Fine Spray Abatement by Conventional and Complex Mesh Type Collectors

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This work presents new experimental data obtained both on conventional and complex mesh type collectors and a simplified design model based on a mechanistic description of the separation phenomena. Experimental collecting efficiencies as a function of droplet size and gas velocity, were determined in an experimental loop designed and built at the Chemical Engineering Department of the University of Pisa. For this purpose several mesh type collectors furnished by Costacurta S.p.A. Vico were tested. A Malvern Particle Sizer instrument, based on measurements of the diffraction of an He-Ne laser beam by droplets moving through the measuring section, was used to accurately measure in a non-intrusive manner the total concentration and volumetric droplet distribution in the two-phase mixture entering and leaving the collector. Analysis of the experimental data obtained in this work and of the limited published data shows that the design model can be used for predicting separation efficiency both of conventional and complex mesh type collectors, without the need of introducing any adjustable parameters. This result is significant because reliable design models are essential for the design and optimisation of complex separation units.

1. Introduction

Knitted mesh type collectors have become a widely accepted tool in many industrial plants as a means for removal of entrained liquid particles from vapour and gas streams. The high removal efficiency, low cost, negligible pressure drop, availability in various material of construction are the reason why they have been used for a broad range of spray abatement uses.

Conventional mesh type collectors are made by knitting wires to form a layer that may be rolled spirally to form cylindrical elements commonly used for small-diameter applications, or folded into several layers to form a pad of the desired thickness. There are several mesh types available, which are identified by mesh thickness, density, wire diameter and wire material. The wire used for the knitted layer typically has a diameter in the 80-280 microns range and the typical thickness used for the pads is in the 65-150 mm range, with 100 mm being the standard pad thickness usually employed for ordinary service. The specific area of commonly used wire mesh pads ranges from 250 to 650 m^2/m^3 with void fractions between 97 and 99%. These separators allow to obtain high removal efficiency in the droplet size range of 10-100 μm. Although several trade name units are available, all knitted mesh pads basically perform on the same principle. The gas or vapour stream carrying the entrained liquid droplets passes through the knitted mesh pad. The gas or vapour stream moves freely, whereas the inertia of the droplets causes them to contact the extensive surface of the wire, where they are retained until they coalesce and eventually drain as large droplets. The most common application of wire mesh eliminators is horizontally for vertical upward gas flow, although they can also be used in horizontal flow applications. The working principle is based on inertial force and, at a fixed superficial gas velocity, separation efficiency can be increased only by changing geometrical properties of the separator like pad thickness, density and/or wire diameter. It is necessary to point out that for this type of separator the dp_{100}, that is the minimum droplet size that can be separated with an efficiency of 100%, is not a function of the pad thickness. When the mean diameter of the droplets is below the critical value of 10 μm, the conventional mesh collectors do not allow a high removal efficiency. Therefore, to further extend the range of performance of this type of collectors into new areas of more difficult fine spray removal, complex mesh collectors have been developed. These separators consists of knitted mesh pads that incorporate a multifilament yarn into the basic wire-mesh structure. The metal wire typically has a diameter in the 80-280 microns range, whereas the fibre diameter is in the range of 10 to 50 microns. These characteristics make this type of separator denser and more compact than the conventional mesh collector, allowing a greater liquid retention and therefore higher removal efficiency at lower droplets diameter. On the other hand, the throughput capacity of complex mesh pads is limited when compared to that possible with conventional mesh pads. Common materials of the multifilament yarns are Polypropylene, Dacron, Teflon, and glass fiber. The typical thickness used for the pads is 50 to 100 mm. A typical metal wire mesh pad and a complex mesh pad are shown in Figure 1.

Fig. 1 Picture of conventional (left) and complex mesh pad (right).

Despite their extensive use, open literature regarding the performance characteristics of mesh type collectors is still scarce. This work presents new experimental data obtained both on conventional and complex mesh type collectors and a simplified design model based on a mechanistic description of the separation phenomena.

Experimental collecting efficiencies as a function of droplet size and gas velocity, were determined in an experimental loop designed and built at the Chemical Engineering Department of the University of Pisa. A Malvern Particle Sizer instrument, based on measurements of the diffraction of an He-Ne laser beam by droplets moving through the measuring section, was used to accurately measure in a non-intrusive manner the total concentration and volumetric droplet distribution in the two-phase mixture entering and leaving the collector. Details of the experimental loop can be found in [1,2]. Table 1 shows the main geometric characteristics of the industrial packing tested in the present work (manufactured by Costacurta S.p.A VICO). It must be pointed out that fibre diameter, fibre material and specific surface area were varied in this work in order to investigate the influence of each parameter. The tested pads were 50 mm thick.

Style	Metal wire diameter (mm)	Fibre diameter (μm)	Void fraction (-)	Metal weight (kg/m^3)	Fibre weight (kg/m^3)	Fibre Material
A	0.27	-	0.982	143.5	-	-
D	0.27	28	0.970	143.5	10.6	Polypropylene
E	0.27	28	0.958	143.5	21.8	Polypropylene
F	0.27	21	0.976	143.5	13.9	Teflon
G	0.27	22	0.971	143.5	15.3	Dacron
H	0.27	9	0.974	143.5	21.5	Glass fibre
I	0.27	9	0.965	143.5	44.2	Glass fibre
L	0.27	28	0.961	190	14	Polypropylene
M	0.27	28	0.944	190	28.8	Polypropylene
N	0.27	21	0.968	190	18.4	Teflon
O	0.27	22	0.961	190	20.2	Dacron
P	0.27	9	0.965	190	28.4	Glass fibre
Q	0.27	9	0.954	190	58.3	Glass fibre

Table 1. Geometric characteristics of conventional and complex mesh type collectors

2. Separation mechanisms and design methods

Some articles have been published on the use of conventional mesh type collectors. All of these articles essentially suggest how to install spray collectors properly. Attention has been focused on identifying the maximum gas and liquid velocities to avoid flooding in working conditions and to evaluate separation efficiency.

Conventional industry "rules of thumb" are based on the computation of an appropriate superficial gas velocity, u_{max}, from which the cross section area of the pad is determined. This velocity is computed from a modified Souder-Brown equation:

$$u_{max} = K \cdot \sqrt{\frac{\rho_l - \rho_g}{\rho_g}} \quad (1)$$

where ρ_l and ρ_g are respectively the density of the liquid and the gas phases. The constant K depends on several system factors including liquid viscosity, surface tension, entrainment loading, content of dissolved and suspended solids, the operating pressure, mesh structure and de-entrainment height. For most solutions, mesh pads can operate effectively between 30% and 110% of their permitted design velocity given by Eq. 1. However this method of designing mesh type collectors is very rough, because it does not consider either the drop size, on which collection efficiency is strongly dependent, or the liquid load that can induce flooding of the pad.

For this reason, some authors have analysed the separation phenomena in detail. From a theoretical point of view, the collection efficiency involves three different separation mechanisms [3,4] which are shown in Figure 2 (this illustrates gas flowing past a single cylinder placed normal to the flow):

a) *Inertial impaction* involves drops that impact the target wire of the mesh and are collected on leaving the gas streamline due to their inertia,
b) *Interception capture* involves drops that remain in the gas streamline, but due to their size, brush against the wire mesh and are collected. This mechanism occurs in general with droplets approximately the target dimension or larger,
c) *Diffusion capture* involves only sub micron-size particles and is significant only at a very low gas flux.

Holmes and Chen [4] pointed out that inertial capture is the predominant mechanism of droplet capture for a wire mesh separator. This implies that the fractional separation

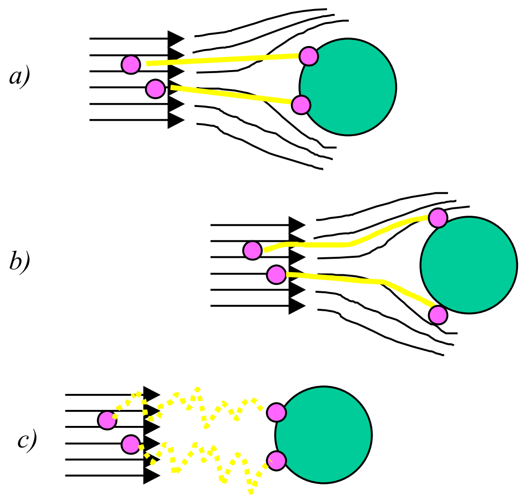

Fig. 2. Mechanisms of droplet collection

efficiency of the eliminator can be evaluated by taking into account only the contribution due to inertial capture and neglecting interception and diffusion capture. Some relations have been published to evaluate the inertial capture efficiency for a single wire target, η_{ST} [5,6]. All these relations agree that the inertial capture efficiency is a function of the Stokes' number, St, defined as

$$St = \frac{\rho_l \cdot u \cdot d_d^2}{18 \cdot \mu_g \cdot d_T} \qquad (2)$$

where u is the superficial gas velocity, μ_g the gas viscosity and d_d and d_T indicate the droplet and target diameters respectively. The results obtained on single targets point out that inertial capture efficiency increases with the Stokes' number, and therefore with the increase of gas velocity and droplet size, and the decrease of the target diameter. The extension of the analysis from capture on a single target to capture in a knitted mesh has been considered by some authors [2,7]. Carpenter and Othmer [7] suggested the following semiempirical equation to compute the collection efficiency of conventional mesh type collectors:

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

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

3. Simplified design model

The model that will be presented is based on the following hypothesis: (a) no reentrainment, (b) no buildup of liquid, and (c) no mixing after passage through each layer. The first two hypotheses are also common to the model suggested by [7].

The main assumption that makes the present model different from other works is the new schematisation of the mesh pad. 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. [3]. For this reason, a simplified approach is herein 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 $\bar{n}$, has been introduced. By studying the behaviour of one of these reference cells, which are identical across the pad, it is possible to evaluate the removal efficiency of the collector.

The vendors usually give the weight of metal wires for unit volume of pad, w_m, and the weight of the fibres for unit volume, w_f, therefore the free volume and the surface area have to be evaluated. The length of metal wire, l_m, and of fibre, l_f, for unit volume of the pad can be computed from geometrical analysis as:

$$l_m = \frac{4 \cdot w_m}{\pi \cdot d_m^2 \cdot \rho_m} \quad \text{and} \quad l_f = \frac{4 \cdot w_f}{\pi \cdot d_f^2 \cdot N_f \cdot \rho_f}, \qquad (4)$$

where N_f is the number of single fibres that make the non-metallic monofilament, d_m and d_f are the metal wire diameter and the fibre diameter, respectively, and ρ_m and ρ_f are the metal and fibre densities.

The free volume of the complex pad, ε_c, can be evaluated as:

$$\varepsilon_c = 1 - \left(\frac{\pi}{4} \cdot d_m^2 \cdot l_m + \frac{\pi}{4} \cdot d_f^2 \cdot N_f \cdot l_f \right) = 1 - (1 - \varepsilon_m) \cdot \left[1 + N_f \cdot \left(\frac{d_f}{d_m} \right)^2 \cdot \frac{l_f}{l_m} \right], \qquad (5)$$

where ε_m is the free volume of the metal pad supporting non-metallic fibres.

Analogously it is possible to evaluate the specific surface area of complex pad as:

$$a_e = \pi \cdot d_m \cdot l_m + N_f \cdot \pi \cdot d_f \cdot l_f = a_m \cdot \left(1 + N_f \cdot \frac{d_f}{d_m} \cdot \frac{l_f}{l_m} \right), \qquad (6)$$

where a_m is the specific surface area of the metal pad supporting the non metallic fibres.

Now it is necessary to evaluate the diameter of an equivalent wire, d_e, that shows the same specific surface area and fractional volume occupied by solid material of the complex pad. The equivalence of the specific surface area gives:

$$a_e = \pi \cdot d_e \cdot l_e, \qquad (7)$$

and the equivalence of the volume gives:

$$\frac{\pi}{4} \cdot d_e^2 \cdot l_e = \frac{\pi}{4} \cdot d_m^2 \cdot l_m + \frac{\pi}{4} \cdot d_f^2 \cdot N_f \cdot l_f. \qquad (8)$$

Therefore, the equivalent wire diameter is given by:

$$d_e = \frac{d_f^2 \cdot l_f \cdot N_f + d_m^2 \cdot l_m}{d_f \cdot l_f \cdot N_f + d_m \cdot l_m}, \qquad (9)$$

The last parameter that has to be evaluated is the characteristic length, d_{eq}, of the reference cell. This length is defined as usually suggested for the equivalent pipe diameter in tubes with non circular cross section (i.e. d_{eq} = 4·cross section/wetted perimeter). For conventional mesh pad the wetted perimeter is a function of l_m, of the packing cross section, A, and of the distance between two successive layers, z and can be evaluated as:

$$P_m = l_m \cdot A \cdot z. \qquad (10)$$

For complex mesh the wetted perimeter has to be computed taking into account for the presence of non-metallic fibres and therefore it can be evaluated as:

$$P_c = P_m \cdot \left(1 + N_f \cdot \frac{d_f}{d_m} \cdot \frac{l_f}{l_m} \right) \qquad (11)$$

Finally the characteristic length of a complex mesh can be computed as:

$$d_{eq} = \frac{4 \cdot A \cdot \varepsilon_c}{P_m \cdot \left(1 + N_f \cdot \frac{d_f}{d_m} \cdot \frac{l_f}{l_m} \right)} = \frac{4 \cdot \pi \cdot \varepsilon_c \cdot d_m}{a_m \cdot z \cdot \left(1 + N_f \cdot \frac{d_f}{d_m} \cdot \frac{l_f}{l_m} \right)} \qquad (12)$$

Now it is necessary to define the thickness of the reference cell. A mesh 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 collector is schematised as composed of wires set perpendicularly to the gas flow direction. It follows that the number of layers, $\bar{n}$, necessary to fill each cell can be estimated as:

$$\bar{n} = \frac{d_{eq}}{d_e} \qquad (13)$$

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. According to the present model, to predict the efficiency of the separator it is sufficient to analyse the behaviour 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

$$C_1 = C_0 \frac{(\bar{n}-1)}{\bar{n}} + C_0 \frac{1}{\bar{n}}(1-\eta_{ST}) \tag{14}$$

where the first right hand term represent particles that are not in front of the wires, and therefore are not separated, and the second right hand term represents 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, the concentration of liquid droplets, C_n, after a generic number of layers n, with n less or equal to the number of layers $\bar{n}$ necessary to cover the whole cross section, is

$$C_n = C_0(1-\eta_{ST}) \tag{15}$$

For a generic number of the layers, 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 $\bar{n}$:

$$M = \text{int}\left[\frac{n}{\bar{n}}\right] \tag{16}$$

It easily follows that the concentration of droplets in the gas stream after M layers can be computed as

$$C_{M\cdot\bar{n}} = C_0(1-\eta_{ST})^M \tag{17}$$

and eventually that the separation efficiency of a mesh pad with a generic number of layers ca be evaluated as

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

Equation 18 makes it possible to compute the separation efficiency if the efficiency of a single target, η_{ST}, is known. The theoretical analysis by [5], that allows the evaluation of separation efficiency of single target, can induce underestimation of the separation efficiency when it is applied to an array of targets that are close to each other. To take into account the mutual influence between single targets the following empirical relation is introduced as closure equation:

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

whereas if

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

where the Stokes number is defined as by eq.2, in which for the conventional mesh type d_T is equal to the wire diameter, d_m, whereas for the complex mesh type the target diameter of the composite wire has been assumed equal to the equivalent wire diameter, d_e (see eq.9).

This simplifying hypothesis is justified by analysis of Figure 3, where all the experimental data obtained with complex separators have been plotted. It can be noted that even if the specific surface area changes in the range of 1946-10320 m^2/m^3 the experimental data obtained at Stokes numbers greater than 1 display separation efficiencies of nearly 100%.

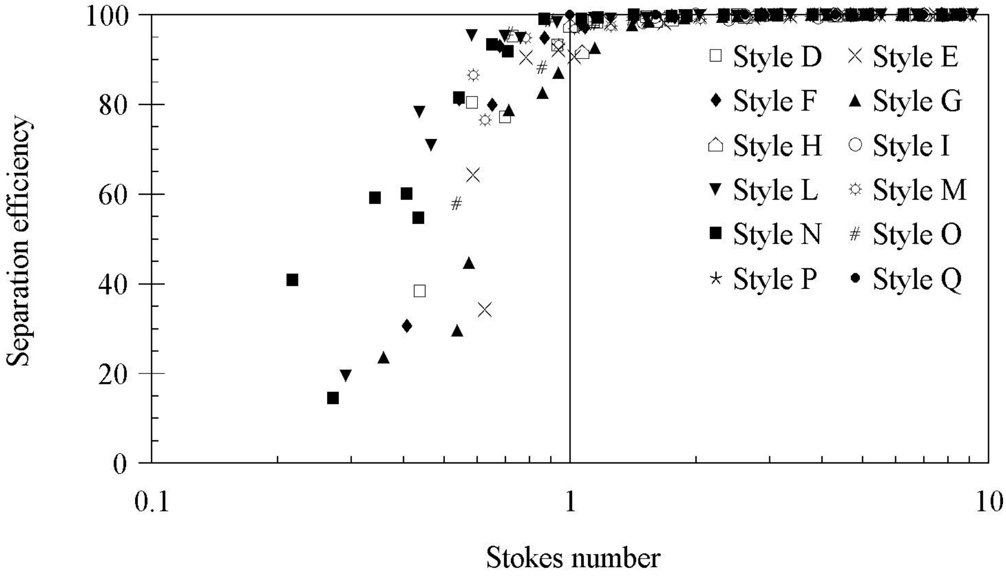

Fig. 3. Experimental separation efficiency vs. Stokes number for some complex mesh type collectors.

4. Analysis of experimental results

Figure 4 shows a comparison between experimental separation efficiency of two different collectors that have the same basic metallic wire mesh structure (e.g. complex mesh pad style F, 50 mm thick, and conventional mesh pad, style A, 65 mm thick), obtained for a superficial gas velocity of 1 m/s. The continuous lines show the separation efficiency computed according to the present model. The first immediate result is the higher separation efficiency of complex mesh type compared to that of the conventional one. This means smaller dp_{100} achievable while maintaining fixed both geometrical characteristics of the unit and working conditions. This kind of performances allows a new set of applications, following the actual market trend.

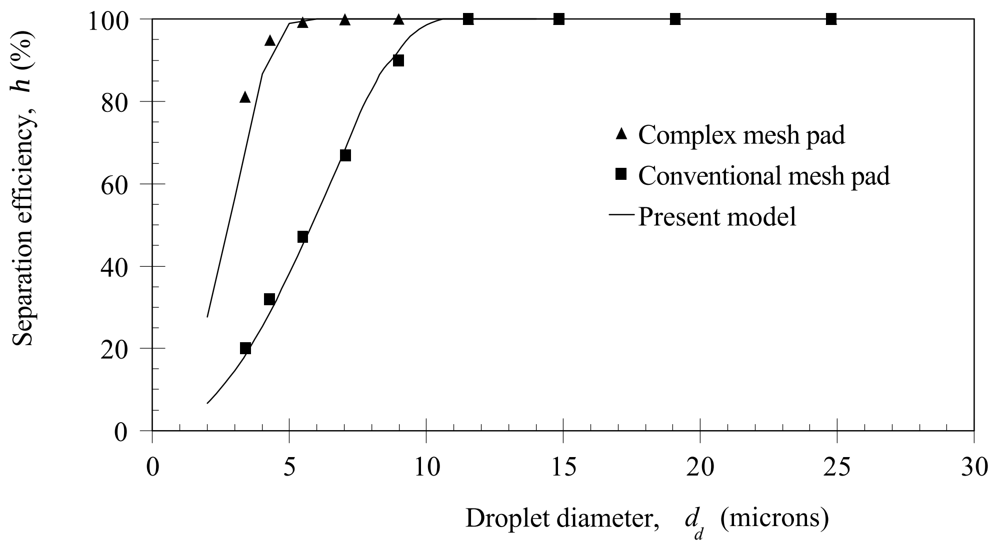

Fig. 4 Experimental separation efficiency of conventional and complex mesh type collectors (Superficial gas velocity 1 m/s). The continuous lines show the separation efficiency computed according to the present model.

Moreover, Figure 4 shows that by using the presented mechanistic model it is possible to evaluate the separation efficiency of both the conventional and the complex mesh types.
Figure 5 shows a comparison between computed and measured efficiency of a complex mesh pad, style N, working at different gas loads. Also in this case, the model presented in this paper predicts the experimental performances of the collector with a sufficient degree of accuracy.

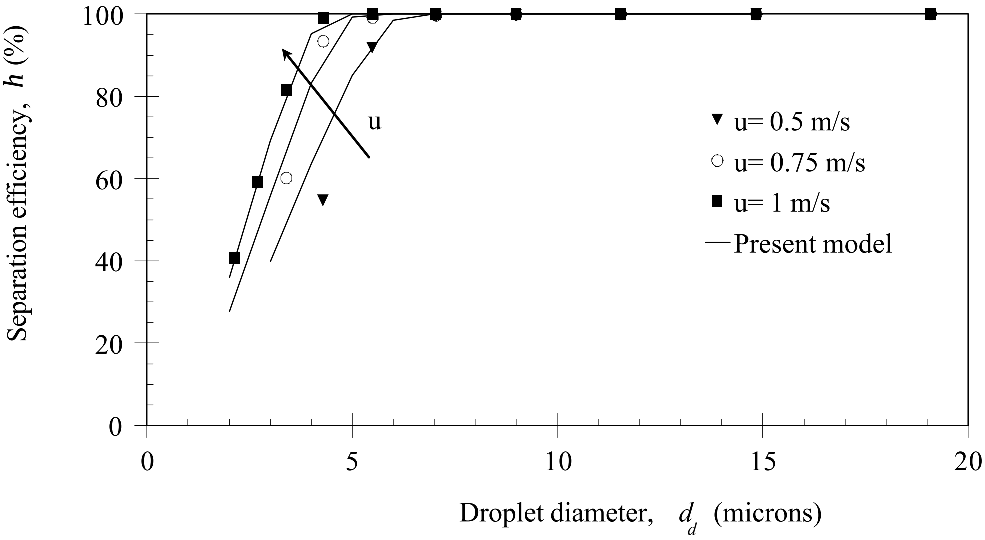

Fig. 5 Separation efficiency vs. drop diameter, effect of superficial gas velocity. Comparison between experimental measurements and the presented model (pad style N).

5. Conclusions

In recent years, increasing research effort has been dedicated to the experimental investigation of both conventional and complex mesh pads and to the development of design models. The purpose of this is to move the design of mesh type collectors away from the conventional industry "rule of thumb". The experimental data on droplet removal efficiency presented in this paper were obtained using a laser-based droplet sizer, the Malvern Particle Sizer. This paper has presented a mechanistic model for predicting removal efficiency of conventional and complex mesh type collectors. Analysis of the experimental data shows that the proposed model allows the measured efficiency to be predicted with sufficient accuracy notwithstanding that no adjustable parameter has been used. This result is significant because reliable mechanistic models are essential for the design and the optimisation of complex separation units.

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