial velocity must be performed in predictive simulations in case of change of spray water flow-rate compared to the one used during the initial characterization of the water spray system. The last difficulty lies on the experimental measurement of water droplets initial velocity used as input data in spray modeling. Water droplets from sprinkler or deluge spray nozzles are produced by impingement of the water jet on the deflector of the nozzle. Water droplets velocity measurements are consequently performed several tens of centimeters below the water spray nozzle (see Malet and Parduba, 2016 for instance). At this elevation, the water droplets are under-relaxed and so the velocity measurements do not correspond strictly to initial velocity of water droplets.

As an alternative way for defining the features of spray nozzles, a numerical method for determining water droplets size distributions and water droplets initial velocity is then developed using both the SYLVIA two-zone model (https://gforge.irsn.fr/gf/download/docmanfileversion/7153/32393/SYLVIA_english.pdf) and experimental data (Pretrel et al., 2016). Indeed, this approach proposes to perform a calibration of spray modeling by means on full-scale fire tests in enclosure, for which the fire power and the ventilation system are perfectly controlled.

After a brief description of SYLVIA software (see also the appendix) and of the water spray modeling, this work addresses a new calibration approach for assessing the input parameters of this modeling by using large-scale scale fire tests in DIVA facility (Pretrel et al., 2016). Then, this technique is validated on other fire tests having different pressure heads for the water spray nozzles. The results of this study are discussed thoroughly and show that this new approach can be a valuable and efficient tool for determining the overall features of water spray systems based on the spray modeling used in this work.

2. Brief description of sylvia software

The SYLVIA software (https://gforge.irsn.fr/gf/download/docmanfileversion/7153/32393/SYLVIA_english.pdf) is developed at the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) to simulate a full ventilation network, fire scenarios in a highly confined and ventilated facilities, and airborne contamination transfers inside nuclear installations. This software is based on a zone approach which consists