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Experimental study on spray characteristics of pressure-swirl nozzles in pressurizer

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ABSTRACT

Spraying system in the pressurizer of Pressurized Water Reactor (PWR) power plant system is of great importance for system pressure control. An experimental study on the spray characteristics, including mass flow rate, spray flux distribution, spray cone angle and drop size spectrum, was conducted. A testing loop with nine swirling nozzles was established for the study. In order to measure the spray cone angle and drop size spectrum, two original devices including a spray droplet collector and a photographic chamber were designed and employed. The former was used to collect the spray droplet along the cross-section diameter, and the latter was made to isolate and measure the targeted spray droplet. Based on the experimental data, the curves of flow rate and spray cone angle versus nozzle pressure drop were obtained. Several typical spray flux distributions were derived and the results indicated that the flux distribution changes significantly with even small pressure changes. Thus, it was proposed that instability of the spray flux distribution should be considered in the pressurizer. Based on the spray drop pictures recorded by the high speed camera, Probability Density Function (PDF) of the drop size was obtained and compared with four 'standard' empirical distributions. It was found that the Nukiyama–Tanasawa distribution provides a better fit to the experimental PDF of the spray drop size. The present work introduces the experimental methodology and results of spray behaviour of the nozzle in pressurizer. The work is expected to be helpful for the optimization design of spraying systems.

1. Introduction

Liquid sprays generated by nozzles are important for many technical processes, such as energy conversion, coating, and cooling. In cooling systems, especially, spraying has significantly superiority due to the excellent ability of heat and mass transfer. It is well known that the latent heat exchange is a major factor for the cooling efficiency when a large number of droplets are injected into the ambient gaseous environment. As a result, the spraying systems have been widely used in nuclear energy engineering, such as the pressurizer (Diao, 1988; Kim and Griffith, 1987; Chen et al., 2011), the containment spray system (Lemaitre and Porcheron, 2009; Robert, 1996) and the reactor core spray system (Anglart et al., 2010; Torres et al., 1999).

For the spraying system, the purpose of the nozzle is to generate a multitude of individual drops spreading over a wide angle. There have been various studies on the formation mechanism of sprays. Most of the studies showed that in the entire process of forming drops there are two stages, which are the forming of ligaments and then droplets (Kim et al., 2003; Weber, 1931; Tratnig and Brenn, 2010). Based on the theoretical analysis, some researches have attempted to find a reliable way to predict the spraying performance. However, the results were unsatisfactory. As the most important parameter, spray drop size is modelled by three different methods: the empirical method, the Maximum Entropy (ME) method and the Discrete Probability Function (DPF) method (Babinsky and Sojka, 2002). But the problem with the empirical method is that it is not accurate when extrapolating the data which is outside the experimental range (Gonzalez-Tello et al., 2008; Paloposki, 1994). The most important part of applying the ME method is the appropriate adjustment to the source terms made by referring to the experimental distribution (Li and Tankin, 1988, 1989; Sellens, 1989). The DPF method may lose the predictive power because it is difficult to obtain experimental results as the input conditions (Sovani et al., 2000). Therefore, experimental investigation plays an important role in the study of sprays produced by nozzles.

For the experimental studies conducted in the past, most of them mainly focused on the measurement of the drop size. Kim et al. (2003) set up a test rig for the spray experiment. The initial droplet size was measured by phase-Doppler interferometry for sprays which was generated by a planar research nozzle and a practical gas turbine air blast nozzle. The measured drop size ranged from 10 μm to 200 μm. Porcheron et al. (2010) made a special

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Nomenclature

A	area m^2
C	discharge coefficient
C^*	constant component of discharge coefficient
C_v	variable component of discharge coefficient
D	drop diameter μm
$\overline{D}$	mean size of drop diameter μm
d	diameter mm
f	drop size distribution function
h	height mm
n	drop number
P	pressure Pa
r	radius m
s	standard deviation
W	mass flow rate kg/s
x	sample

Greek symbols

α	spray cone angle degree
δ	inclination angle of swirl groove degree
γ	coefficient of variation
λ	area ratio of swirl flow to direct flow
π	circumference ratio
θ	shrinking angle of swirl chamber degree
ρ	density kg/m^3
σ	empirical distribution parameter
Δ	difference

Subscripts

d	direct flow through central direct flow conical diffuser
e	nozzle exit
i	size class
iv	ideal value
j	measuring position
LH	log-hyperbolic distribution
LN	log-normal distribution
NT	Nukiyama–Tanasawa distribution
n	nozzle
o	orifice of the atomizer
RR	Rosin–Rammler distribution
s	swirl flow through swirl groove

facility to simulate the reactor containment. In order to perform thermal hydraulic containment studies, the interferometrics laser imaging was used to measure the droplet size. The measured drop size ranged from 60 μm to 250 μm. Tratnig and Brenn (2010) carried out the experiments to study a kind of pressure-swirl atomizers. Local drop size was measured with phase-Doppler anemometry at some points in each spray cross section. The drop size was measured to be less than 100 μm. In some other studies, spray cone angle as an additional parameter was measured by digital camera (Gong and Fu, 2007; Tratnig and Brenn, 2010). An experimental investigation was made on the discharge coefficients and the spray cone angle of a solid cone swirl nozzle (Halder et al., 2004). The spray cone angle was measured by taking the photographs of spray with the help of a wide angled lens camera and flood light illumination.

However, the instruments and methods mentioned above are not suitable to the nozzles used in Pressurized Water Reactor (PWR) power plant system, such as the sprinkler in pressurizer. These nozzles have the larger spray field and mass flow. The diameter of the spray field can have a value of $\geqslant$4.0 m. Diao (1988) analysed the performance of five types of nozzles with the range of the pressure drop from 0.127 MPa to 0.245 MPa and the flow rates from 5×10^3 kg/h to 5×10^4 kg/h, which falls in the operation regime of pressurizer of PWR system. But the detailed method for the experiment was not given. The resulting spray produced by the nozzle usually has the larger drop size and spray field. It is unfortunate that the partial drop size in these sprays exceeds the upper limits of the capacity of the advanced instrument distinctly, such as phase Doppler and laser diffraction techniques. Zaidi et al. (1998) carried out a comparative study of these techniques to investigate drop sizes in the two-phase flow, and provided their respective defects and measuring ranges. Accordingly, it appears more important to find a suitable method to measure the drop size for the special object.

In this study, a detailed experimental method is presented to characterize the spray, which is of lower pressure drop and large flow rate. As an important property which was usually neglected for conventional nozzles due to their small flow rate, the spray flux distribution was measured and analysed in this work. In addition, two photographic methods were taken respectively to characterize the spray cone angle and the drop size spectrum. In order to carry out the above measurements, some devices, including a spray droplet collector, a waterproof light source and a photographic chamber, were designed and employed.

2. Experimental loop

The experiments were carried out by using the test rig sketched in Fig. 1. This rig consisted of a spray pool, a pressure pump, pipes, a spray nozzle, a series of control valves and devices for process monitoring such as pressure sensor and mass flow meter. The loop could be run in three modes: the major-loop mode, the bypass mode and the drainage mode. Operation mode of the loop is controlled by a series of control valves. After startup of the system, the bypass valve was opened gradually to obtain an initial flow rate through the bypass pipe. Then the major-loop control valve was put into operation to get a proper flow rate close to target value. Finally, the desired flow was obtained accurately by means of vernier regulation of the reducing valve.

The liquid used for the present experiment was tap water, which was stored in an open quadrate pool (4000 mm × 4000 mm × 800 mm). It was obvious that the pool also served as a sprays droplet collector. In order to clear the working liquid, two filters, stainless steel fibrous filter and Y filter, were installed at the inlets of the pump and the reducing valve respectively. In addition, the turbine mass flowmeter and the pressure sensor were used to measure the values of the mass flow rate and the pressure drop of the liquid through the nozzle. The flowmeter ranges from 2.0×10^3 to 2.0×10^4 kg/h and the pressure sensor is in 0–1.0 MPa. During the experiments, the environmental parameters including the ambient temperature, the atmospheric pressure and the medium temperature were monitored.

The nozzles used in the experiments were a series of pressure-swirl nozzles for spraying system in the pressurizer of the PWR power plant system. They consist of some swirling grooves, a central direct flow conical diffuser, a swirl chamber and a nozzle exit, as sketched in Fig. 2. A part of liquid is driven into the swirl grooves and then rotated into swirl chamber, where the liquid is accelerated. Due to the centrifugal inertial force, the liquid clings to the internal wall of the swirl chamber and forms a thin liquid film.