Annals of Nuclear Energy 120 (2018) 656–665

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Re-entrainment in and optimization of a vane mist eliminator

Feng Mao, Ruifeng Tian [*], Yixuan Chen, Bowen Chen, Bo Wang, Lanxin Sun

Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin 150001, China

ARTICLE INFO

Article history:
Received 11 November 2017
Received in revised form 1 June 2018
Accepted 5 June 2018

Keywords:
Re-entrainment
Shear airflow
Film breakup
Critical speed

ABSTRACT

The mechanism for breakup of a thin film on a vertical curved wall under the effect of airflow shear is studied as the main reason for re-entrainment in a vane mist eliminator. A force-balance model in boundary layer flow is established to illustrate the thin-film breakup mechanism. A theoretical formula is deduced for the critical airflow speed that results in film breakup in a corrugated-plate (CP) channel. This formula is related to the fluid properties of the film and the airflow, the wall-film thickness, and the structure of the CP channel. An experimental study is undertaken to establish the critical airflow speed for wall-film breakup in different CP channel structures. Planar laser-induced fluorescence (PLIF) is used to measure the film thickness on the CP. The relationship between wall-film thickness and Reynolds number is studied first. On that basis, the relationship between wall-film thickness and critical airflow speed is studied in different CP channel structures. The experimental data are consistent with the theoretical predictions and show that a thicker liquid film requires a lower critical airflow speed, at the same time, film surface fluctuations accelerate the film breakup. Combining theoretical and experimental data, it is proposed that the structural factor k_1 and the gas–liquid property factor k_2 determine the criteria for the breakup of the liquid film, and obtain an optimal angle based on k_1.The optimum bending angle of the CP is 26.6°, this giving the highest critical airflow speed.

1. Introduction

Vane mist eliminators are used widely in fields involving two-phase separation, especially for steam–water separation in nuclear power (Nakao et al., 1998), thermal power (Narimani and Shahhoseini, 2011; Rafee et al., 2010), solar energy (Eck et al., 2008), geothermal energy (Zarrouk and Purnanto, 2015), and desalination (Venkatesan et al., 2013). There are several ways to improve the separation efficiency of vane mist eliminators, such as to increase the moisture flow speed, increase the bending angle, reduce the corrugated plate (CP) spacing, and increase the channel twist number. However, because of the re-entrainment phenomenon that captured water was carried by shear airflow, these approaches do not always improve the separation efficiency. The current view is that breakup of the liquid film on the curved wall of the vane mist eliminator plays an important role in inducing re-entrainment.

The breakup of the wall liquid film is closely related to the shape of the wall and the fluid properties. Most early studies were based on three theoretical models used commonly to analyze liquid-film breakup, namely the force-balance model, the minimum-energy model, and the surface-wave disturbance model.

In 1964, Hartley et al. (Hartley and Murgatroyd, 1964) first proposed a force-balance model when studying stable dry spots formed by breakup of isothermal films. Subsequently, the effects of gas–liquid interface shear force, gravity, wall viscous force, inertial force, heat capillary force, and other force factors were added into the force-balance model. For example, Zuber et al. (Zuber and Staub, 1966) took thermal effects into account, such as thermal capillary force and vapor pressure on the liquid film, and studied the thermal cracking of the liquid film using the force-balance model. Murgatroyd and others (Murgatroyd, 1965; Penn et al., 2001) took into account the imbalance between the gas–liquid two-phase interface shear force and the viscous force of the liquid–solid interface and proposed a force-balance model driven by shear stress. Joo et al. (Joo et al., 1991) analyzed the small disturbances of the liquid film and developed a surface wave perturbation model based on the long wave theory of the free liquid film.

In recent years, ever more researchers have focused on the breakup of isothermal films under the action of gas flow on a curved wall. Studies into the mechanism of liquid-film breakup on a profiled plate began in 1985 when Owen and Ryley (Owen and Ryley, 1985) studied liquid-film breakup at a wall corner theoretically using the force-balance model. The effect of the

---

[*] Corresponding author at: Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, room211, sanjia lab, NO.145, Nantong Street, Harbin 150001, China.

E-mail address: tianruifeng@hrbeu.edu.cn (R. Tian).

https://doi.org/10.1016/j.anucene.2018.06.011
0306-4549/

Nomenclature

U	velocity of film surface (m/s)
u	velocity of film (m/s)
f	external force on fluid element (N/m^2)
h	average film thickness (mm)
θ	bending angle (°)
d	corrugated-plate spacing
R、r	radius (mm)
H	distance from channel top to measurement point (m)
c_f	dimensionless resistance coefficient
g	gravitational acceleration (m/s^2)
Re_l	Reynolds number of liquid
Re_g	Reynolds number of gas
L	corrugated-plate fold length (mm)
He	corrugated-plate height (mm)
n	corrugated-plate twist number

Greek symbols

σ	liquid-film surface tension (N/m)
τ_w	shear stress on liquid film at solid–liquid interface (N/m^2)
τ_g	shear stress on liquid film at gas–liquid interface (N/m^2)
μ_l	kinematic viscosity of liquid (m^2/s)
β	angle (°)
μ_g	kinematic viscosity of gas (m^2/s)
ρ_g	gas density (kg/m^3)
δ	film thickness (mm)
ν	dynamic viscosity of film (N·s/m)
ρ_l	liquid density (kg/m^3)
τ_i	shear stress on plate by shear airflow (N/m^2)

radius R of a curved wall was introduced into the radial stress model. The view is that the liquid film is equilibrated under the action of the inertial centrifugal force and surface tension. Wegener et al. (Wegener et al., 2008) studied the breakup of a liquid film at the corner of a horizontal wall under the action of air shear, measuring the liquid film under different working conditions. The results showed that if the bending angle of the wall is greater than 60°, the effect of high-speed airflow on the breakup of the liquid film is minimal and can be neglected altogether if the bending angle is increased further. Maroteaux et al. (Maroteaux et al., 2002) established a critical condition for liquid film rupture at the corner position based on the surface wave perturbation model. Azzopardi (Azzopardi et al., 2002) considered the influence of the parameters of gas–liquid two-phase motion when studying the breakup of liquid film at a wall corner in a wave channel. From their experimental results, they drew the dimensionless critical curve for liquid-film breakup.

There are generally three relationships between the gas and liquid in flow direction: the same, opposite, and vertical. The biggest difference of them is that the breakup mechanism is different since the driving forces on liquid film by gas are different. Despite the various aforementioned studies, most are concentrate on the first two situation, and there is little research (Azzopardi et al., 2002) on the third kind of situation which is exact conducted in vane mist eliminators.

In the present study, we develop a theoretical model based on the force-balance model in boundary layer flow to predict the criteria for the onset of film breakup at a corner point of a CP wall. We then measure the thickness of the liquid film on the wall using planar laser-induced fluorescence (PLIF). Based on this, we study the relationship between wall film thickness and critical airflow velocity in a channel formed from differently structured CPs, and we propose criteria determined by structural factor k_1 and gas-fluid property factor k_2 for the breakup of the liquid film at the corner point. After analyzing the experimental results, we consider a structure that would increase the critical airflow velocity.

2. Theory

In a vane mist eliminator, a liquid film forms on a vertical CP wall by capturing liquid particles from a horizontal shear flow of moisture. When the flow speed of the moisture reaches a critical value, the liquid film breaks up at the wall corner of CP wall. In the present study, we use the force-balance method to analyze this breakup of the liquid film on the CP. Since the thickness of liquid film on the CP wall is much less than characteristic length of CP channel (δ/L<less than1), we can use boundary layer theory to describe how it flows.

Before deducing the force-balance model of liquid-film breakup, we must obtain the velocity distribution in the film. To analyze the velocity distribution in a boundary layer on a curved surface, we introduce an orthogonal curved coordinate system for the horizontal cross section of the CP channel, as shown in Fig. 1. Point O is the origin of the coordinate system, the x direction is along the curved wall, the y direction is perpendicular to the wall, P_0 is the projective point of point $P(x, y)$ on the x axis, and the radius of curvature of arc near P_0 is $R(x)$, which is a variable of x.

The following are the two-dimensional Navier–Stokes (NS) equations in this coordinate system (Schlichting et al., 1988):

$$\frac{\partial u}{\partial t}+\frac{R}{R+y}u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+\frac{vu}{R+y}$$
$$=-\frac{R}{R+y}\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\left\{\frac{R^2}{(R+y)^2}\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{1}{R+y}\frac{\partial u}{\partial y}-\frac{u}{(R+y)^2}\right.$$
$$\left.+\frac{2R}{(R+y)^2}\frac{\partial v}{\partial x}-\frac{R}{(R+y)^3}\frac{dR}{dx}v+\frac{Ry}{(R+y)^3}\frac{dR}{dx}\frac{\partial u}{\partial x}\right\} \tag{1}$$

$$\frac{\partial v}{\partial t}+\frac{R}{R+y}u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+\frac{u^2}{R+y}$$
$$=-\frac{R}{R+y}\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\left\{\frac{\partial^2 v}{\partial y^2}-\frac{2R}{(R+y)^2}\frac{\partial u}{\partial x}+\frac{1}{R+y}\frac{\partial v}{\partial y}\right.$$
$$\left.+\frac{R^2}{(R+y)^2}\frac{\partial^2 v}{\partial x^2}-\frac{v}{(R+y)^2}+\frac{R}{(R+y)^3}\frac{dR}{dx}u+\frac{Ry}{(R+y)^3}\frac{dR}{dx}\frac{\partial v}{\partial x}\right\} \tag{2}$$

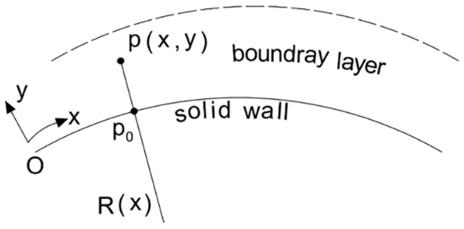

Fig. 1. Boundary layer on a curved surface.