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Study on flow pattern and separation performance of air–water swirl-vane separator

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ABSTRACT

Two-phase mixture has a complicated separating process inside a swirl-vane separator which plays an important role in assuring a low wetness of the steam to turbine. To understand the flow pattern inside the swirl-vane separator and analyze the separation performance, a simplified swirl-vane steam separator made of transparent acrylic resin is studied by experiment in which the mixture of air and water is used as the working fluids. Experimental results reveal that the separation efficiency of the separator strongly depends on the flow pattern and the water velocity. The separation efficiency in the annular flow is higher than that of the mist flow and the churn flow. The pressure drop is mainly affected by the air flow rate and the water droplet diameter. Furthermore, a numerical model assuming water as sphere droplets and neglecting its deformation is developed to simulate the separator with Euler two-phase model and RSM turbulence model. It is founded that although the separation efficiency is not sensitive to the size of the big water droplets, it is affected significantly by the micro scale water droplets. By assuming that 94% water droplet equals the Sauter mean diameter and the other 6% is 0.4 times of the Sauter mean diameter, the separation efficiency predicted agrees well with the experimental results for the studied case.

1. Introduction

Steam separators in nuclear reactors remove water from gas to assure high quality steam to dryers and eventually turbines, which is vital to assure the safety of the turbine and achieve the high economic efficiency (Green and Hetsroni, 1995). The two-phase mixture flow structure is quite complicated inside the steam separator, especially in the swirl-vane type separator. Research on it has been carried out mainly through experimental method. The test was done to find the separator with the best performance using air–water mixture as the working fluid (Chen et al., 2006a,b; Ding et al., 1983). Then the selected separator was evaluated by the test using the mixture of steam and water to make sure that it meets the requirements of the reactor. These researches mainly focus on the comparison of various sizes of the separators and the measurement is rough (Green and Hetsroni, 1995).

Recently, dedicated test was carried out to accumulate the experimental database for evaluate the numerical simulation model for separators. In the ARTIST project (Güntay et al., 2004; Kapulla et al., 2008), the flow field in the steam separator is measured through LDA, as well as the droplet retention coefficient which was defined as the ratio of the droplets retained in the separator to the droplets going into the steam separator. Kataoka et al. (2008) developed and tested a one-fifth scale model of a steam separator made of transparent acrylic resin using air–water mixture. Thereby two kinds of flow pattern were studied, i.e., annular flow and churn flow, with the air superficial velocity and water superficial velocity in the range of 12–24.1 m/s and 0.05–0.11 m/s, respectively. It was concluded that the separation efficiency was sensitive to the flow pattern, while the pressure drop was significantly affected by the swirl vane angle (Kataoka et al., 2009a,b).

Recently, CFD has been used to get the detailed flow structure inside the separator due to improving computer technology. Investigated the swirling flow characteristics in the swirl vane section and developed a new drag coefficient model to improve the calculation of centrifugal force. Both k–ε turbulence model and Reynolds stress model (RSM) were used. It was concluded that RSM captured the general trends of flow field better than k–ε model (Ogino et al., 2008). To analyze the effect of swirl vane diameter, two kinds of steam-water separators were simulated using Fluent (Pang et al., 2011).

The CFD simulation model for the swirl vane steam separators is still under development due to the complicated flow structure inside it. Even though researchers around the world carried out some experimental work for the development of numerical simulation model, the database is far from enough. Therefore, a small-scale

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Nomenclature

C_D	drag force coefficient
C_L	lift force coefficient
C_{vm}	visual force coefficient
d_0	the Sauter mean diameter of the water droplet at the inlet, mm
d_i	diameter of the water droplet (mm)
f_i	probability density of droplet diameter d_i (mm)
F_L	lift force
F_{VM}	visual mass force
G	gas phase
J_G	air superficial velocity (m/s)
J_L	water superficial velocity (m/s)
k	the k phase
L	water phase
m_1	mass of water from down comer (kg)
M_D	drag force
M_k	interface force
Q_L	water volume flow rate (m^3/s)
p	pressure (Pa)
$\vec{u}$	velocity
m_2	mass of water from accumulated around atomizer (kg)
α	volume fraction
ρ	density (kg/m^3)
Δt	time (s)
τ_k	shear stress
τ_k^t	turbulent shear stress

swirl vane type separator is developed and tested with a large range of air velocity and water velocity. The mist flow pattern is firstly observed, as well as churn flow and annular flow. Moreover, numerical method is developed to simulate the separation process by assuming an appropriate water state, and the results are evaluated by the experimental results.

2. Experimental and numerical method

2.1. Experimental apparatus

The test loop used for this study is schematically shown in Fig. 1. It consists mainly of a water loop and two air loops. Air is supplied by air compressor to the accumulator. It is purified by filter and then separated into two parts. One part goes to the atomizer to break the water. The other part goes directly to the test section. The accumulator in water loop is pressurized and water is forced to go through the filter to the atomizer, where water is broken into many small droplets. Then the water droplets go to the test section with air. The separator is connected to the atomizer by a removable tube. By removing this tube, the size of the water droplet formed by the atomizer is measured by the laser particle analyzer. In this way, the water film formed around the inner wall of the tube will not affect the measurement. Meanwhile, the removable tube is part of the developing section. The developing section length could be changed by using different length of the removable tubes. To examine whether the developing section is long enough to assure that the axial velocity of mixture is almost zero, smog is forced into the removable tube and its flow trajectory is observed. Some water droplets deposit on the tube wall between the atomizer and the swirl vane. The amount of water depositing on the wall increases with the length of tube. To minimize this effect and assure the axial velocity is almost zero at the same time, the developing section length is about 0.9 m.

The test section shown in Fig. 2 consists of a lower riser, a hub, four swirl vanes, a riser, an orifice and a down comer. It was made of transparent acrylic resin for visualization and the optical measurements by high speed camera. It is a downscaled steam separator used in AP1000 and the ratio of the test section to the original one is 1:3.5. To simply the separator model, there are no perforations on the riser wall. The structures above the orifice are also neglected. The reason is that the focus is on the swirl-vane separation process.

The instruments used in the test are shown in Table 1. The separation process of the two-phase mixture flowing through the test section is recorded by a high speed camera. The frame rate is 1000 Hz. The light is applied to the test section by a plane laser beam formed by a prism as shown in Fig. 2.

The separation efficiency is defined to evaluate the performance of the separator. It is the ratio of the separated water m_1 from the down comer to the water mass going to the test section, as shown by Eq. (1). The separated water m_1 from the down comer is stored in the water tank 2. After the test, it is measured by the weight balance. The amount of water going to the test section is the water from the accumulator minus the water accumulated in the atomizer section.

$$\eta = \frac{m_1}{Q_L \rho_L \Delta t - m_2} \tag{1}$$

2.2. Numerical method

The flow inside the test section is simulated by Fluent 6.0 using Euler method. It is assumed that the flow is steady. In the experiment, water droplets collides, coalescences or breaks all the time. Therefore, the shape of the water and the diameter of the water droplet keep changing. To simplify the simulation and reduce the time for the simulation, the change of the water shape and the size of the droplets are neglected. It is assumed that the water is always in the state of sphere droplets, neglecting the effect of the breaking and coalescence. The droplet diameter should be carefully chosen to represent the water state in the whole separation process.

Continuity equation

The basic control equation for the gas and liquid is as following.

$$\nabla \cdot (\alpha_k \rho_k \vec{u_k}) = 0 \tag{2}$$

Momentum equation

$$\nabla \cdot (\alpha_k \rho_k \vec{u_k}\, \vec{u_k}) = -\alpha_k \nabla_p + \alpha_k \rho_k \vec{g} + \nabla \cdot [\alpha_k (\tau_k + \tau_k^t)] + M_k \tag{3}$$

τ_k is shear stress. τ_k^t is the turbulent shear stress, which is solved by Reynolds stress model (RSM). MK is the interface force, and consisted of drag force M_D, lift force F_L and visual mass force F_{VM}. The drag force is calculated according to by the following equation:

$$M_D = \frac{3}{4}\frac{C_D}{d}\alpha_L \rho_L |(\vec{u_L} - \vec{u_G})|(\vec{u_L} - \vec{u_G}) \tag{4}$$

$$C_D = \begin{cases} \frac{24}{\mathrm{Re}}(1 + 0.0.15\mathrm{Re}^{0.687});\ \mathrm{Re} \leqslant 1000 \\ 0.44;\ \mathrm{Re} > 1000 \end{cases} \tag{5}$$

$$\mathrm{Re} = \frac{\rho_\alpha d |(\vec{u_L} - \vec{u_G})|}{|\vec{u_G}|} \tag{6}$$