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Study on performance of wave-plate mist eliminator with porous foam layer as enhanced structure. Part I: Numerical simulation

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HIGHLIGHTS

- Wave-plate mist eliminator with porous foam as enhanced structure was proposed.
- Separation efficiency and pressure drop were studied by CFD method.
- Computational field was simplified to 2D layout with randomly arranged circles.
- Flow field in foam layer and droplet trajectories were investigated numerically.

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ABSTRACT

Wave-plate mist eliminator with porous foam layers as enhanced structures on vanes to improve separation efficiency for tiny droplets was proposed in this paper. Overall separation efficiency, grade separation efficiency and pressure drop of the mist eliminators were systematically studied by using Computational Fluid Dynamics (CFD) method. The Shear Stress Transport (SST) k-ω turbulence model and Discrete Phase Model (DPM) were adopted to describe the motion of gas phase and liquid phase, respectively. The computational field was simplified by introducing an assumption that the real 3D structure of porous foam can be equivalent to 2D layout with randomly arranged circles. The CFD results showed that the separation efficiency was enhanced by increasing the foam layer thickness. Moreover, a gradual increase in the foam porosity at fixed PPI (pores per inch) value made the separation efficiency increased to a maximum value, then fall to a lower level, while by decreasing the PPI value of the foam at fixed porosity, the separation efficiency increased. Pressure drop was increased both with the increase in the foam layer thickness and PPI value as well as the decrease of the porosity. Furthermore, the flow field and the droplet trajectories were also analyzed.

1. Introduction

Wave-plate mist eliminator (also called vane demister) is a kind of separating devices which is widely employed in the circumstances where it need to remove large quantities of liquid droplets from the gas stream. For instance, in coal-fired power plant, wave-plate mist eliminators are always installed in cooling towers and Wet Flue Gas Desulfurization (WFGD) system. It helps to separate corrosive liquid from gas in order to protect downstream equipment from damage and restrict pollutant emission into the environment (Wang et al., 2008). Wave-plate demisters are also increasingly used in flash chambers in multi-stage desalination plants, for removal of entrained liquid droplets from vapor streams (Venkatesan et al., 2013).

Separation efficiency is the most important performance of demisters. The gas stream flow direction changes when it is forced to pass through the channels consisting of series wave-plates with sharp bends. Due to the inertia force, those carried droplets firstly deviate from the gas streamline, and then deposit on vane surface. The collected droplets converge into a liquid film and drain out from the surface under the gravity. On the other hand, recirculation zones are generated when the gas-flow moving direction changes, associating with the production of pressure drop. Basic geometry parameters, such as channel width, channel length, and bend angle, have great influence on the wave-plate demisters' separation efficiency and pressure drop.

Experiment is an effective method which has been adopted by researchers to investigate mist eliminators' performance

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Nomenclature

a_1, a_2, a_3	constants in Eq. (8)
C_D	the drag coefficient, dimensionless
d_p	pore diameter, mm
d_s	strut diameter, mm
D_d	droplet diameter, mm
$\bar{D}_d$	average droplet diameter for Rosin-Rammler distribution, mm
$D_{(3,2)}$	Sauter mean diameter, μm
D_ω	cross-diffusion term in Eq. (4), kg m^{-3} s^{-2}
Eu	Euler number, dimensionless
F_x	other forces exert on droplet
G_k	production of turbulent kinetic energy k in Eq. (3), kg m^{-1} s^{-3}
G_ω	production of specific dissipation rate ω in Eq. (4), kg m^{-3} s^{-2}
H	vertical height of part of demister, mm
k	turbulent kinetic energy, m^2 s^{-2}
m	total number of the droplets
M	liquid mass flow, kg s^{-1}
M_d	mass fraction of the droplets in Rosin-Rammler distribution
n	foam thickness, mm
n_{SP}	spread parameter for Rosin-Rammler distribution, dimensionless
p	pressure, Pa
Re	Reynolds number of continuous phase, dimensionless
Re_p	Reynolds number of particle, dimensionless
S	channel spacing, m
S_V	surface-to-volume ratio, mm^{-1}
t	time, s
u	velocity, m s^{-1}
x, y	Cartesian coordinates in the horizontal and the vertical directions, m
X	positions along the specific lines from left wall to right wall, m
Y	positions of the specific lines above the demister air inlet, m
Y_k	dissipation of turbulent kinetic energy k due to turbulence in Eq. (3), kg m^{-1} s^{-3}
Y_ω	dissipation of specific dissipation rate ω due to turbulence in Eq. (4), kg m^{-3} s^{-2}

Greek symbols

α	vane turning angle, °
δ_{ij}	Krönecker delta
η	overall separation efficiency
η_i	grade separation efficiency
ρ	droplet density, kg m^{-3}
μ	dynamic viscosity, N s m^{-2}
ω	specific dissipation rate, s^{-1}
Γ_k	effective diffusivity of turbulent kinetic energy k in Eq. (3), kg m^{-1} s^{-1}
Γ_ω	effective diffusivity of specific dissipation rate ω in Eq. (4), kg m^{-1} s^{-1}

Subscripts

i,j	indexes
d	droplet
g	gas
in	air inlet
E	entered droplet
R	removed droplet

Abbreviations

CFD	Computational Fluid Dynamics
DPM	Discrete Phase Model
DRW	Discrete Random Walk
EIM	Eddy Interaction Model
LES	Large-Eddy Simulation
RANS	Reynolds Average Navier-Stokes
RSM	Response Surface Method
RSTM	Reynolds Stress Transport Model
SST	Shear Stress Transport
WFGD	Wet Flue Gas Desulfurization

(Azzopardi and Sanaullah, 2002; Banitabaei et al., 2012; Foster et al., 1974; Koopman et al., 2014). However, an experimental study still requires complicated facilities and can be quite time consuming. Due to the rapid development of the computer industry, Computational Fluid Dynamics (CFD) method has been frequently used in the recent years to predict demisters' performance and optimize their geometrical parameters, owing to its huge time and expense saving advantage.

Simulation accuracy is one of the first issues need to be solved when using the CFD method. Earlier researches focused on the comparisons between published experiment results and simulation data by using different computing models. Wang and James (1998) simulated a droplet separation procedure of a wave-plate mist eliminator by using CFX software. It was suggest that the low Reynolds number k-ε turbulence model matched better with experimental results of Phillips and Deakin (1990) rather than the standard k-ε turbulence model. Jøsang and Melaaen (2002) made a comparison between k-ε turbulence model and Reynolds Stress Model. Results showed that first order scheme with k-ε turbulence model have better prediction with their earlier experiment (Jøsang and Melaaen, 2000). Ruiz et al. (2016) proved that Reynolds Average Navier-Stokes (RANS) model with a turbulence dispersion of droplet appropriately predicted the performance of demister, even more effective than Large-Eddy Simulation (LES).

In order to further improve the accuracy, interactions between droplets and eddies were taken into account by using the Eddy Interaction Model (EIM). Three kinds EIMs were added into the simulation of Wang and James (1999). Results showed the modified EIM was in good agreement with available experimental data except for very small droplets. Galletti et al. (2008) worked on the influence of air velocity and droplet diameter on separation efficiency of wave-plate demisters with drainage channels by using a varied EIM. Reynolds Stress Transport Model (RSTM) and Shear Stress Transport (SST) k-ω turbulence model as well as EIM model were used in Estakhrsar and Rafee's (2013) research. Their study demonstrated that eddy lifetime constant greatly affected the prediction accuracy of removal efficiency. A similar method called Discrete Random Walk (DRW) was used in Kauousi's et al. (2013) research, both with the SST k-ω turbulence model. It was suggested that, by comparing with the experimental data provided by Ghetti (2003), the DRW model promoted the simulation accuracy for the small droplets but reduced the simulation accuracy for the larger ones.

Another important research direction is the optimization of demister geometry parameter. Zhao et al. (2007) firstly used Response Surface Method (RSM) to optimize the design of wave-plate demisters. The influence on separation efficiency by structural parameters, such as bend angle, channel width, height of curve and upright region, were numerically studied in their work. Same approach was adopted by Narimani and Shahhoseini (2011) to investigate the separation efficiency dependence on gas velocity, channel width and bend angle. Zamora and Kaiser (2011) conducted a CFD study on the separation efficiency of four

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