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A correlation giving improved description of the capacity and efficiency of vane-type gas-liquid separators

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Abstract

Vane-type demisters are attractive droplet separators since they combine robustness and sufficient separation efficiency with a low pressure-drop, a high capacity and some fouling resistance. Experience shows that their optimal operation is close to the maximum capacity point and even that at this point the separation efficiency is better at higher pressures. This paper proposes a generalised expression for this point, as a function of gas and liquid flow and properties, drawing on knowledge about other, related, unit operations, namely cyclone separators and distillation towers. The generalized expression relates the dimensionless velocity with the Archimedes number and a flow parameter. The expression builds on earlier work on a criterion for the inception of droplet entrainment in two-phase film flow, pioneered by Ishii and Grolmes, and is supported by considerable experimental work published over the last 50 years.

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Types of vane packs and state of the knowledge

Originally vane type separators were designed as "in-line-separators" as shown in Figure 1a : in horizontal lines with a liquid-lean gas flow liquid droplets are separated from the gas in a vane-pack due to the inertia of the droplets while the gas is zig-zagging through parallel vanes. The droplets impacting on the surfaces of the vanes coalesce and are incorporated into a film on the vanes, which is then guided downwards to a collection tray.

[Figure 1 about here.]

Three types of vanes are seen:

- simply a set of parallel corrugated plates [1], see Figure 1 b),
- the same, but with simple collection pockets [2], Figure 1 c), lower three and
- vanes with "double pockets" [3]: see Figure 1c, top image.

The corrugated plate pack is the original, now non-confidential, concept and, despite the lower capacity and efficiency, has better properties in fouling environments. The double pocket design has a larger holding capacity for the liquid to be drained away; the single pocket design is most often used since it provides good capacity and efficiency. Vane type separators are attractive because of their:

- Robustness, consisting of a rigid structure without loose elements, this is preferred for protection of rotating equipment downstream
- Fouling resistance, in this respect they are better than wire-mesh, which may have minor fouling-accumulating spots in the structure

- Ability to handle surges in the liquid load (especially the double-pocket design)
- Lowish pressure loss, especially when compared to cyclonic devices.

Interesting is the lowish pressure loss. In the optimisation of cyclonic devices it is known that almost any equipment modification with the purpose of increasing the separation efficiency is done at the cost of an increased pressure drop [4]. This type of optimisation cannot be found in the history of vane separators. This may be attributed to the fact that in separating droplets with vanes, the condition of the feeding stream is already such that the droplet size is large enough to be caught by the vane pack, so that modifications to improve the separation efficiency are redundant, as discussed later in this paper. In atmospheric conditions vanes can separate all droplets larger than about 15 μm (see [5]). Moreover, if needed, it is possible to modify the droplet size distribution by installing a coalescing wire mesh pad upstream of the vane pack to enlarge the size of the droplets sufficiently for capture in the vane pack.

Modern separators often use vane packs in different configurations as well: vane packs can be used as secondary mist separators, where a first stage is used to separate slugs, or a vane pack can be used where the gas flow is vertically upwards through the pack, and the liquid film thus drains counter-currently downwards against the gas flow (please see the left and right image in Figure 2, respectively). Further to pressurised operation this last configuration is applied in high-vacuum distillation units as well. This configuration will be mentioned at the end of this paper.

[Figure 2 about here.]

Inertia separators, such as vane-packs, separate droplets the best at the highest velocity possible. This velocity is close to, and limited by, the flooding point, above which droplets start to be re-entrained from the film on the vane surface. Recently Fadda et al. [6] determined the variation of the flooding velocity in vane packs at elevated pressure and found that for very high pressure operation (up to 130 bar) the flooding velocity reduced by a factor of 3 when the pressure increased by a factor 4! In Figure 3 their data are given, as well as the prediction for the flooding velocity proposed in this paper, clearly a close match.

[Figure 3 about here.]

Song et al [7] experimentally investigated the effect of the vane configuration on the separation efficiency using the latest online particle sizing equipment finding grade efficiency curves with fish-hook shapes for the fines particles, similar to those found in gas-solid separation equipment, also in cyclones.

In this article a new model is introduced for the flooding velocity, i.e. the separator capacity, which is the main focus of this work. First the efficiency of vane packs as a function of droplet size and how and why elevated pressure influences the efficiency will be discussed, thereafter separator capacity. The information on capacity available in the literature will be described and it will be shown that all the data can be captured in one new capacity correlation.

On the separation efficiency of vane-packs

In the past 50 years much research has been devoted to describing the paths of the gas and the droplets inside vane packs, mostly concentrating on air/water systems at atmospheric conditions (e.g. [8]). One finds typically that droplets of size 40 μm (the separator cut size) are caught at lowish gas velocities (1–3 m/s), while the cut size goes down to to 15 μm when the velocity is high (10–15 m/s). If these separators were designed for solid particle separation one would conclude from these cutsizes that the device is far from sufficiently efficient. However, droplets are generally significantly larger than solid particles; their size being dependent on the flow history upstream of the separator, on the gas velocity and on the physical properties of the gas and liquid. Most likely the cut size in the separator itself is influenced by the flow and physical properties of the liquid and gas as well. We consider two aspects.

First the cut size of the separator. Pek [9] has analysed the critical droplet size (cut size) in vane packs for various gas/liquid systems (air/water; steam/water; natural gas/condensate) at various pressures as reported in [3, 9]. Mostly the vane-pack was operated near the flooding point, hence likely at maximum efficiency. Pek [9] states that, similar to the description of a cut-point for cyclonic devices in Hoffmann and Stein [10], the critical droplet size in a vane pack is related to the physical properties of the gas/liquid system and the inlet gas velocity by:

$$d_c = K\sqrt{\frac{\mu_g}{\Delta\rho v_g}} \tag{1}$$

In this formula μ_g is the gas viscosity, $\Delta\rho$ the difference in liquid and gas density and v_g the gas velocity in the vane pack. K is a factor that accounts for the effects of, among other things, the vane design, such as the spacing between the vanes. This expression is derived from a force balance on a droplet moving, due to its inertia, relative to the gas as the gas flows around a corner in the vane pack, the argument being similar to that in the "time-of-flight" cyclone efficiency models [10].

Table 1 shows the data for the operating conditions, for the fluid physical properties and for the critical sizes as calculated according to reference [9]. That is to say that these are given as a multiple of the critical size for air/water. Supposing that the cut point for air/water is 15 μm, this shows that for pressurised conditions the cut point increases with a factor of 4 to 60 μm, which is very significant.

Does this mean that the vane-pack is not fit for pressurised operation? Actual practice shows that this is not necessarily the case, and likely for two reasons: the droplets grow larger at high pressure operation, and better-than-expected capture might result from "bulk separation" as discussed below.

Suppose the flow upstream of the in-line vane pack separator is a fully developed 2-phase annular mist flow where the droplet size of the mist can be calculated with a formula of "Harwell" as given in [10]. According to the "Harwell" method, the 10% size on the cumulative size distribution curve is:

$$d_{10} = 0.2 D_t \frac{\mathrm{Re}^{0.1}}{\mathrm{We}^{0.6}} \left(\frac{\rho_g}{\rho_l}\right)^{0.6} \tag{2}$$

with $\mathrm{Re} \equiv \frac{\rho_g v_g D_t}{\mu_g}$ and $\mathrm{We} \equiv \frac{\rho_g v_g^2 D_t}{\sigma}$.

The values for d_{10} are included in Table 1 as is the ratio of d_{10} to the cut size. For D_t a value 0.3 m is assumed. It is clear that the incoming droplet size relative to the cut size grows larger as the pressure increases, giving rise to a reduction in the limit load and therefore to an increase in the bulk separation. The separation efficiency of an in-line-vane separator at high pressure thus does not deteriorate, rather the opposite. In cases where droplets grow because of condensation it is likely that pressurized operation, which is at much lower velocities, would result in droplet growth due to the increased residence time.

[Table 1 about here.]

Another effect leading to better separation efficiency is that separation is enhanced in cases where the liquid loading is so large that "bulk-separation" of the part of the droplet cloud that exceeds the "critical load" (or the carrying capacity of the gas) will lead to the removal of a fraction of the incoming droplet mass. Experience shows that this type of separation is almost irrespective of droplet-size. In [10] this type of separation is described and is quantified using a model due to Muschelknautz [11].

An expression for the critical load in vane packs based on an expression of Muschelknautz and coworkers recommended for cyclones is proposed here. This expression is in terms of the so-called "cut size for wall separation" [12] of the separator, d_{cw}, and may therefore take into account the differences in configuration and operation of cyclones and vane packs, respectively, so that this relation can be proposed, as an initial suggestion, to be applicable also to vane-pack separators. This expression for the critical load is:

$$c_{oL} = 0.025 \left(\frac{d_{cw}}{d_{\mathrm{med}}} \right) (10 c_o)^k \tag{3}$$

where

$$k = 0.15 \quad \text{for} \quad c_o \geq 0.1 \quad \text{and} \quad k = -0.11 - 0.10 \ln c_o \quad \text{for} \quad c_o < 0.1 \tag{4}$$

where the loading, c_o, and the critical load, c_{oL}, should be expressed as mass fractions in kg solid or liquid per kg of gas. d_{med} is the median of the size distribution of the incoming particles. Initially the powder fraction separated just after the inlet due to the "mass loading" effect was assumed unclassified, but in later developments it is considered to be classified [12]. Our experience, however , is that taking the wall separation as independent of the particle or droplet size gives correct predictions.

Making the following assumptions:

- the separator geometry is constant
- the inlet loading is taken as constant
- the ratio of the wall tangential velocity and the average axial velocity is constant

it is possible to derive an expression elucidating the effect of the physical properties of the gas and liquid on the critical load from Equation (3) in this paper by simplifying Equation (31), in the paper of U. Muschelknautz [12] using his equations (12) and (24–28) giving:

$$c_{oL} = \sqrt{\frac{\mu_g}{\Delta\rho v_{\text{in}} d_{10}}} A(\text{geom}, c_o) \tag{5}$$

where A is a constant, which is a function of the cyclone geometry and inlet solid or liquid loading only. Using this analysis it is possible to calculate the magnitude of the limit load in cyclones (and presumably vane packs) at pressurized conditions relative to that at atmospheric conditions for air/water systems. These numbers have been added to Table 1. The limit load is seen to decrease with increasing pressure, meaning that the effect of bulk separation will be more pronounced at higher pressures leading to better separation performance.

Data available in the open literature on pressurized vane-pack operation are mainly from Kall [3] and Pek [9]. These data confirm the Fadda information that good separation can be obtained at very high pressures. All the other information from operation at atmospheric pressure shown in Table 1 constitutes supporting evidence for the very good separation in this type of separator as well.

Factors limiting the capacity of the vane pack

When all liquid droplets are caught on the vane wall, and subsequently drained away, the separator operates ideally. However, as the gas the rate increases, interface interactions between gas and the film on the wall can lead to re-entrainment of liquid. Ishii and Grolmes [13] have given an overview of the stability of a liquid surface with a gas flowing over it. Based on this they published inception criteria for droplet entrainment in cocurrent gas/liquid film flow. At high gas velocities relative to the film, roll waves may be generated (see Figure 4) from which droplets can escape above a certain film Reynolds number, $\mathrm{Re}_{\mathrm{trans}}$. $\mathrm{Re}_{\mathrm{trans}}$ being 160 for horizontal and vertical upward flow. At film Reynolds numbers below $\mathrm{Re}_{\mathrm{trans}}$ entrainment may still occur and a surface undercutting mechanism was proposed to account for this. We have previously used these two types of phenomena to describe entrainment in demisting cyclones [10, 14].

[Figure 4 about here.]

Ishii and Grolmes [13] have shown that besides the mechanisms described above (roll wave and wave undercut) there is a third mechanism in two-phase pipe-flow responsible for re-dispersion: liquid impingement (please see Figure 4 c). Similar to heavy rain splashing on the street, large liquid drops may impinge on a wetted surface and generate small drops which, if not captured again, will ultimately escape from the vane pack.

Pek [9] slightly modified the model of Ishii and Grolmes to smoothen out the curves related to their model, replacing their function with a discontinuous first derivative in their Figure 12 by the single function: $(11 + 1.39\mathrm{Re}^{-0.5})$, which appears as a single smooth function overlaying the breaking function of Ishii and Grolmes (please see Figure 5).

[Figure 5 about here.]

Pek shows the gas velocity at the inception of entrainment to be described by three parameters: the dimensionless gas velocity, $\mathrm{Nv} = \frac{v_g \mu_l}{\sigma}\sqrt{\frac{\rho_g}{\rho_l}}$, the Archimedes number, $\mathrm{Ar} = \frac{\rho_l}{\mu_l^2}\sqrt{\frac{\sigma^3}{g\Delta\rho}}$, and the liquid film Reynolds number, $\mathrm{Re} = \frac{\rho_l v_l \delta}{\mu_l}$. These dimensionless groups contain the following physical and operational parameters: the cross-sectional mean gas velocity, the surface tension and viscosity of the liquid, the effect of gravity and the ratio of liquid to gas momentum. According to Ishii and Grolmes and to Pek there are two possibilities:

a) $\mathrm{Re} > \mathrm{Re}_{\mathrm{trans}}$

$$\text{entrainment occurs if} \qquad \mathrm{Nv} > 8.73\mathrm{Ar}^{-0.4}(0.11 + 1.39\mathrm{Re}^{-0.5})$$

b) $\mathrm{Re} < \mathrm{Re}_{\mathrm{trans}}$ or $\mathrm{Re} > \mathrm{Re}_{\mathrm{trans}} + \mathrm{Ar} \leq 225$ (Ar taken as $\mathrm{Ar} = 225$)

$$\text{entrainment occurs if} \qquad \mathrm{Nv} > 0.11 + 1.39\mathrm{Re}^{-0.5}.$$

Ar is the square of the reciprocal of the "viscosity number" used by Ishii and Grolmes.

Pek suggested that the phenomena discussed above leading to the inception of entrainment in two-phase pipe flow, are similar to the phenomena leading to entrainment from the gas/liquid interface in a vane pack. And hence it is here proposed that a modified criterion could be applied to describe the maximum capacity of vane type gas liquid separators. Pek held that crucial for the capacity is the bottom section of the vanes as there the liquid flow is highest and hence if droplet re-entrainment starts then it would most likely occur from that region. He defined a liquid film Reynolds number in which the product of the velocity term and the characteristic dimension is Γ, being the volumetric liquid flow per unit wetted perimeter (also called the "liquid loading" in the context of a liquid film running on a solid wall) at the bottom of the vanes. He derived equations similar to the above (with different proportionality constants) being:

- for $\mathrm{Ar} \geq 225$

$$\text{entrainment occurs if} \qquad \mathrm{Nv} > 3.5\mathrm{Ar}^{-0.4}(0.11 + 1.39\mathrm{Re}^{-0.5})$$

The constant of proportionality is smaller than for the case of straight two phase pipe flow (3.5 instead of 8.73), which seems reasonable since the corrugation of the vane wall is likely to enhance reentrainment in comparison with a wall that is straight in the flow direction. The three gas/liquid systems used in the supporting experiments were air/water ; steam/water and gas/condensate at various pressures (as in table 1), and were taken from [3, 9]). Pek showed reasonable agreement between theory and experiment.

Clear from data and equation is that the capacity is negatively influenced by an increased liquid rate via Γ in Re. The wetted perimeter, for computation of Γ, the liquid loading, is estimated as the horizontal vane length available for drainage. One might expect that for vertically larger vanes, the capacity would decrease since the liquid load at the vane bottom will be larger. This was found to be marginally the case in [3]; for venetian blinds, however, the capacity was found to be larger for higher vanes [1]. Pek stressed the need for more experimental evidence to conclude on a general predictive relation.

An improved maximum capacity model for vane packs

In this section a new model for the capacity of vane packs is proposed, based on the concepts of Pek, but modifying the criterion in one important way, drawing on experience from another field: the capacity of packed columns in distillation equipment.

Usually in describing the capacity of packed columns in distillation equipment for countercurrent flow of gas and liquid in packed towers one uses the so-called flow parameter, Φ, as the parameter to describe the influence of the liquid-to-gas ratio on the capacity (see e.g. references [15–17]):

$$\Phi \equiv \frac{Q_l}{Q_g}\sqrt{\frac{\rho_l}{\rho_g}}$$

With Q the volumetric rate in m^3/s. For a particular combination of gas and liquid one finds a relation for the influence of Φ on the capacity, $v_{g,c}$, of the form:

$$v_{g,c} = \frac{K_p}{1 + K_c * \Phi^n} \text{ m/s}, \tag{6}$$

with $K_c \approx 2$, and $n \approx 0.8$, K_p is an empirical constant which we quantified by comparing with experimental data as follows. This correlation has been fitted to the most extensive set of data on the capacity of vane packs that we have found in the open literature, and this is depicted in Figure 6. These data are given in ref. [1]: the vane pack had no pockets (the author called the pack "venetian blinds") and the liquid mass fraction, $(1-x)$, ranged from 0.01 to 0.9, and hence the flow parameter $\Phi = (1-x)/x\sqrt{\frac{\rho_g}{\rho_l}}$ ranged from 0.0004 to 0.2, which is very wide indeed, since normal practice, in our experience, is to select a flow parameter of $\Phi = 0.01$ as a preferred maximum for vane separators. The best fit with the data was obtained with the formula:

$$v_{g,c} = \frac{10}{1+k\Phi} \text{ m/s} \tag{7}$$

with $k \approx 15(+/-5)$.

Some of the curve fitting points are included in Figure 6.

[Figure 6 about here.]

As seen in the figure, this clearly accounts well for the influence of the liquid loading on the vane capacity. In an effort to fit all available capacity points in a revised correlation it was therefore chosen to replace the influence of Re, as in the equations of Pek [9], by the influence of Φ using this formula.

Data on maximum capacity used in this paper for the formulation of a predictive relation for the capacity include the data originally used by Pek (such as from [3]) but in addition data from Sorokin [1] and Koopman [8]. The full data set used in this paper is as follows:

- Sorokin [1] : no-pocket vanes, 1 bar; air/water and wide range of liquid loads
- Koopman [8]: Single-pocket vanes; 1 bar; air/water

- Pek [9]: Single-pocket vanes, high pressure; gas/condensate-glycol
- Kall [3]: Semi double-pocket vanes, many pressures; air/water and steam/water

In table 2 all the data are grouped and corresponding values for Nv and Ar are given. Please note that the second-to-last column represents a liquid phase consisting of two immiscible liquids, glycol and condensate, the condensate forming a "live" mixture of natural gas and condensate, so that the complex and varying equilibrium contributes to the uncertainty when calculating the gas velocity. In this type of system, the properties of the liquid most likely to cause reentrainment should be used in the model calculations.

The correlation that best matched the data available is as follows: Entrainment occurs if:

$$\mathrm{Nv} > \frac{1.5\mathrm{Ar}^{-0.45}}{1+10\Phi} \tag{8}$$

An expression for the maximum gas velocity, which replaces the dependency of the liquid film Reynolds number, Re, with the flow parameter, Φ is therefore proposed here. This is, as mentioned, consistent with the experience in packed towers [15–17] and with the data of Sorokin [1]. This expression is:

$$v_{g,c} = 1.5\sqrt{\frac{\rho_l}{\rho_g}}\frac{\sigma}{\mu_l}\frac{\mathrm{Ar}^{-0.45}}{(1+10\Phi)}, \tag{9}$$

which, for Ar = 225 (corresponding in Ishii and Grolmes [13] to $\mathrm{N_v} = \frac{1}{15}$, the point where their empirical expression changes from one form to the other) reduces to:

$$v_{g,c} = 0.13\sqrt{\frac{\rho_l}{\rho_g}}\frac{\sigma}{\mu_l}\frac{1}{(1+10\Phi)}, \tag{10}$$

In Figure 7 all the different types of data are collected in a parity plot, showing the good fit between model and experiment, despite the wide variety in operating conditions and geometries to generate the data. The excellent predictive power of Equation (8) is also supported by Figure 3, where the sparse data of Fadda for operation with gas/condensate and various densities, viscosities and surface tensions are compared with this equation. Only limited data are available in the open literature, further testing is available in the commercial domain, hence not available in public. Where the authors have knowledge of the data, these confirm the correlation.

[Figure 7 about here.]

The following remarks should be made.

- Non-pocket vanes, at (very) high liquid loads, have a lower capacity than predicted by the present model. Obviously the absence of separating pockets constitutes a limiting factor. In this sense the data of Sorokin are not typical.

- In the case where two immiscible liquids are present, glycol and condensate, the separator capacity is determined by the most critical fluid, namely the one most likely to give rise to reentrainment: in this case it is glycol (see the black square in Figure 7); for condensate only (white square in Figure 7) the separator could have been designed at much higher velocity, e.g. with a smaller size of the vane pack for the same inlet flow.

On the capacity of other vane pack geometries

Influence of vane geometry

The objective of adding pockets to the corrugations of the vane pack is, as mentioned, to increase the capacity. From the tests, and also confirmed by manufacturers [2], it is shown that at low gas velocities the capacity of single-pocket vanes is the same as for those without pockets, but that the decrease in efficiency with increasing gas velocity, once the upper capacity is exceeded, is substantially slower for double-pocket vanes.

Influence of vane separator design

Since the capacity reduces at increased liquid loads, as we have shown above, one should keep the flow parameter, Φ, below a certain value. A value of 0.01 is a well-accepted maximum for design. At higher values, either at a constant high load, or in case of occasional liquid slugs, it is better to have a pre-separation step included in the equipment design, so that a large fraction of the liquid is separated before the stream is charged to the vane separator.

Vane separators have the advantage of being a rigid construction, and giving rise to only a low pressure drop. This also means that the separation efficiency may be low if for some reason the incoming droplet size is very small indeed. In such cases one should add a coalescing wire mesh mat upstream of the vane pack. Another possible upstream design modification is the addition of a perforated plate or mixing baffle to improve the distribution of the incoming gas over the cross-section (see [18]).

Influence of flow direction

As mentioned, vane packs can be flowed-though vertically in an upward direction as well. This has been investigated by Verlaan [17] . The upper capacity limit turned out to depend on the fluid properties in the same manner as found for horizontal flowed-through packs. Hardly any influence of liquid rate was detected when the vanes had an internal drainage system, however, in the absence of such a drainage system (like for "Euroform" vanes) the influence was substantial (See [17] fig 3.54b: $v \approx (1 + 50\Phi)^{-1}$) . More data are needed to develop a flooding correlation for such vanes similar to the one for horizontal vane packs presented here.

Conclusion

This study has drawn on knowledge about other, related, unit operations, namely cyclone separators and distillation towers, to improve the description of the efficiency and capacity of vane packs. The influence of elevated pressure, of liquid viscosity and of surface tension is discussed. It is shown why vane separators perform sufficiently well, remarkably even better under conditions where one would initially hesitate to use these devices. An equation with a wide range of application is proposed for the capacity of vane-packs, which are flowed-through in the horizontal direction.

[Table 2 about here.]

Notation

A	constant in Equation (5)	[-]
c_o	solid or liquid loading ratio in cyclones	[-]

D	diameter	[m]
d	particle diameter	[m]
K	factor in Equation (1)	$[\mathrm{m}^{\frac{1}{2}}]$
K_p,K_c,n	constants and exponent in Equation (6)	[-]
k	exponent in Equation (3) and constant in (7)	[-]
Q	volumetric flow rate	$[\mathrm{m}^3\mathrm{s}^{-1}]$
v	velocity	$[\mathrm{m\,s}^{-1}]$
x	gas mass fraction in vane packs	[-]

Greek

Δ	difference	
Γ	liquid loading	$]\mathrm{m}^2\mathrm{s}^{-1}]$
Φ	flow parameter	[-]
μ	viscosity	$[\mathrm{kg\,m}^{-1}\mathrm{s}^{-1}]$
ρ	density	$[\mathrm{kg\,m}^{-3}]$
σ	surface tension	$[\mathrm{N\,m}^{-1}]$

Subscripts

10	10% on the cumulative undersize distribution
c	critical or cut, *cw* cut for wall separation
g	gas
l	liquid
L	limiting
med	median
t	tube or conduit

trans	transition

Dimensionless parameters

Re	Reynolds number
Ar	Archimedes number
Nv	dimensionless gas velocity
We	Weber number

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List of Figures

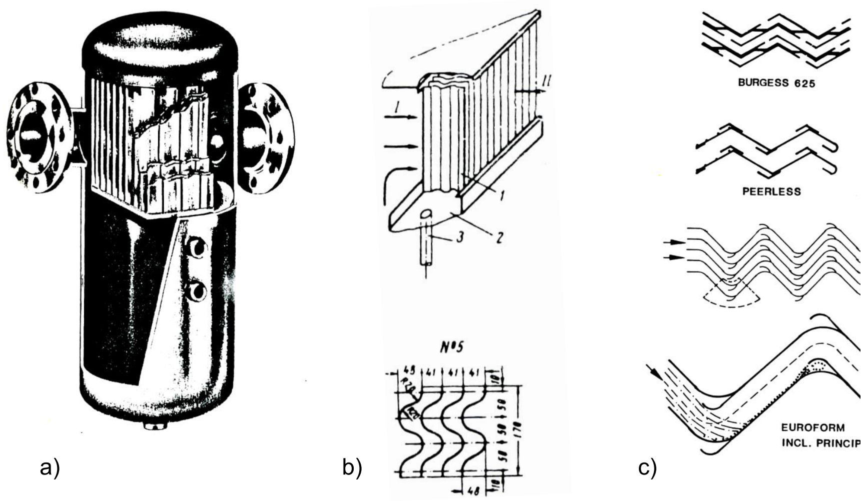

Figure 1: sketches showing the alternative designs of vane packs and the vessel into which they are incorporated (from [9] and [1])

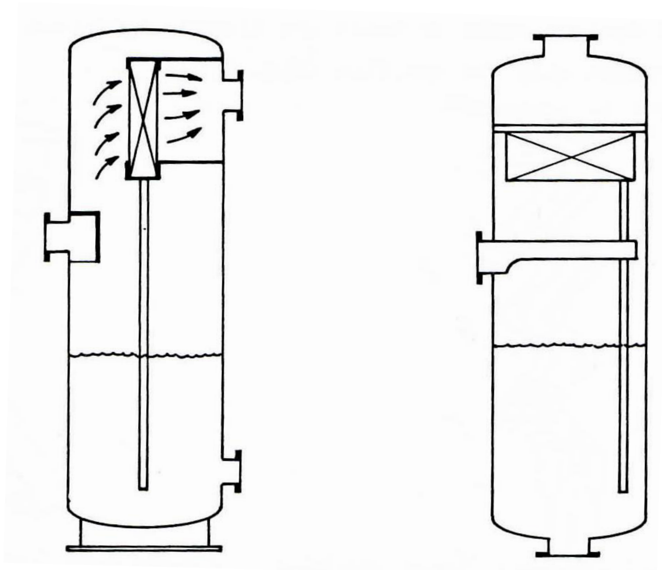

Figure 2: Other vane packs with horizontal and vertical flow (from [19])

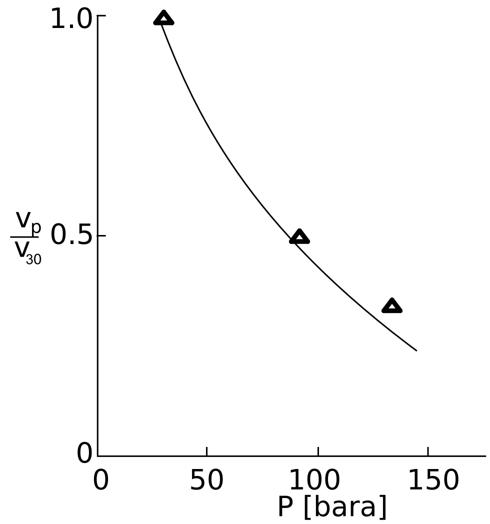

Figure 3: The reduction in flooding velocity as function of pressure, according to [6] (points), including the predictions proposed in this article (curve)

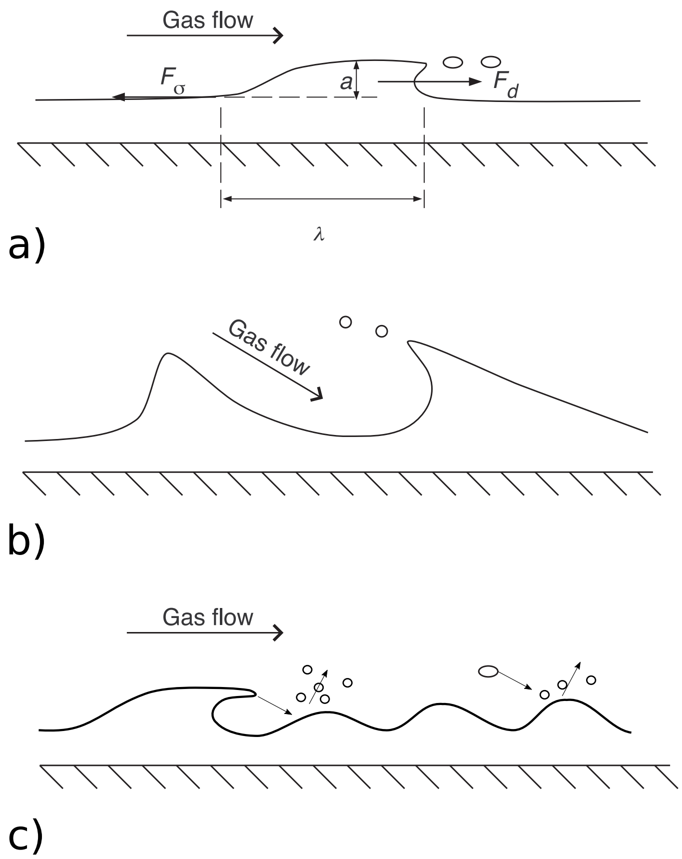

Figure 4: Entrainment mechanisms envisaged by Ishii and Grolmes [13]. a) roll wave shearing b) wave undercut c)liquid impingement.

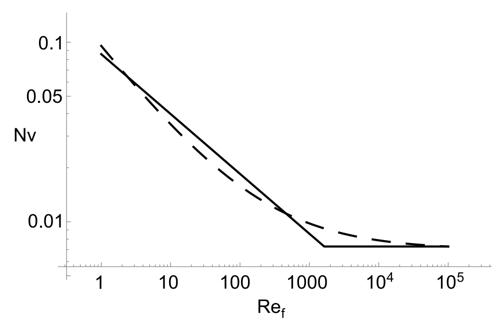

Figure 5: The expressions of Pek [9] (broken) and Ishii and Grolmes [13] for the dimensionless gas velocity at the inception of entrainment as a function of liquid film Reynolds number. Both expressions fit the experimental points equally well.

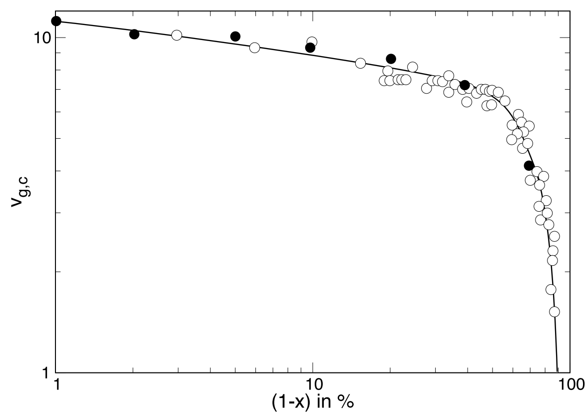

Figure 6: Capacity curve for “non-pocket” vanes (as per ref. [1]). Circles are the experimental points in [1], disks are calculated using Equation (7) the curve is a guide for the eye

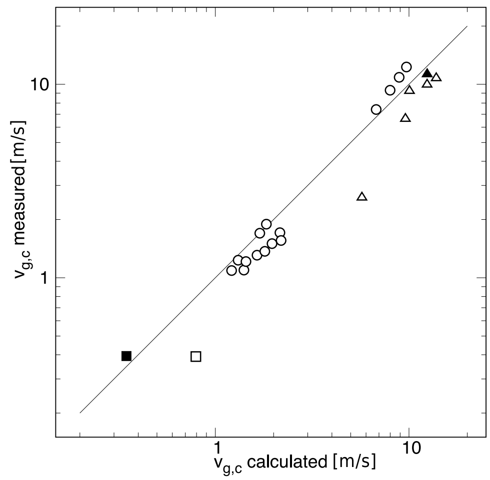

Figure 7: Parity plot between the experimental points given in various papers (squares: Pek [9], circles: Kall [3], open triangles: Sorokin [1]), filled triangle: Koopman [8] and the predictions of the model proposed in this paper, Equation (9).

List of Tables

Table 1: Properties and estimated critical droplet sizes of the systems considered

Reference		[3]	[3]	[3]	[9]	[9]
system		air water	steam water	steam water	gas cond'sate	glycol
Pressure	bar	1	56	70	69	69
Gas density	kg/m^3	1.24	28.7	36.5	75	75
Liquid density	kg/m^3	1000	766	740	1100	685
Surface tension	N/m	0.073	0.021	0.018	0.035	0.011
Gas velocity	m/s	10.5	1.9	1.65	0.41	0.41
Vane cut diam., d_c	μm	15	41	45	75	97
d_{10} in flow	μm	43	216	241	1405	932
d_{10}/d_c	-	3	5	5	19	10
$c_{oL}/c_{oL,\mathrm{a/w,atm.p.}}$	-	1.0	0.5	0.5	0.2	0.3

Table 2: Data on the capacity of vane separators limited to $\Phi < 0.05$ and the calculated capacity velocity according to the model proposed in this article, Equation (7)

Reference	[3]		[1]						[8]	[3]		[3]					[9]	
system	air/water		air/water						air/water	steam/water		steam/water					gas/cond.	gas/glycol-cond.
p [bar]	1		1						1	56		70					69	
ρ_g [kg/m^3]	1.2		1.2						1.2	29		37					75	
ρ_1 [kg/m^3]	1000		990						995	766		740					685	1100
μ_g [Pa s]$\times 10^6$	18		18						18	18		19					12	
μ_l [Pa s]$\times 10^3$	1.2		1.2						1.2	0.12		0.094					0.6	50
σ [N/m]$\times 10^3$	73		63						75	21		18					11	35
v_g [m/s]	12.5	10.9	11.0	10.3	9.7	9.0	8.2	6.7	11.4	1.9	1.7	1.7	1.5	1.4	1.3	1.2	0.4	0.4
v_l [m/s]$\times 10^3$	16	17	0.1	0.3	0.6	1.2	2.5	8	0.08	4.6	7.8	1.9	4.7	6.8	10	14	0.35	0.22
Φ [-]$\times 10^3$	36.3	43.8	0.3	0.8	1.8	3.8	8.8	34.3	0.2	12.4	23.8	5.2	14.1	22.2	35.4	52.4	2.6	2.1
Ar$\times 10^{-3}$	118	118	0.3	110	110	110	110	110	110	144	1904	1904	2436	2436	2436	2436	28	0.23
Nv$\times 10^3$	7.8	6.8	7.3	6.8	6.4	6.0	5.4	4.4	6.3	2.1	1.9	1.9	1.7	1.6	1.5	1.4	7.4	152.9
$v_{g,\text{calc}}$ [m/s]	9.2	8.7	12.1	12.1	12.0	11.7	11.2	9.1	12.9	1.8	1.6	1.6	1.5	1.4	1.3	1.1	0.8	0.3