Design of Wire Mesh Mist Eliminators

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Knitted wire mesh mist eliminators are used extensively in many industrial plants. Their widespread application is essentially due to the low cost and efficient removal of entrained liquid droplets from vapor and gas streams. Despite the broad range of entrainment removal applications, open literature on this topic is limited. All the available design relations are based on semiempirical equations with an uncertain range of application. In this work, a set of new experimental data was obtained by investigating the performances of commercial eliminators, and a mechanistic model is presented. Comparison between experimental data and the proposed model shows that it can be used to predict separation efficiency both for horizontal and vertical arrangements.

Introduction

Separation of liquid droplets from gas or vapor streams is one of the most common operations in chemical plants. Liquid separation may be required not only to recover valuable products or to protect downstream equipment from corrosive liquids, but can also be necessary to improve emissions controls.

Droplet size is a critical parameter in selecting the most appropriate liquid separator. If droplet size is between 500 and 1000 μm, a simple gravity settling drum may be sufficient to obtain high liquid separation efficiency. On the other hand, if the mean droplet size is less than 1 μm, fiber coalescers are necessary.

The goal of this article is to study liquid separation if the droplet size is in the range of 5–100 μm. In this case knitted wire-mesh mist eliminators can be used to achieve highly efficient removal. Knitted-mesh mist eliminators can be classified as "impingement type separators"; their working principle is based on inertial force, and they can guarantee high separation efficiency in the droplet-size range studied in this work.

Wire-mesh contactors are made by knitting wires to form a layer, shown in Figure 1a, that may be rolled spirally to form cylindrical elements, commonly used for small-diameter applications, or folded up in several layers to form a pad of the desired thickness (see Figures 1b–1d). The wire used in the knitted layer typically has a diameter in the 80–280-μm range and the typical thickness used for the pads is in the 65–150-mm range.

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In this work some knitted wire-mesh mist eliminators, set in layers with different geometrical characteristics, were tested in horizontal and vertical arrangements, using air and water as working fluids and operating at ambient conditions.

Available Methods for Designing Wire-Mesh Mist Eliminators

Few articles on this topic have been published in the literature despite the extensive use of these separators. Some articles suggest how to install mist eliminators in some common equipment in order to avoid trouble; the suggestions are mainly aimed at ensuring uniform gas and liquid velocities to avoid overloading a part of the unit, but few articles show how it is possible to evaluate the efficiency of the separator. Proper installation is certainly necessary, but without a doubt, it is more important to have reliable design tools that make it possible to select the proper separator for each case.

The usual design is based on the computation of maximum gas velocity, which according to the Souders–Brown relation, can be expressed as

$$u_{\max} = K \cdot \sqrt{\frac{\rho_l - \rho_g}{\rho_g}}, \tag{1}$$

where the constant K depends on the deentrainment height (York, 1954) and on the physical properties of the working fluids, and ρ_l and ρ_g are, respectively, the density of the liquid and the gas phases. The K values are experimentally de-

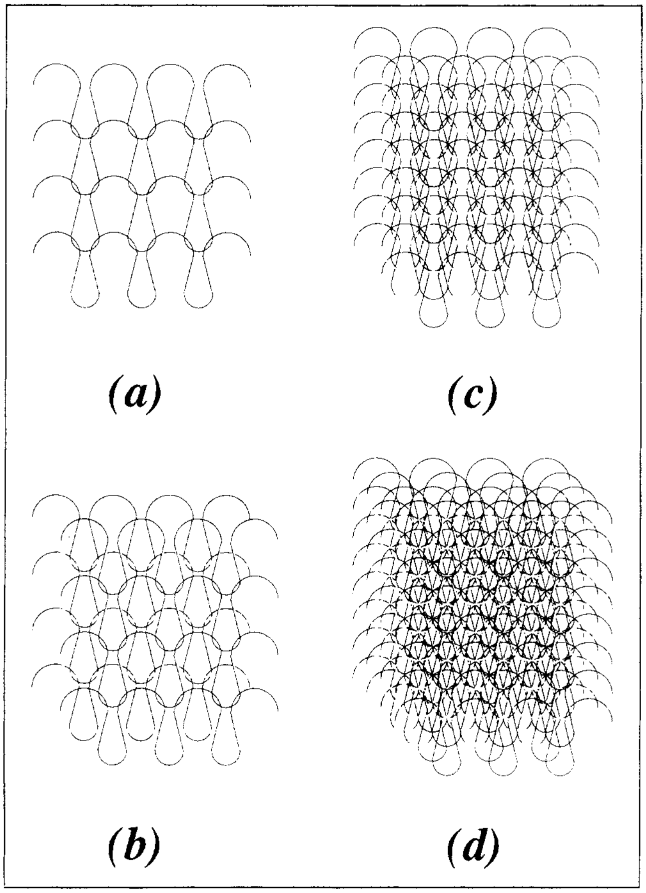

Figure 1. Wire-mesh mist eliminator: (a) single layer; (b) two-layer pad; (c) four-layer pad; (d) eight-layer pad.

termined by vendors; a typical value of 0.107 m/s is commonly used, even if lower values are suggested for high entrainment loadings or when the liquid phase is dirty.

The method of designing wire-mesh separators, based on the constant K, is very rough because it does not take into account the drop size, on which the collection efficiency is strongly dependent. For this reason, some authors have analyzed the separation phenomena in detail, suggesting different semiempirical relations. From the theoretical point of view the collection efficiency, in fact, involves three different separation mechanisms (Gerrard et al., 1986; Holmes and Chen, 1984; Feord et al., 1993):

- *Inertial capture* involves the drops that, leaving the gas stream line because of their inertia, impact the target wire of the mesh and are collected.
- *Interception capture* involves the drops that remain on the gas stream line, but because of their size, brush against the wire of the mesh and are collected.
- *Diffusion capture* involves only submicron-size particles and for this reason is negligible in the study of this type of unit.

Inertial and interception capture mechanisms are involved in the particle-size range in which wire-mesh mist eliminators work. Holmes and Chen (1984) showed that for this type of equipment the primary mechanism responsible for efficiency is inertial impaction. This implies that the total separation efficiency can be evaluated by taking into account only the contribution due to inertial capture. For this mechanism simple relations have been published (Langmuir and Blodgett, 1946; Pich, 1966) to evaluate the inertial capture efficiency for a single wire target, η_{ST}. All these relations agree that the inertial capture efficiency is a function of the Stokes number, St, defined as:

$$St = \frac{\rho_l \cdot u \cdot d_d^2}{18 \cdot \mu_g \cdot D_w}, \tag{2}$$

where u is the superficial gas velocity, μ_g the gas viscosity, and d_d and D_w indicate the droplet and wire diameters, respectively.

The relation suggested by Langmuir and Blodgett (1946) is important from a theoretical point of view because it makes it possible to evaluate the capture efficiency of a single target, but since the aim here is to predict the efficiency of industrial mesh collectors, η_n, it is necessary to introduce dependence on the geometry of the wire mesh packing. All the published equations refer to the analysis proposed by Carpenter and Othmer (1955), who suggested the following semiempirical equation:

$$\eta_n = 1 - \left(1 - \frac{2}{3} \cdot a_e \cdot \eta_{ST} \cdot \frac{z}{\pi}\right)^n, \tag{3}$$

where a_e is the specific surface area of the separator, z the distance between two successive layers, n the number of layers, and η_{ST} the efficiency of a single target.

The Experimental Loop

Experimental collecting efficiencies as a function of droplet size and gas velocity, were determined in atmospheric working conditions in two experimental loops designed and built at the Department of Chemical Engineering of the University of Pisa. For this purpose, industrial and nonindustrial mist eliminators, furnished by Costacurta S.p.A., were tested in both the vertical and horizontal loop. These rigs are mainly made up of a spray-generation circuit and a carrier air circuit. The spray is generated using an ultrasonic nozzle fed by a volumetric pump, giving liquid flow rates ranging from 0 to 2,600 L/h, and by a compressor supplying air at 6 atm at flow rates up to 280 Nm^3/h. This particular nozzle makes it possible to obtain sprays with the required droplet diameter distribution, that is, a great number of drops with a diameter of less than 10 μm and an overall mean diameter of less than 20 μm.

The test section, shown in Figure 2, consists of a 4.5-m-long Plexiglas measuring section with a rectangular cross section, 120 mm wide and 190 mm high. The use of a Malvern Particle Sizer instrument, based on measurements of the diffraction of an He–Ne laser beam by droplets moving through the measuring section, allowed accurate measurements of total concentration and of the volumetric droplet distribution. Particular care was given to the acquisition of the experimental data in order to minimize the disturbances due to the measuring system and to maximize the reproducibility of the acquired data. Each datum represents the mean of six different

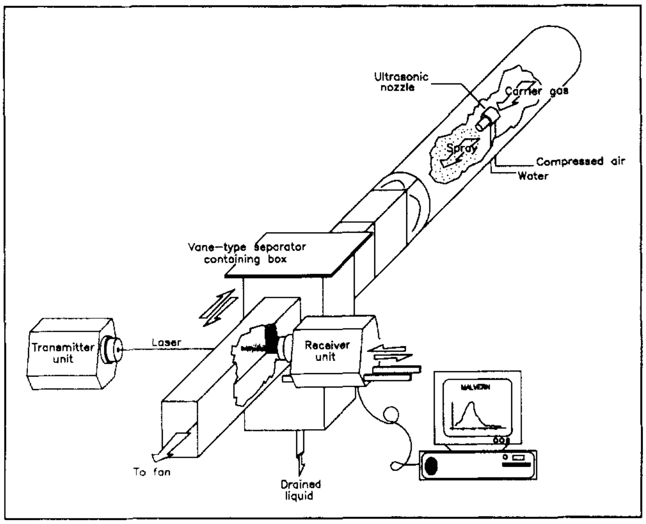

Figure 2. Test section in the horizontal experimental loop.

acquisitions. The accuracy of the measured efficiency is quite high and the maximum uncertainty on the measured efficiency is below 5%. Figure 3 shows typical droplet distributions upstream and downstream from the mist eliminator, and the measured efficiency as a function of droplet diameter.

This article analyzes several different industrial wire-mesh mist eliminators, all metallic. The main geometric characteristics of each packing are shown in Table 1. It must be em-

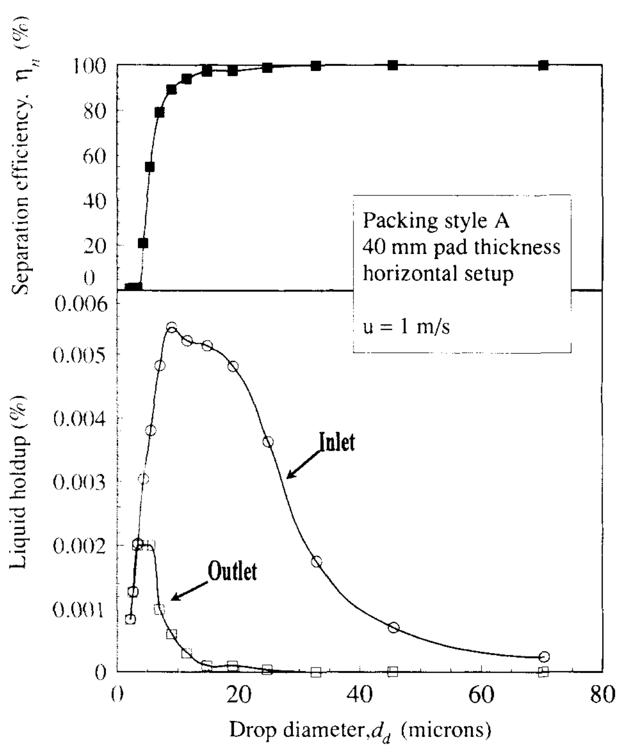

Figure 3. Typical separation efficiency (a) and droplet distributions before and after the mist eliminator (b) vs. drop diameter.

Table 1. Geometric Characteristics of the Tested Packings

Style	A	B	C	D	E
Wire diameter (mm)	0.27	0.27	0.27	0.15	0.15
Packing density (kg/m^3)	145	190	200	128	190
Specific area (m^2/m^3)	267	360	363	459	643
Void fraction	0.98	0.975	0.974	0.984	0.975
Pad thickness (mm) [No. of layers]	150 [28] 65 [12] 40 [8]	150 [42] 100 [28]	65 [22] 40 [13] 20 [7]	150 [45]	65 [46]
Equiv. mesh diameter (mm)	2.35	2.64	3.16	1.23	2.08

phasized that wire diameter, specific surface area, and pad thickness are varied in this work in order to investigate the influence of each parameter.

A Model to Simulate Wire-Mesh Behavior

The model that will be presented is based on the following assumptions: (a) no reentrainment, (b) no buildup of liquid, and (c) no mixing after passage through each layer. The first two hypotheses are common to the model suggested by Carpenter and Othmer (1955), whereas the last represents one of the differences between the present model and the works published to date.

The main assumption that makes the present model different from the previous works is the new schematization of the separator. It goes without saying that using the real geometric characteristics makes it necessary to develop very complex models. Unfortunately, the increased complexity of computation does not correspond to an increase of accuracy in prediction, as can be noted by comparing the present experimental results with the theoretical results obtained by Feord et al. (1993).

For this reason, in the present work a simplified approach is suggested. To evaluate the separation efficiency, a reference cell with a square cross section whose characteristic length will be defined as d_{eq} and a thickness given by a number of layers that will be defined as being equal to $\bar{n}$, has been introduced. By studying the behavior of one of these cells, which are identical across the pad, it is possible to evaluate the removal efficiency of the packing. A representation of a single layer of a wire-mesh pad is shown in Figure 1a.

The characteristic length, d_{eq}, has been evaluated as usually suggested for the equivalent pipe diameter in tubes with a noncircular cross section,

$$d_{eq} = 4 \cdot \frac{\text{cross section}}{\text{wetted perimeter}}. \tag{4}$$

The cross section is given by the product between the packing cross section, A_p, and the packing void fraction, ϵ, while the wetted perimeter, P, can be computed as:

$$P = \frac{l_w \cdot A_p \cdot z}{V_p}, \tag{5}$$

where l_w is the total length of the wires in the packing, z is the distance between two successive layers, and V_p is the volume of the packing.

From the definition of the specific surface, a_e, it follows that

$$a_e = \frac{\pi \cdot D_w \cdot l_w}{V_p}, \tag{6}$$

and therefore

$$\frac{l_w}{V_p} = \frac{a_e}{\pi \cdot D_w}. \tag{7}$$

Finally, the characteristic dimension, d_{eq}, can be evaluated as:

$$d_{eq} = 4 \cdot \frac{A_p \cdot \epsilon}{\frac{l_w}{V_p} \cdot A_p \cdot z} = \frac{4 \cdot \pi \cdot \epsilon}{a_e} \cdot \frac{D_w}{z}. \tag{8}$$

Now it is necessary to define the thickness of the reference cell. A mist eliminator pad is formed by a large number of layers that are staggered with respect to the others and that are set in such a way as to cover the whole cross section of the pad. In this work the separator is schematized as composed of wires set perpendicularly to the gas-flow direction.

With reference to Figure 4, it follows that the number of the layers, $\bar{n}$, necessary to fill each cell can be estimated as:

$$\bar{n} = \frac{d_{eq}}{D_w}. \tag{9}$$

To evaluate the separation efficiency it is necessary to compute the concentration of the particles, C_n, in the gas stream after a generic number of layers, n. Before the first layer the concentration of the carried droplets is uniform across the section and equal to C_0. As underscored previously, in the present model we assume that no mixing occurs across the separator. From this hypothesis it follows that only the particles that arrive in front of a wire can eventually be separated in each layer.

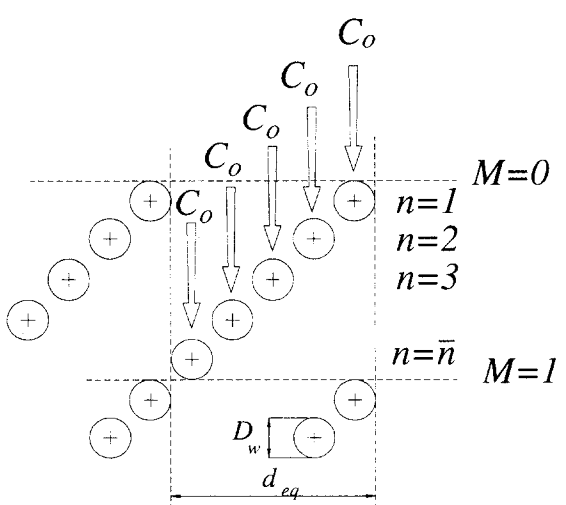

Figure 4. Droplet flow within the packing.

According to the present model, to predict the efficiency of the separator it is sufficient to analyze the behavior of the reference cell. With this assumption, the fraction of the cross section that is covered by wires in each layer can be evaluated as $1/\bar{n}$, and only this part of the cross section participates in the separation process.

The concentration of the particles after the first layer, C_1, can finally be computed as

$$C_1 = C_0 \cdot \frac{(\bar{n}-1)}{\bar{n}} + C_0 \cdot \frac{1}{\bar{n}} \cdot (1 - \eta_{ST}), \tag{10}$$

where the first righthand term represents the particles that are not in front of the wires, and therefore are not separated, and the second righthand term represents the particles that are in front of the wires but are not separated, the latter term being a function of the efficiency of the single target, η_{ST}.

Following the same approach for the second layer, Eq. 10 becomes

$$C_2 = C_0 \cdot \frac{(\bar{n}-2)}{\bar{n}} + C_0 \cdot \frac{2}{\bar{n}}(1 - \eta_{ST}), \tag{11}$$

whereas the concentration of liquid drops, C_n, after a generic number of layers n with n less than or equal to the number of layers $\bar{n}$ necessary to cover the whole cross section (see Eq. 9), is

$$C_n = C_0 \cdot \frac{\bar{n}-n}{\bar{n}} + C_0 \cdot \frac{n}{\bar{n}}(1 - \eta_{ST}) = C_0 \cdot \left(1 - \frac{n}{\bar{n}} \cdot \eta_{ST}\right). \tag{12}$$

When the number of layers is equal to $\bar{n}$, the outlet concentration becomes:

$$C_{\bar{n}} = C_0 \cdot (1 - \eta_{ST}). \tag{13}$$

If the number of layers is greater than $\bar{n}$ and less than $2 \cdot \bar{n}$, the droplet concentration in front of the wires becomes equal to $C_{\bar{n}}$. The generic concentration of droplets after a generic number of layers n with $\bar{n} < n \leq 2 \cdot \bar{n}$ can thus be computed as

$$C_n = C_{\bar{n}} \cdot \left[\frac{\bar{n}-(n-\bar{n})}{\bar{n}} + \frac{(n-\bar{n})}{\bar{n}} \cdot (1-\eta_{ST})\right] = C_0 \cdot (1-\eta_{ST}) \cdot \left[\frac{\bar{n}-(n-\bar{n})}{\bar{n}} + \frac{(n-\bar{n})}{\bar{n}} \cdot (1-\eta_{ST})\right]. \tag{14}$$

If the number of the layers is absolutely generic, it is necessary to evaluate the number, M, of reference cells that are present in the pad. This parameter is a function of the number of layers that form the separator, n, and of the number of layers, $\bar{n}$:

$$M = \text{int}\left[\frac{n}{\bar{n}}\right]. \tag{15}$$

The concentration of the droplets in the gas stream after $M \cdot \bar{n}$ layers can be computed as

$$C_{M\cdot\bar{n}} = C_{M\cdot\bar{n}-\bar{n}}\cdot(1-\eta_{ST}) = C_{M\cdot\bar{n}-2\bar{n}}\cdot(1-\eta_{ST})^2 = C_{M\cdot\bar{n}-3\bar{n}}\cdot(1-\eta_{ST})^3 = \cdots = C_0\cdot(1-\eta_{ST})^M. \quad (16)$$

The concentration after a generic number of layers, n, can be evaluated as

$$C_n = C_{M\cdot\bar{n}}\cdot\left[\frac{\bar{n}-(n-M\cdot\bar{n})}{\bar{n}} + \frac{(n-M\cdot\bar{n})}{\bar{n}}\cdot(1-\eta_{ST})\right] = C_0\cdot(1-\eta_{ST})^M\cdot\left[\frac{\bar{n}-n'}{\bar{n}} + \frac{n'}{\bar{n}}\cdot(1-\eta_{ST})\right], \quad (17)$$

where $n' = n - \bar{n}\cdot M$ represents the number of layers that are not sufficient to form a complete cell.

Finally, the wire-mesh separation efficiency of a bed with a generic number of layers can be evaluated as

$$\eta_n = 1-(1-\eta_{ST})^M\cdot\left[\frac{\bar{n}-n'}{\bar{n}} + \frac{n'}{\bar{n}}\cdot(1-\eta_{ST})\right]. \quad (18)$$

Equation 18 makes it possible to compute the separation efficiency if the efficiency of a single target, η_{ST}, is known. In the literature, many different equations are available to compute the efficiency of a single target and one of the most commonly used has been suggested by Langmuir and Blodgett (1946). As pointed out by Lucas (1983), the theoretical approach by Langmuir and Blodgett (1946) can induce underestimation of the separation efficiency when it is applied to an array of targets that are close to each other. This is the case of wire-mesh mist eliminators, and for this reason in the present article the following empirical relation has been introduced as closure equation: if

$$St \le 1 \quad \text{then} \quad \eta_{ST} = St, \quad (19)$$

whereas if

$$St \ge 1 \quad \text{then} \quad \eta_{ST} = 1, \quad (20)$$

where the Stokes number has been defined according to Eq. 2.

This simplified hypothesis is justified by analysis of Figure 5, where all the experimental data obtained in the horizontal loop have been plotted. It will be noted that, with the partial exception of packing type A, 40 mm thick, all the experimental data obtained at Stokes numbers greater than 1 display separation efficiencies of nearly 100%. These results disagree with the results obtained using the relation by Langmuir and Blodgett (1946), and one reason for this discrepancy may be the complex geometry of wire-mesh mist eliminators, which causes a mutual influence between single targets.

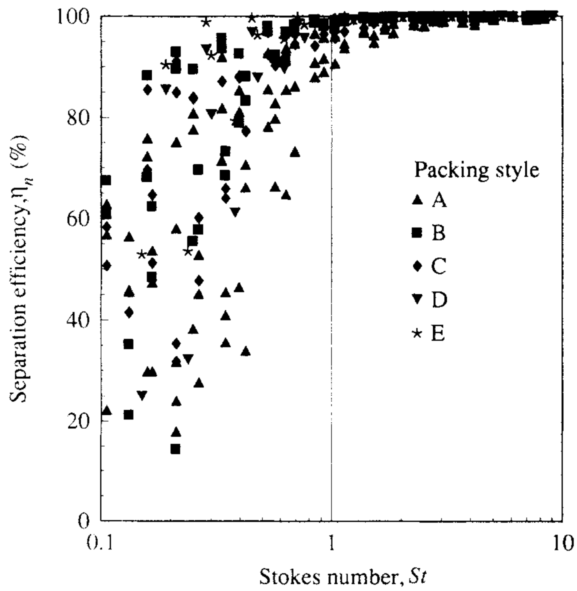

Figure 5. Separation efficiency vs. Stokes number; all the experimental data obtained in horizontal setup.

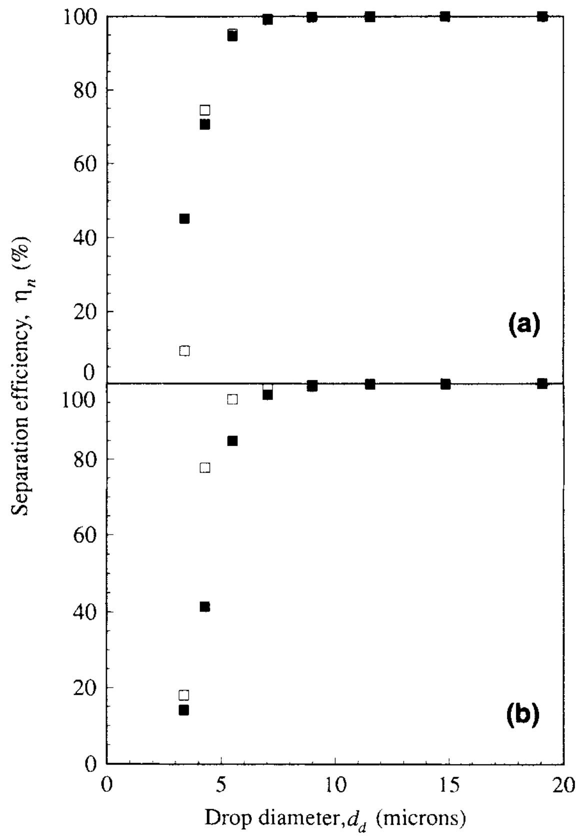

Figure 6. Separation efficiency vs. drop diameter: (a) packing style A, 2 m/s superficial gas velocity, pad 150 mm thick; (b) packing style D, 1 m/s superficial gas velocity, pad 150 mm thick.

■ Vertical setup; □ horizontal setup.

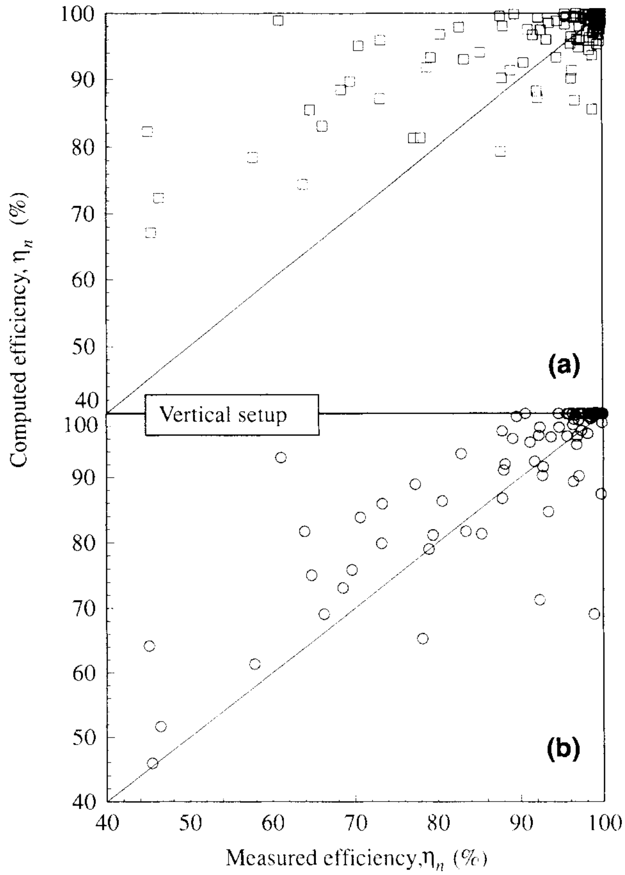

Figure 7. Separation efficiency.

Comparison between experimental measurements with (a) Carpenter and Othmer (1955) model, and (b) present model (vertical setup).

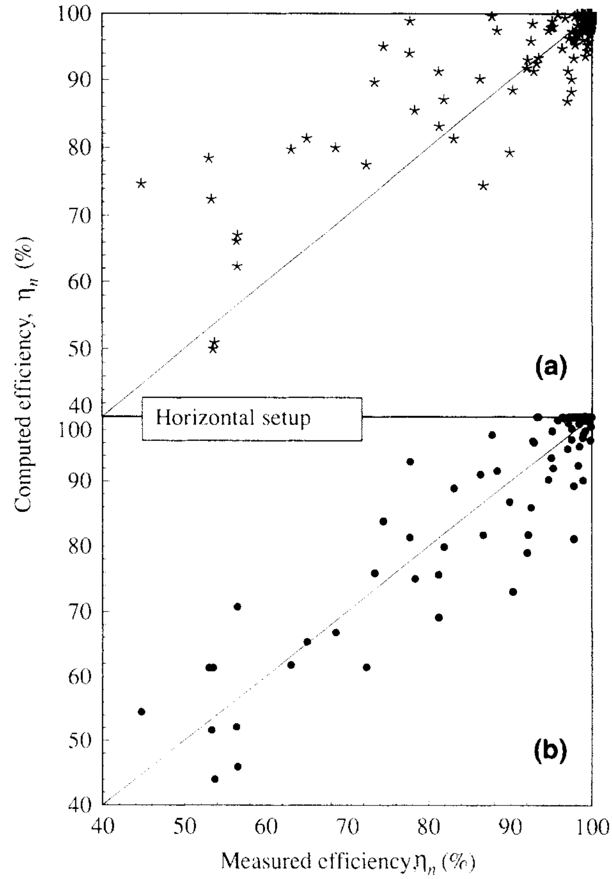

Figure 8. Separation efficiency.

Comparison between experimental measurements with (a) Carpenter and Othmer (1955) model, and (b) present model (horizontal setup).

Analysis of Experimental Results

When a gas/liquid separator has to be decided on, the first problem is to choose between the horizontal and the vertical configuration. From the point of view of separation efficiency, differences arise if the working conditions are close to the flooding point or if there is a high value of the slip velocity between the gas and liquid phases. In horizontal flow the force of gravity does not modify the axial gas velocity, whereas in the vertical configuration it induces a difference between the gas, flowing faster, and the carried liquid droplets. If analysis is restricted to low gas velocity, in a range of working conditions where reentrainment can be neglected, no difference seems to arise in the experimental separation efficiency. This experimental behavior can be explained if the slip velocity between the gas and liquid phases is computed. In the case of an air–water system working at room conditions, droplets with diameters less than 30–35 μm obey Stokes' law. In this case the limiting drop velocity can be easily computed, and it is possible to deduce that the limiting drop velocity, and consequently the slip velocity, remains below the value of 0.04 m/s and therefore can be neglected. This observation allows us to conclude that from the point of view of separation, outside the range where flooding phenomena occur, the horizontal and vertical configurations should yield the same performances. This theoretical result is confirmed by experimental evidence, as shown in Figure 6, where experimental data relative to two different packings are plotted.

It is now possible to compare the experimental data obtained in this work and the computed values obtained using both the present model and the model suggested by Carpenter and Othmer (1955). Figure 7 shows the parity plot relative to the vertical setup. Analysis of the figure shows that the model makes it possible to evaluate separation efficiency with a slightly higher accuracy than with the model suggested by Carpenter and Othmer (1955). The same results were obtained for the horizontal setup (see Figure 8). Also in this case, the model suggested by Carpenter and Othmer (1955) introduces a systematic error, overestimating the experimental separation efficiency.

Higher accuracy, with respect to the results obtained using Carpenter and Othmer's model, is not the most important goal achieved using the present model. In the last few years a new tendency in separation design has emerged, and nowadays packings made up of two mesh pads in series are often preferred to thick packings made from a single type of mesh. The first pad, made of fine wires, works beyond the flood point. Because of high gas velocity, it captures droplets of small size that coalesce in larger drops and some of them are reentrained in the gas phase. These large drops are easily separated in the second pad working below the flood point. Because the first pad works beyond the flood point, at high

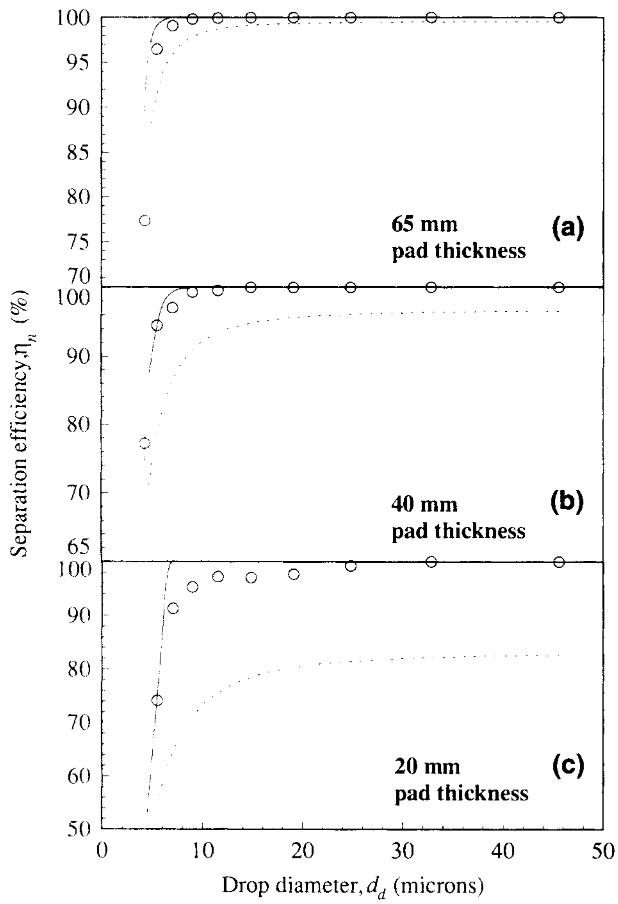

Figure 9. Separation efficiency, effect of packing length.

Packing style C, superficial gas velocity 2 m/s. (a) packing 65 mm thick; (b) packing 40 mm thick; (c) packing 20 mm thick (present model continuous lines, Carpenter and Othmer (1955) model dashed lines).

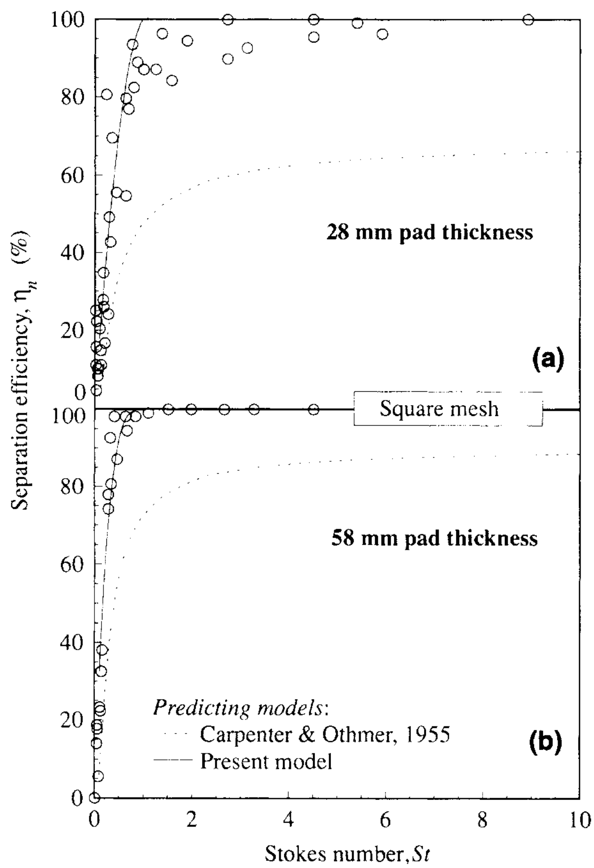

Figure 10. Separation efficiency vs. Stokes number.

Comparison between experimental measurements with Carpenter and Othmer (1955) model (dashed lines) and present model (continuous lines). Experimental data obtained by Bürkholz (1970), square mesh (a) packing 28 mm thick; (b) packing 58 mm thick.

gas velocity, it does not require a large number of layers; thus, for proper design, the separation efficiency must be predicted with high accuracy for thinner packings than those tested so far.

Figure 9 shows a comparison between the experimental data obtained in this article, the present model, and the model proposed by Carpenter and Othmer (1955). The acquisitions refer to three packings with the same geometrical properties, differing only in packing thickness. It will be noted that the two models agree for experimental data for pad thicknesses greater than 65 mm, a dimension commonly tested in papers published so far; if the packing size is smaller, the relation suggested by Carpenter and Othmer (1955) introduces systematic errors that increase with decreasing pad thickness. This result must be emphasized because, as pointed out earlier, the trend is toward packings composed of different pads that will be thinner than the pads used and tested so far.

All the experimental data illustrated earlier were obtained in the present work. Bürkholz (1970) performed a systematic experimental study on wire-mesh mist eliminators. He analyzed the behavior of a commercial mesh pad and the behavior of two other homemade packings with a perfectly square mesh set perpendicular to the direction of gas flow. The experimental results obtained on the second type of packing are extremely important because in this case the equivalent mesh diameter, d_{eq}, can be easily measured and assumes the dimension of the square mesh side. Figure 10 shows the comparison between the present model, the model by Carpenter and Othmer (1955), and the experimental results obtained by Bürkholz (1970) using two pads of square mesh with different thicknesses. It can be seen that the present model predicts experimental results with high accuracy, whereas the model by Carpenter and Othmer (1955) induces systematic errors, especially for the thinner pad. Figure 11 shows experimental data obtained by Bürkholz (1970) using a wire-mesh mist eliminator and the theoretical trends obtained with the present model and with the model by Carpenter and Othmer (1955). Also in this case, in the working range of the separator where the separation efficiency is greater than 50%, higher accuracy is obtained using the present model than with the model by Carpenter and Othmer (1955).

The last parameter that must be analyzed for correct design of wire-mesh separators is dp_{95} (Bürkholz, 1986). By fixing the geometrical characteristics of the unit and the working conditions, dp_{95} represents the smallest droplet diameter that can be separated with an efficiency greater than 95%. Figure 12 shows a comparison between experimental data obtained in this work and by Bürkholz (1970), and computed

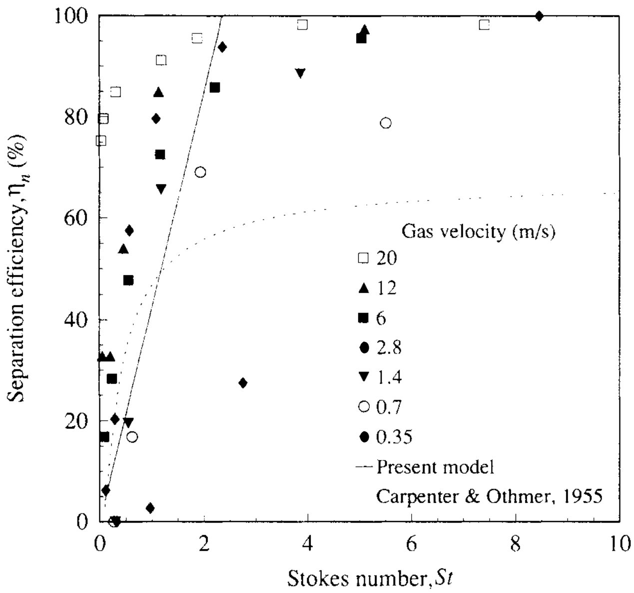

Figure 11. Separation efficiency vs. Stokes number.

Comparison between experimental measurements with Carpenter and Othmer (1955) model (dashed lines) and present model (continuous lines). Experimental data obtained by Bürkholz (1970), mesh pad with a specific surface area of 77 m^2/m^3 and a thickness of 65 mm.

data, according to the present relation and to the relation by Carpenter and Othmer (1955). It must be pointed out that the comparison between experimental data obtained by Bürkholz (1970) and theoretical models has been limited to the present model because, with the model of Carpenter and Othmer (1955), an efficiency of 95% is not achievable. The figure shows that the present relation allows predicting dp_{95} with acceptable accuracy.

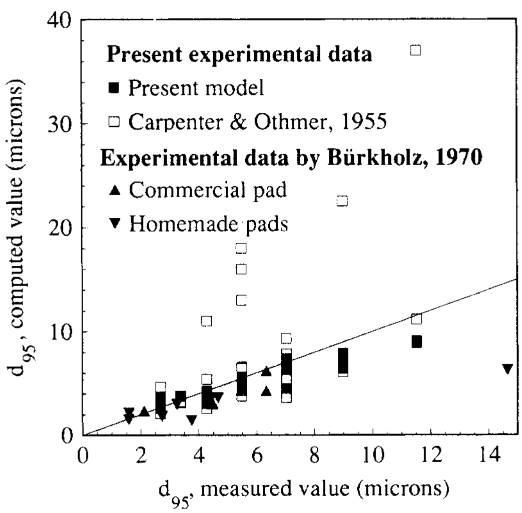

Figure 12. Comparison between experimental measurements of d_{95} obtained in this work and by Bürkholz (1970) with Carpenter and Othmer (1955) model and present model.

■ Comparison between present measurements and present model; □ comparison between present measurements and Carpenter and Othmer (1955) model; ▼ comparison between experimental data by Bürkholz (1970), commercial pads, and present model; ▲ comparison between experimental data by Bürkholz (1970), homemade pads, and present model.

Conclusions

The experimental data on droplet removal efficiency presented in this article were obtained using a laser-based droplet sizer, the Malvern Particle Sizer. This technique makes it possible to obtain nonintrusive measurements and, above all, it allows measuring both the concentration and the size of the droplets. New experimental data on vertical and horizontal setups were obtained showing that, if no reentrainment occurs, the horizontal and vertical configurations display similar removal efficiencies.

This article has presented a new model for predicting removal efficiency. Analysis of the experimental data obtained in this article and of the limited published data shows that the present model and the model published by Carpenter and Othmer (1955) agree for packings with thicknesses greater than 65 mm. For thinner pads the model suggested by Carpenter and Othmer (1955) systematically underestimates the experimental efficiencies, whereas the present model enables good prediction of experimental removal efficiencies. This is an important improvement because separation units will be formed by two mesh pads in series to optimize pressure drop/removal efficiency and the size of these pads is generally smaller than the critical dimension of 65 mm.

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Notation

C_0 = inlet liquid drop concentration
π = 3.14159...

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