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Scaling laws for gas–liquid flow in swirl vane separators

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HIGHLIGHTS

- Model for swirl vane separator performance is established with similarity criteria.
- Scaling laws are developed to correlate downscale test with prototype separator.
- Effects of key similarity criteria on separation performance are studied.
- The vital role of droplet size distribution on separation performance is discussed.

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ABSTRACT

Laboratory tests on gas–liquid flow in swirl vane separators are usually carried out to help establish an experimental database for separator design and performance improvement. Such model tests are generally performed in the reduced scale and not on the actual working conditions. Though great efficiency is often obtainable in the reduced model, the performance of the full-sized prototype usually cannot be well predicted. To design downscale model tests and apply the experimental results to predict the prototype, a general relationship to correlate them is required. In this paper, the relation of the similitude-criterion concerning the pressure loss is presented by using the dimensionless analysis, and mathematical models for critical droplet diameter, grade efficiency and overall separation efficiency are established by analyzing the features of the droplet trajectory in gas swirling flow field. The essential similarity criteria accounting for pressure loss and separation efficiency are obtained, respectively. On this basis, the scaling laws which enable a comparison between the reduced model and the full-sized prototype under similar conditions are also developed. It is found that the overall separation efficiency is significantly affected by the size distribution of the small droplets, especially when the mean diameter is smaller than the critical droplet diameter.

1. Introduction

Swirl vane separators in nuclear reactors are used for separating more than 80% of the liquid water from the steam–water mixture to feed the qualified steam to dryers and turbines (Green and Hetsroni, 1995). The performance of separator is significantly affected by operation conditions, and it should assure acceptable steam quality especially under the conditions of high steam load, working pressure and circulation ratio. To better predict the separator performance over a wide range of conditions, studies on its main influencing parameters and their effects on the gas–liquid separation are necessary.

Since the separation efficiency and the pressure loss are the key features of the swirl vane separator, a considerable number of investigations based on them have been performed with analytical (Bürkholz, 1989; Hoffmann and Stein, 2002; Brunazzi et al., 2003; Kolev, 2006; Austrheim, 2006) and experimental methods (Mauro et al., 1990; Green and Hetsroni, 1995; Sun et al., 1995; Ikeda et al., 2003; Kataoka et al., 2008, 2009a–c; Xiong et al., 2014). By ignoring the axial variation of the droplet mass concentration and assuming that the Stokes flow around the droplet is valid, the analytical models for separation efficiency were developed by Brunazzi et al. (2003) and Kolev (2006). In the Stokes law region, Austrheim (2006) assumed that there exists a critical radial position that determines the droplet separation and suggested a mathematical model for grade efficiency. However, the ideal Stokes flow around the droplets is valid only for very small droplets that have very low relative velocity to the gas flow, i.e., the droplet Reynolds number is less than unit. Under the working conditions of the swirl

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Nomenclature

a	constant
A	combined parameter
b	constant
B	separation parameter
C	constant
C_D	drag coefficient
d_p	droplet diameter (m)
$d_{p,c}$	critical droplet diameter (m)
$d_{p,c}(r,\theta)$	critical droplet diameter at arbitrary position (r,θ) (m)
$d_{p,c(\max)}$	maximum critical droplet diameter (m)
$d_{p,c(\max)}(r,\theta)$	maximum droplet diameter at arbitrary position (r,θ) (m)
$d_{p,\max}$	maximum droplet diameter (m)
$d_{p,\mathrm{m}}$	mean droplet diameter (m)
Eu	Euler number
$f(d_p)$	droplet diameter probability density function (PDF)
$f_m(d_p)$	droplet mass percentage PDF
$f_m(d_p,r,\theta)$	droplet mass percentage PDF at arbitrary position (r,θ)
$F_m(d_p)$	mass percentage of d_p
g	gravitational acceleration (m/s^2)
h	central hub height (m)
H_{sep}	cylinder height (m)
L	radial displacement of droplet (m)
m	model scaling factor
n	number of swirl vanes
N_h	criterion for geometric similarity
N_p	nondimensional density
N_s	swirl number
N_r	criterion for geometric similarity

Greek symbols

α	shape parameter
β	scale parameter
δ	boundary layer thickness (m)
η	separation efficiency
μ	dynamic viscosity (Pa s)

Subscripts

0	initial condition
c	critical value
g	gas phase
l	liquid phase
m	mass percentage
r	radial direction
p	constant
Δp	pressure loss (Pa)
r^0	initial radial position of droplet (m)
r_c	critical radial position of droplet (m)
R_i	central hub radius (m)
R_o	cylinder radius (m)
Ro	Rossby number
Re_g	gas Reynolds number
Re_l	liquid Reynolds number
Re_p	droplet Reynolds number
t_{mig}	radial migration time (s)
Δt	separation time (s)
u_g	gas superficial velocity (m/s)
u_l	liquid superficial velocity (m/s)
u_r	radial velocity (m/s)
u_θ	tangential velocity (m/s)
$u_{\theta(\delta_\theta)}$	tangential velocity at the boundary layer edge (m/s)
u_z	axial velocity (m/s)
u_z^0	initial axial velocity downstream the swirl vanes (m/s)
$u_{z(\delta_z)}$	axial velocity at the boundary layer edge (m/s)
We	Weber number
x_l	exit moisture
y	radial distance from the wall (m)
δ_z	axial boundary layer thickness (m)
δ_θ	tangential boundary layer thickness (m)
$\bar{\delta}_l$	mean liquid film (m)
η_{d_p}	grade efficiency
η	separation efficiency
ν	kinematic viscosity (m^2/s)
θ	swirl vane angle (°)
ρ	density (kg/m^3)
ω	angular velocity (rad/s)
ζ	separation factor
z	axial direction
θ	tangential direction
model	model separator
prototype	prototype separator
sep	separation section

vane separators, the droplet size is generally very large (Dibelius et al., 1977) and the droplet Reynolds number is far more than unit, which makes this assumption incorrect. Then the scaling laws developed by Kolev (2006) cannot serve as a basis to correlate the model test with the prototypical separator. Besides, the scaling laws considered in other models (Bürkholz, 1989; Hoffmann and Stein, 2002; Austrheim, 2006) are not based on dimensional numbers derived from rigorous mathematical analysis which limits their general use. On the other hand, as the full-sized separator tests under prototypical conditions are difficult and costly to implement, previous experimental tests are mostly conducted with the downscale models in low pressure air–water loops. The pressure loss of the separator in both low pressure air–water loops and high pressure steam–water loops was measured by Mauro et al. (1990) and an increase of the loss coefficient was observed with the system pressure. Kataoka et al. (2008, 2009a,b) developed and conducted a one-fifth scale model test with the air–water as working fluids. The separation efficiency, pressure loss and droplet diameter distribution were measured to establish an experimental database applicable to mathematical models and their verifications. To better understand the separation process and provide experimental data for the validation of numerical simulation, experiments on a small-sized separator were carried out by Xiong et al. (2014). In addition, some reduced model tests focusing on the swirler optimization were also performed to obtain the ideal geometries and features (Jensen et al., 1996; Ikeda et al., 2003; Kataoka et al., 2009c; Matsubayashi et al., 2012). However, separation characteristics vary for different working fluids and the separator performance changes under different operation conditions such as gas (liquid) load and working pressure. Although the separator performs well in the reduced model, the performance of the prototype separator cannot be well predicted from these experimental results due to the lack of the scaling laws.

The objective of this paper is to investigate how the downscale model test can be used for predicting the performance of the prototype separator. By analyzing the characteristics of gas–liquid flow in the swirl vane separator, the mathematical models for pressure loss and separation efficiency are established with several defined