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An experimental study on the depressurization of the containment by water spray in a small scale facility

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ABSTRACT

The containment of a nuclear reactor acts as the ultimate barrier for radionuclides to be leaked in the environment. Severe accidents in nuclear reactors may result in the pressurization of the containment and may provide different potential leak paths. So, to enhance the safety of new designs of Indian pressurized heavy water reactors, an additional safety measure called containment Spray System is introduced. The system is designed to cater/mitigate the conditions after design basis accidents. As a contribution to the safety analysis of condition post severe accident, experiments are carried out to investigate the system performance. The accidental conditions are simulated by injecting the saturated steam into the test vessel filled with air at atmospheric pressure and temperature. The effect of different spray parameters such as nozzle geometry, spray mass flow rate and Sauter mean diameter on vessel pressure and temperature is measured. Three initial vessel pressure 1.5 bar, 2.0 bar, 2.5 bar and five different nozzles with nozzle orifice diameter as 1.65 mm, 2.10 mm, 2.45 mm, 2.75 mm and 3.10 mm are chosen for the experimental investigation. The vessel pressures are chosen based on the post accidental conditions in Indian pressurized heavy water reactor. Experiments are conducted with water at room temperature as the spray medium. The experiments are carried out in a vessel of 500 mm diameter and 1200 mm height. These studies are carried out to optimize the containment spray system configuration for best effectiveness. It is seen that the Sauter mean diameter and nozzle geometry influences the depressurization rate of the vessel. The depressurization rate is inversely proportional to the Sauter mean diameter while it increases with the increase in the spray mass flow rate/ Reynolds Number.

1. Introduction

The engineered safety features/systems in a nuclear power plant are designed to avoid or mitigate the consequences in case of any abnormal occurrences, particularly reduce the radioactivity release to the public in case of an accident. The severe accidents in the reactor may result in pressurization of containment with high enthalpy steam/vapors along with fission products from the core. Subsequently, it will pressurize the containment and may lead to the leakage of radionuclides and other radioactive fission products through small leak paths. To mitigate the consequences, Indian pressurized heavy water reactors are having vapor suppression and mainly iodine scrubbing systems. These systems are capable of mitigating post accident conditions. To further enhance the safety, a new vapor suppression system known as containment spray system is envisaged for Indian pressurized heavy water reactor. The main objective of this system is to suppress the steam and scrub the iodine as fast as possible. The containment spray system is having fast vapor suppression and iodine scrubbing compared to the existing systems in old Indian pressurized heavy water reactor (Bajaj and Gore, 2006). The efficiency of the containment spray system is much higher than the suppression pool used for vapor suppression in 220 MWe and 540 MWe Indian pressurized heavy water reactor plants (Jain et al., 2014). The containment spray system includes a combination of water sprays which acts to suppress the containment pressure and thereby to minimize the release of radioactivity to the public.

Containment spray system is a new system in Indian nuclear reactors. The specific information about the spray function and its effects on the containment depressurization is not available in the open literature, although different researchers have investigated this problem for pressurized water reactors. The

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Nomenclature

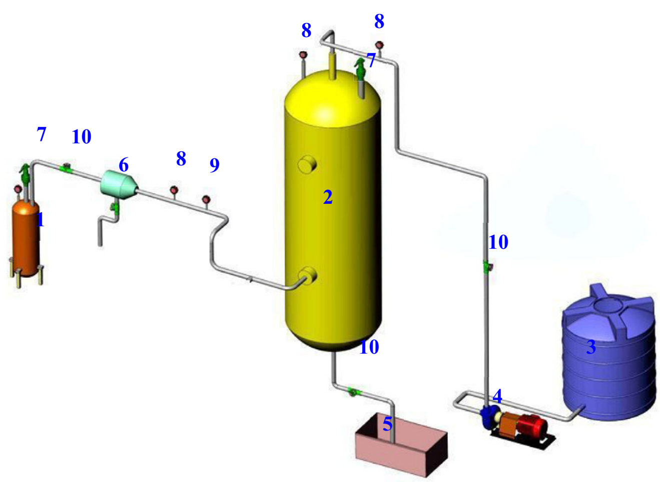
A_o	outlet orifice area of nozzle $\left(\frac{\pi D_o^2}{4}\right)$ (m^2)
D_{32}	sauter mean diameter (μm)
D_o	diameter of the nozzle outlet orifice (mm)
D_s	diameter of the swirl chamber (mm)
D_{sw}	inlet slot dimension (mm)
$f(r)$	size distribution function of the spray
g	acceleration due to gravity (m^2/s)
K	nozzle constant $\left(\frac{A_i}{D_o D_s}\right)$
L_s	swirl chamber height (mm)
m_{inj}	spray mass flow rate through nozzle (lpm)
m_w	droplet mass (kg)
P_i	initial pressure of the vessel (bar)
P_t	vessel pressure at time 't' (bar)
Re	Reynolds number $\left(\frac{\rho v_o D_o}{\mu}\right)$
t	time (sec)
T_w	droplet temperature (°C)
T_g	gas temperature (°C)
v	velocity of the droplet (m/s)
Z	axial distance from the nozzle exit (mm)
ΔZ	compartment height (m)

Greek symbols

μ	dynamic viscosity of water (Pa.s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
τ	decay constant (sec)

effectiveness of the system for Indian reactor conditions, in terms of pressure suppression is an important area of investigation. In the present work, a pilot experimental facility is used to study the effect of Sauter mean diameter, spray mass flow rate and the nozzle geometry on the containment pressure and temperature variation for different accident conditions in Indian pressurized heavy water reactor. ASTEC lumped parameter code is also used to predict the experimental scenario.

Many researchers have studied the containment depressurization process in small scale facilities for different applications and reactors. Sagawa (1968) conducted experimental study on spray cooling in nuclear reactor containers. The studies were performed in a 6.0 m height and 2.0 m diameter vessel. They used a multi jet spray nozzle. The depressurization by spray cooling, evaporation from water surfaces, evaporation from sprayed wall surfaces and heat absorption rate of sprayed water were investigated. They simulated the loss of coolant accident by introducing high temperature water into the test vessel sitting at atmospheric conditions. They varied the number of spray nozzles and the nozzle exit orifice diameter to control the spray mass flow rate through nozzle. The average diameter of spray droplets is 600 μm and the sprays were evenly distributed. They observed that the heat absorption during the spray becomes less and less complete as the steam concentration in the vessel or its pressure is lowered. Cheng et al. (2001) studied condensation heat transfer in the presence of non-condensable gas and effect of spray systems on iodine removal and gas dynamics in the containment. It was found that indeed the design parameters of a spray system like spray flow rate, droplet diameter, pH of spray water and the initial spray water temperature, affect the gas and iodine behavior inside containment significantly. Karameldin et al. (2001) investigated the containment conditions post severe accident. They suggested that the depressurization time totally depends on the spray mass flow rate and the droplet diameter. It was seen that the depressurization time was more in case of large droplets instead of small droplets. They proposed a passive containment cooling spray system with optimal spraying parameters for droplets diameter, travel distance, and mass flow rate are determined to be 3 mm, 30 m, and 100–125 kg/s, respectively. Takahashi et al. (2001) explored the heat transfer in direct contact condensation of steam to sub cooled



1. Steam Generator 2. Test Vessel 3. Water tank 4. Pump 5. Condensate tank 6. Steam separator 7. Safety Relief Valve 8. Pressure Gauge 9. Temperature Gauge 10. Control Valve

(a)

Fig. 1a. Experimental setup for containment Spray System (CSS) studies.