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Influence of spray characteristics on local light gas mixing in nuclear containment reactor applications

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ABSTRACT

The action of spray on the mixing of different gases is used in numerous industrial applications, such as the chemical industry or the nuclear containment. The present paper concerns the impact of a spray on the break-up of a light gas layer (helium) initially confined in the top of a closed volume. Numerical calculations were performed in order to simulate the evolution of the helium concentration when the spray is activated. The objective of the paper is to show how the boundary conditions used for describing the spray can be important on the local gas mixing. Several sensitivity studies were performed that show the importance of the droplet boundary conditions: droplet size distribution, droplet velocity profiles, number of droplet classes, etc. Influence of these parameters on local gas concentration can be even higher than the one induced by a different turbulence model or some numerical parameters. Influence of the nozzle position inside the vessel is also analyzed. Extrapolation to an industrial application based on nuclear reactor containment is then discussed and recommendations are given for CFD simulations on the impact of spray systems on the gas mixing in nuclear reactors.

1. Introduction

The action of spray on the mixing of different gases is used in numerous industrial applications, such as the chemical industry (use of spray curtains to dilute a gas leak from a storage tank) or the nuclear containment (automatic use of spray systems during a nuclear accident, in which hydrogen can be released).

During the course of the nuclear accident, spray systems are automatically activated inside the containment, as emergency devices designed for preserving the containment integrity in case of a severe accident in a Pressurized Water Reactor (PWR). These systems are used to prevent overpressure, to cool the containment atmosphere, to remove fission products from the containment atmosphere and to enhance the gas mixing in case of hydrogen presence in the reactor containment. The efficiency of these sprays can depend partially on the evolution of the droplet size distribution in the containment, due to gravity and drag forces, heat and mass transfer with the surrounding gas, and droplet collisions. Spray modelings are thus part of thermal–hydraulic containment codes. The two major phenomena involved in spray behavior in such applications are the thermodynamical effect of a spray (steam condensation on droplets, evaporation...) and the dynamical effect (entrainment and mixing of gases). Considering the large volume of the reactor containment (60,000–70,000 m^3), CFD (Computational Fluid Dynamics) calculations of all the containment flows are a very challenging task and few demonstrative calculations have thus been done, until now, on typical accidental sequences.

Huang and Fang [4] studied the hydrogen risk in CANDU6 reactors using the MELCOR code. They showed the benefits of recombiners, proposed for hydrogen risk mitigation in CANDU6 where in the past igniters were used. The GOTHIC code is also used for hydrogen risk analysis. Several calculations of the containment response to different types of accident, with hydrogen, have been presented, such as Chen et al. [1] who studied the hydrogen risk in the containment of a MARK I reactor, and Lin et al. [9], for the MARK III containment. Movahed et al. [13] studied the hydrogen risk in the EPR (European Pressurized Reactor) using the CFD GASFLOW code and with the LP (Lumped-Parameter) code COCOSYS. The results show that CFD calculations give a much more detailed view of the situation and that lumped-parameter calculations cannot be regarded a priori as conservative. Xiong et al. [18] studied, also with GASFLOW, the effect of spray and Passive Auto-catalytic Recombiners (PAR) on the hydrogen risk. Strong effect of spray activation modes on hydrogen distribution is observed. The hydrogen risk is significantly increased by the direct spray, while the recirculation spray has minor effect on it. However, the efficiency of the PAR is not substantially affected by spray activation modes.

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Nomenclature

PWR	Pressurized Water Reactor
CFD	Computational Fluid Dynamics
CSS	Containment Spray System
LP	Lumped-Parameter
EPR	European Pressurized Reactor
PAR	Passive Auto-catalytic Recombiners
PIV	Particle Image Velocimetry
ILIDS	Interferometric Laser Imaging for Droplet Sizing
PDI	Phase Doppler Interferometer
CPU	Central Processing Unit
RNG	Re-Normalization Group
HVF	Helium volume fraction
NPP	Nuclear Power Plants

The last decade has shown more and more studies devoted to CFD simulations of real containment severe accident conditions, some of them involving spray activation: Kim et al. [6], Xiao et al. [17], Xiong et al. [18], Seleznev et al. [15], Huang et al. [3]. However, even if spray calculations and some few code validations on spray tests are presented in these papers, no detailed information is given on the spray detailed inputs, i.e. on boundary conditions. No sensitivity studies to the spray parameters have been mentioned in these papers.

In order to achieve such large scale CFD calculations, exhaustive code validations and verifications are needed. Considering the important number of phenomena involved in the event of an accident in the reactor, validation on separate-effect tests is mandatory. In the past, validation of spray modeling has been performed on large-scale facilities such as CVTR, NUPEC, or CSE using several spray nozzles as presented in the OECD State of the Art Report SOAR [16] and in Malet [10].

In the last decade, new facilities have been developed for containment studies using spray systems: reduced size facilities, allowing a high density of instrumentation for a better analysis of the involved phenomena, including non-intrusive instrumentation and a 'separate-effect' approach avoiding interaction of sprays and the possible resulting deviation in the analysis [7].

This paper focuses on how a stratification of light gas occurring in a closed vessel can be broken by a single spray, leading to atmosphere homogenization. For this purpose, a separate-effect test, performed in an IRSN facility (TOSQAN), is used for code assessment: a spray is activated under helium–air stratified conditions and the mixing of the gases is measured at different positions inside the vessel. An eulerian–lagrangian modeling is used for the spray simulations. In this paper, a description of the test as well as of the CFD calculations will be first given. The general phenomenology of the test will be described in terms of thermodynamics and dynamical phenomena, for which the vessel can be divided into two zones, the one above the spray nozzle, and the one below the spray nozzle. Code-experiments comparison is then presented. Since detailed modeling of spray input data is necessary to obtain good code validation of this specific test 'at small scale', sensitivity studies to parameters of the droplet size distribution are presented. Other sensitivity studies to the droplet velocities, to the nozzle position and to the turbulence modeling are also given, before, drawing some recommendation for real-scale calculations.

2. Description of the experiments

2.1. Facility and available instrumentation

The TOSQAN facility and the associated measurement levels are presented in Fig. 1. It is a closed cylindrical vessel (7 m^3 volume, 4 m high, 1.5 m internal diameter). The vessel walls are thermostatically controlled by heated oil circulation. The inner spray system is located on the top of the enclosure on the vertical axis. It is composed of a single nozzle producing a full-cone water spray. This nozzle can be moved along the vertical axis. In the lower part of the vessel, the water impacting the sump is removed to avoid water accumulation.

Mass flow-rate, temperature and pressure of the injected water spray are measured, as well as the mass flow-rate of the removed water and of the injected helium. Gas temperatures are measured by over 100 protected thermocouples and helium volume fractions by mass spectrometry at different heights. PIV (Particle Image Velocimetry) and ILIDS (Interferometric Laser Imaging for Droplet Sizing) are available measurements techniques for droplet characteristics inside the vessel and PDI (Phase Doppler Interferometer) is

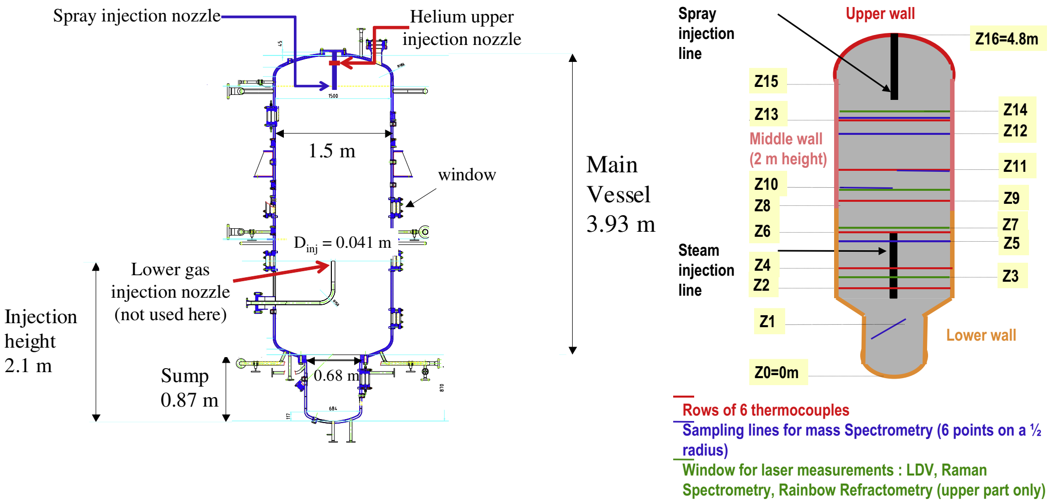

Fig. 1. Experimental vessel and associated instrumentation.