Nuclear Engineering and Design 276 (2014) 98–106

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

An analytical model for droplet separation in vane separators and measurements of grade efficiency and pressure drop

Hans K. Koopman[a,*], Çağatay Köksoy[b], Özgür Ertunç[b], Hermann Lienhart[b], Heinz Hedwig[b], Antonio Delgado[b]

[a] Siemens AG, Energy Sector, Power Generation Freyeslebenstrasse 1, 91052 Erlangen, Germany
[b] Institute of Fluid Mechanics, Friedrich-Alexander University, Erlangen-Nuremberg Cauerstrasse 4, 91058 Erlangen, Germany

HIGHLIGHTS

- An analytical model for efficiency is extended with additional geometrical features.
- A simplified and a novel vane separator design are investigated experimentally.
- Experimental results are significantly affected by re-entrainment effects.
- Outlet droplet size spectra are accurately predicted by the model.
- The improved grade efficiency doubles the pressure drop.

ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form 17 May 2014
Accepted 19 May 2014

ABSTRACT

This study investigates the predictive power of analytical models for the droplet separation efficiency of vane separators and compares experimental results of two different vane separator geometries. The ability to predict the separation efficiency of vane separators simplifies their design process, especially when analytical research allows the identification of the most important physical and geometrical parameters and can quantify their contribution. In this paper, an extension of a classical analytical model for separation efficiency is proposed that accounts for the contributions provided by straight wall sections. The extension of the analytical model is benchmarked against experiments performed by Leber (2003) on a single stage straight vane separator. The model is in very reasonable agreement with the experimental values. Results from the analytical model are also compared with experiments performed on a vane separator of simplified geometry (VS-1). The experimental separation efficiencies, computed from the measured liquid mass balances, are significantly below the model predictions, which lie arbitrarily close to unity. This difference is attributed to re-entrainment through film detachment from the last stage of the vane separators. After adjustment for re-entrainment effects, by applying a cut-off filter to the outlet droplet size spectra, the experimental and theoretical outlet Sauter mean diameters show very good agreement. A novel vane separator geometry of patented design (VS-2) is also investigated, comparing experimental results with VS-1. Experimental separation efficiencies based on recorded mass flow balances are very similar for both geometries. However, based on an analysis of the outlet droplet size spectra, VS-2 outperforms VS-1. It is concluded that re-entrainment effects cloud the performance of VS-2 and that the perforations in the wall sections of VS-2 are not very effective. Pressure drop measurements performed on both geometries reveal that the pressure drop for VS-2 is higher than for VS-1 by a factor of almost two for gas velocities up to 10 m/s.

1. Introduction

The origin of vane separators (also referred to as chevron separators) as applications for the separation of particles or droplets from gas flows, lies in filtering applications for the mining industry. Currently they are applied in chemical plants, in the oil industry, in power plants and in other industries. In the application of

---

[*] Corresponding author. Tel.: +49 (0) 9131 18 82959.
E-mail address: hans.koopman@siemens.com (H.K. Koopman).

http://dx.doi.org/10.1016/j.nucengdes.2014.05.034

Nomenclature

D	diameter, m
δ_R	channel width, m
L	length of straight wall section, m
$\dot{m}$	mass flow, kg/s
R	radius, m
u	radial velocity, m/s
v	angular velocity, m/s
φ	total bend angle, rad
η	efficiency, –
μ	dynamic viscosity, kg/m/s
θ	azimuthal angle of droplet position, rad
ρ	density, kg/m

removing water droplets from saturated steam, vane separators are also known as demisters. In power plants, they are used to mechanically dry the process steam for two main purposes: to protect the equipment from erosion and/or to increase thermodynamic efficiency. The latter can be achieved via a reduction of the necessary evaporation heat in superheating applications or via a decrease in the negative side effects of droplets on the efficiency of turbines. In many cases, larger droplets (50–200 μm) are separated from the flow by coarse separators, usually in the form of cyclone separators. Vane separators can be classified as fine separators and are used for the separation of droplets down to or even below 10 μm in diameter. Vane separators derive their name from their corrugated plates, installed in parallel to create curved flow channels. As the gas propagates through these curved channels, the droplets' inertia as well as centrifugal forces direct the droplets toward the channel wall. Here they coalesce and form a liquid film, which is then extracted from the main gas flow.

An important factor that influences the separation efficiency is the specific geometry of the flow channel; the channel width, the bend angle and the number of stages being significant parameters. Many vane separators are also equipped with some type of pick-off hooks, penetrating the flow channel to separate the liquid film from the gas flow. (Li et al., 2007) reported on the positive influence of pick-off hooks on the separation efficiency. Such pockets increase separation efficiency at lower gas velocities, especially for small droplet sizes, and reduce re-entrainment. However, the pick-off hooks increase pressure drop and are often counterproductive at higher flow velocities, because stagnation pressure builds up in the shielded flow areas, effectively blocking incoming droplets with low inertia and further increasing turbulent pressure drop. In addition, the increased geometrical complexity increases manufacturing costs. In some cases, for instance as listed by Kolev (2011) or as reported by Verlaan (1991), the pick-off hooks are combined with drainage channels to separate the liquid film from the gas flow and thus further reduce entrainment. This comes at the cost of sacrificing potentially large volumes otherwise available to the gas flow, thus increasing the necessary space for the installation of the demisting equipment.

In this paper, classical droplet separation theory is extended to better represent the vane separator geometry and increase the accuracy of predictions for the droplet separation efficiency. The grade efficiencies predicted by the analytical model are compared with experimental results from a simplified vane separator geometry (VS-1). In addition, a novel vane separator geometry (VS-2) is presented, which incorporates several geometrical aspects expected to improve droplet separation, with the avoidance of pick-off hooks. The novel design is tested experimentally and its separation efficiency and pressure drop are compared to the simplified model. The improvement of separation efficiency usually comes at the price of increased pressure loss. This is relevant, because even slight pressure losses have a significant impact on power plant efficiency and thus on electrical output.

2. State of the art

Regehr (1967) defines the droplet separation efficiency of a single bend as the maximum radial droplet migration distance relative to the channel width. This definition was later refined by Bürkholz (1989) by defining the radial droplet migration distance as the product of the time of passage through the bend and the terminal radial droplet velocity under Stokes conditions. This led to the well known equation

$$\eta = \frac{\rho_d v D^2}{18\mu\delta_R}\varphi = St\,\varphi \tag{1}$$

in which δ_R is the constant channel width, St is the Stokes number and φ is the bend angle. For vane separators with a multiple number of stages n, the droplet separation efficiency is defined by Bürkholz (1989) as:

$$\eta_n = 1-(1-St\,\varphi)^n \tag{2}$$

These equations were used by Phillips and Deakin (1990) and, among other authors, applied by Wang and James (1998, 1999) and Zamora and Kaiser (2011). Wilkinson (1999) also applies these equations, but he adjusts the separation efficiency in all but the first bend by a mixing factor f_m, to account for the uneven droplet distribution downstream of the first bend:

$$\eta_n = 1-(1-St\,\varphi)(1-f_m\,St\,\varphi)^{n-1} \tag{3}$$

The mixing factor is a function of the pressure drop coefficient C_{pb} of the bend, the Stokes number and the width-to-length ratio δ_R/L of the straight channel section leading up to the bend:

$$f_m = 1-\exp\left(\frac{cC_{pb}}{cC_{pb}-18St\,\delta_R/L}\right) \tag{4}$$

with $f_m = 1$ for $cC_{pb} > St\delta_R/L$. Based on experimental data, the empirical constant c is suggested to be 0.257 (Wilkinson, 1999). The analysis is based on the fact that total remixing is defined to occur when the distance y that the droplets have been carried by the r.m.s. turbulent transverse gas velocity equals the total width of the channel: $y = LcC_{pb}/St = \delta_R$.

Zhao et al. (2007) use results from a CFD model to investigate the correlation between separation efficiency and five geometrical parameters and operating conditions. The CFD model is validated against experimental results reported by Lang et al. (2003) for a single stage separator. In what they term response surface methodology, the authors employ statistical software to fit response surfaces, defined by the response of the separation efficiency to changes in two different dependent parameters, using a function including linear, quadratic and cross terms of the dependent parameters. The resulting regression coefficients provide insight into which terms cause significant responses. Zhao et al. (2007) arrive at the following function for the separation efficiency:

$$\begin{aligned}\eta = {} & 1.95539+0.004491(\pi-\varphi)+0.001046H_1-0.02186H_2\\ & -0.0074\delta_R+0.182297v-0.00004(\pi-\varphi)^2\\ & -0.000043(\pi-\varphi)\delta_R-0.00047(\pi-\varphi)v\end{aligned} \tag{5}$$

in which $H_{1,2}$ are measures for the in- and outlet section and the length of the bend respectively. Unfortunately, the absence in the