

Theory and Practice of a New Class of Equipment for Separation of Particulates from Gases: the Turbulent Flow Precipitator

F.A.L. Dullien¹

¹ Department of Chemical Engineering, University of Waterloo, Waterloo, Ontario - Canada N2L 3G1

Résumé — Le précipitateur turbulent : un nouveau type de dispositif de séparation de particules présentes dans un courant de gaz. Théorie et technologie — Les principaux séparateurs de particules dans un courant de gaz existants sur le marché sont les séparateurs par inertie, les filtres, les laveurs et les électrofiltres. Chaque type de séparateur est destiné à une utilisation spécifique et possède des avantages et des inconvénients.

Cet article décrit une nouvelle catégorie de dispositifs appliqués à la purification des gaz, les précipitateurs turbulents (PT) qui, malgré leur nouveauté, ont gagné rapidement en popularité parce qu'ils présentent des avantages par rapport à chacun des autres types de séparateurs ; ils ont aussi très peu de limitations. Les précipitateurs turbulents sont beaucoup plus efficaces que les séparateurs par inertie pour la séparation des particules très fines, ne se colmatent pas comme les filtres, ne posent pas de problème de traitement secondaire, exigent moins d'entretien et sont moins coûteux que les électrofiltres. Ils peuvent atteindre une efficacité élevée même en présence de particules submicroniques, et ils ne sont pas soumis à des contraintes liées aux hautes températures et/ou aux environnements corrosifs. Ils peuvent séparer aussi bien des particules solides que liquides contenues dans un courant de gaz.

Le mécanisme de précipitation turbulente consiste à faire pénétrer les tourbillons d'un courant turbulent d'un gaz dans des cavités profondes, caractérisées par l'absence d'un courant net, où la turbulence se dissipe et où les particules fines emportées par ces tourbillons sont captées sur des surfaces collectrices.

Tous les précipitateurs turbulents incluent deux zones bien définies :

- des conduits droits, uniformes et non obstrués dans lesquels s'écoule le gaz turbulent, portant les particules fines en suspension ;
- des zones adjointes collectrices dans lesquelles il n'y a pas d'écoulement net et où s'effectue la séparation des particules présentes dans le gaz.

Ainsi, les précipitateurs turbulents sont des séparateurs dans lesquels les particules sont séparées en dehors du flux gazeux.

Mots-clés : séparateur de particules, précipitation turbulente, purification de gaz, environnement.

Abstract — Theory and Practice of a New Class of Equipment for Separation of Particulates from Gases: the Turbulent Flow Precipitator — The main classes of separators of particulates from gases comprise inertial separators, filters, (wet) scrubbers and electrostatic precipitators, each of which technique has its proper niche and each has its advantages and its disadvantages.

In the present paper a new class of equipment, the turbulent flow precipitator (TFP) for gas cleaning is described that, though at the present only in its infancy, is rapidly gaining popularity because it has some advantages over each and every known type of separator and it has very few limitations. TFPs are far more efficient for the removal of fine particles than inertial separators, unlike filters they do not plug up, they do not present secondary disposal problems and they require less maintenance (and are less expensive) than electrostatic precipitators. They can be very efficient also in the submicron range of particle size and there are no practical limitations as far as high temperatures and/or corrosive atmospheres are concerned. They are equally suitable for the removal of solid and liquid particles from gases.

Turbulent flow precipitators work on the principle of turbulent eddy penetration into deep regions where there is no net flow, where the eddies die out and where the fine particulates carried by the eddies deposit on collector surfaces.

TFPs comprise two well defined regions:

- *straight, uniform and unobstructed flow passages in which the gas carrying the suspended fine particulates is passed in turbulent flow;*
- *and adjacent collection regions where there is no net gas flow and where all of the separation of particles from the gas takes place.*

Hence, a TFP is a filter in which the separation of the particulates from the gas takes place outside the passages where the gas flows.

Keywords: gas cleaning, particules separator, turbulent precipitation, pollution.

LIST OF SYMBOLS

A	surface area of boundary between flow passage and adjacent collection region of TFP
C	Cunningham correction factor
d	particle diameter
D	flow passage diameter of TFP
D_f	fibre (or strand) diameter
E	particulate removal efficiency of TFP
ℓ	depth of penetration of eddies into collection region of TFP
L	length of flow passage of TFP
L_f	depth of filter equivalent of TFP
n	number of times the gas is exchanged between flow passage and adjacent collection region during its passage through TFP
\bar{N}	particulate loading of gas
q	volume flow rate of gas, caused by velocity fluctuations, from a flow passage into adjacent collection region of TFP
Q	volume flow rate of gas through TFP
R	d/D_f
S	height of flow passage of TFP
t_r	residence time of gas in a flow passage
v	mean gas velocity in a flow passage of TFP
v'	turbulent velocity fluctuation
v_∞	approach velocity
V	volume of gas flowing through a flow passage of TFP in the time t_r
V_f	volume of gas passing from a flow passage of TFP into the adjacent collection region in the time t_r
w	effective migration velocity
W	width of a flow passage of TFP.

GREEK LETTERS

β	solids fraction of a filter or a foam
ϵ	weight fraction of particulates carried by the eddies which is deposited on the surface of the strands of the foam in one exchange step of gas between a flow passage and the adjacent collection region of TFP
η	particle collection efficiency of a single fibre (or strand) imbedded in the filter (or the foam)
η_I	particle collection efficiency of a single fibre (or strand) by inertial impaction
$\eta_{I\beta}$	particle collection efficiency of a single fibre (or strand) imbedded in the filter (or the foam) by inertial impaction
η_c	particle collection efficiency of a single fibre (or strand) by interception
$\eta_{c\beta}$	particle collection efficiency of a single fibre (or strand) imbedded in the filter (or the foam) by interception
μ	gas viscosity
ρ_p	particle mass density
ψ	inertia parameter.

INTRODUCTION

The most widely used dry systems for particle separation from air and gases employ filters or electrostatic precipitators for fine dust, fumes, and smoke, mechanical collectors, such as impingers and cyclones, for particles greater than about 5 μm . The author does not know of the existence of any mechanical collector, either in the technical or patent literature, or in practice, that would collect particles of submicron or even micron size with a viable efficiency. This

paper describes the theory and practice of a new type of mechanical collectors called turbulent flow precipitators (TFP), designed on the basis of a new mechanical separation principle [1, 2] and presents collection efficiencies of dust particles as small as $0.5 \mu\text{m}$, obtained with these collectors.

The idea for the separation principle was inspired by the paper of Friedlander and Johnstone [3], who showed that from a gas in turbulent flow dust particles of about 1 micron size deposited at a high rate on the wall of a duct coated with a sticky substance. These authors explained that dust particles were carried by turbulent velocity fluctuations, or eddies, into the viscous sublayer adjacent to the duct wall and then they continued their path until they collided with the wall and were held there by the sticky coating. This mechanism of dust deposition, termed "turbulent deposition", has been the subject of a number of research papers since the original discovery of Friedlander and Johnstone, but no practical suggestion for utilizing the penetration of eddies into a viscous sublayer for the efficient separation of fine particles from gases has been made until the presentation of Dullien and Collins [1].

1 PRINCIPLE OF OPERATION OF TURBULENT FLOW PRECIPITATORS

A turbulent flow precipitator is a highly efficient device for the separation of fine particulates from a turbulent gas stream. It is based on the principle of dividing the gas into two regions, positioned parallel to each other, i.e. a region consisting of one or several parallel, identical, straight, unobstructed flow passages, containing gas in turbulent flow and a second region of a depth which is comparable to the width of a flow passage, where there is not net gas flow in the direction parallel to the axis of a flow channel. The second region is the collection region where separation of the particulates from the gas takes place. It may consist e.g. of spaces between a plurality of closely spaced parallel plates which are oriented perpendicular to the axis of the flow passage (Fig. 1). The boundary between the flow passage and the collection region is formed by the edges of the plates and the spaces between these edges. There is free interchange of gas between the flow passage and the nonflow spaces of the collection region between the plates. Small spacings between next neighbour plates, coupled with a great plate height prevent any net gas flow in the spaces between plates in the direction defined by the axis of the flow channel.

However, turbulent eddies can and do penetrate into the spaces between plates to a considerable depth measured from the boundary between the flow passage and the collection region. Some of the particulates, suspended in the gas, are carried by the eddies near the plate surfaces where they may deposit by any or all of the known mechanisms of particle collection and become separated from the gas.

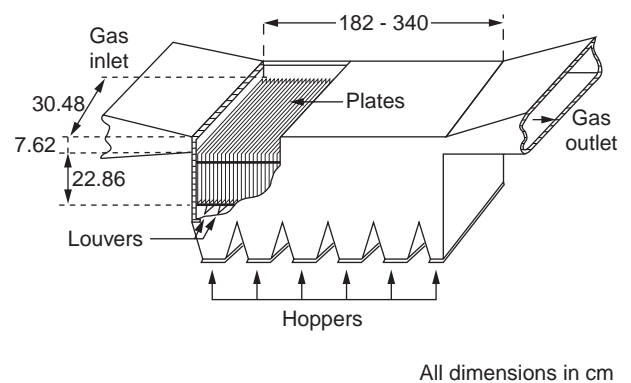


Figure 1

Plate-type TFP.

As an alternate to spaces between closely spaced parallel plates, the collection region may consist of spaces formed by deep and narrow grooves between next neighbour peaks of a pleated sheet or cloth (Fig. 4). The boundary between a gas flow passage and an adjacent collection region is defined by the pleat peaks and the spaces between these peaks. Net flow in the spaces consisting of the grooves in the direction defined by the axis of a flow channel is prevented if the pitch of the pleat is sufficiently small and the pleat height is sufficiently great. Turbulent eddies, however, can and do penetrate into the grooves and the particulates suspended in the gas may deposit on the pleat surface in the grooves and become separated from the gas.

The collection region may consist also of spaces between next neighbour strands of a reticulated foam which form "pores" of dodecahedral shape. The flow passages are circular conduits in the foam (Fig. 5a). Most of the gas flow is turbulent and it passes through the circular conduits. A small fraction of the flow passes through the foam matrix in the viscous flow regime. Turbulent eddies can and do penetrate into the "pores" to a considerable depth, measured from the boundary between a flow passage and the adjacent collection region. Particulates suspended in the gas stream that are carried by the eddies near a strand surface inside the collection region may deposit there and become separated from the gas.

The collection region may consist, instead of the spaces between next neighbour strands of a reticulated foam, also of spaces between next neighbour fibres of a fibrous mat. It may also consist of the cells present in a honeycomb structure.

2 MATHEMATICAL MODELS OF TURBULENT FLOW PRECIPITATORS

2.1 The Deutsch Equation - Material Balance

The mathematical model that has been used for comparing removal efficiencies of TFP's is the analogue of the Deutsch

equation that has been used for a long time for correlating efficiencies of electrostatic precipitators. It is based on a material balance on the particulates in a differential shell of a flow passage, using the assumption of perfect mixing of the particulates in the direction perpendicular to the axis of the flow passage.

The decrease of mass of particulates present in the gas while the gas flows through the shell is equal, with opposite sign, to the mass of particulates deposited in the same time on the collector surfaces in the collection region adjacent to the shell, i.e.:

$$-Q d\bar{N} = \bar{N} w dA \quad (1)$$

where Q is volume flow rate of gas, $\text{m}^3 \text{s}^{-1}$, \bar{N} is particulate loading of gas, kgm^{-3} , A is surface area of boundary between flow passage and adjacent collection region, m^2 and w is “effective migration velocity” of particulates, ms^{-1} .

Assuming that Q and w are constant, Equation (1) can be integrated between the inlet and the outlet of the flow passage:

$$\ell n (\bar{N}_{out} / \bar{N}_{in}) = -wA / Q \quad (2)$$

Hence, the collection efficiency E is:

$$E = 1 - \bar{N}_{out} / \bar{N}_{in} = 1 - \exp\{-wA / Q\} \quad (3)$$

It is convenient to introduce v , the mean gas velocity in a flow passage. The resulting form of Equation (3) depends on the type of TFP considered. In a plate-type TFP $A = LW$ and $Q = vSW$, where L is the length, S is the height and W is the width of a flow passage.

Hence, for a plate-type TFP:

$$E = 1 - \exp\{-Lw / Sv\} \quad (3a)$$

In a TFP where pleated cloth or sheet is used as collection region on two sides of a flow passage $A = 2LW$, and Equation (3) becomes:

$$E = 1 - \exp\{-2Lw / Sv\} \quad (3b)$$

Finally, in a TFP with circular flow passages of diameter D , e.g. in a reticulated foam $A = \pi DL$ and $Q = v\pi D^2/4$, whence:

$$E = 1 - \exp\{-4Lw / Dv\} \quad (3c)$$

Equation (3c) applies also in the case of square flow channels, where D is the edge length of the square.

The advantage of Equations (3a) to (3c) over Equation (3) is that in these the TFP dimensions L and S , or D , are separated from the dimensionless ratio w/v , which can be regarded as the “intrinsic efficiency” of a TFP of a particular design and it can be used for scale-up purposes, provided that it can be shown by experiment that it is independent of L , S , or D . The ratio w/v is a function of the size and other properties of the particulates.

2.2 Residence Time Model

Evidently in all forms of Equation (3) the “effective migration velocity” w is a lumped parameter. It is of interest to explore the physical meaning of w . The flux of gas, $\text{m}^3/\text{m}^2\text{s}$, crossing from a flow passage into the adjacent collection region in the form of turbulent eddies is equal to the mean value of the velocity fluctuation v' at the boundary between the flow passage and the collection region.

Hence, the volume flow $q[\text{m}^3\text{s}^{-1}]$ of gas, caused by velocity fluctuations, from a circular flow passage into the adjacent collection region is:

$$q = \pi DL v' \quad (4)$$

The residence time $t_r[\text{s}]$, of gas in a flow passage is, by definition:

$$t_r = L / v \quad (5)$$

The volume $V_f[\text{m}^3]$ of gas passing from a flow passage into the adjacent collection region and also back from the collection region into the flow passage during the time t_r is, therefore:

$$V_f = \pi DL v'(L/v) = \pi DL^2(v'/v) \quad (6)$$

On the other hand, the net volume $V[\text{m}^3]$ of gas flowing through a flow passage in the time t_r is:

$$V = v(\pi D^2/4)(L/v) = \pi D^2 L / 4 \quad (7)$$

Hence, the number of times, n , the gas is exchanged between the flow passage and the adjacent collection region while it passes through a flow passage is:

$$n = V_f / V = (4L/D)(v'/v) \quad (8)$$

and, therefore, the total residence time of the gas in a flow passage and the adjacent collection region, i.e. in the TFP, is nt_r .

In the course of exchange of gas between a flow passage and the adjacent collection region the turbulent eddies

penetrate into the collection region to a depth ℓ , on the average, and in each exchange step a weight fraction ε of the particulates carried by the eddies is deposited on the surface of the strands present there. Therefore, the removal efficiency E in n exchange steps is:

$$E = 1 - (1 - \varepsilon)^n = 1 - (1 - \varepsilon)^{(4L/D)(v'/v)} \quad (9)$$

$$\approx 1 - \exp\{-4L\varepsilon v' / Dv\}$$

Comparison of Equations (9) and (3c) shows that:

$$w \approx \varepsilon v' \quad (10)$$

i.e. the “effective migration velocity” w can be interpreted as the product of the mean value of the fluctuating velocity v' at the boundary between a flow passage and the adjacent collection region with the mean collection efficiency ε of the particulates in an exchange step of gas between the flow passage and the adjacent collection region.

Next an attempt will be made to estimate the values of ε and v' from measured data.

2.3 Filtration Model - Closure

In the calculations presented below a number of assumptions had to be made that are certainly not accurate and the model can be considered only an outline of a more accurate future model that will be based on a better understanding of the mechanism of particulate collection in the collection region of a TFP.

The data used in these calculations were obtained using an oil mist containing only droplets of a size of 1 micron or less. “Fractional” removal efficiencies of the oil mist were measured by means of an Andersen cascade impactor. The “fractional” removal efficiency of 1 micron particles was found to be $E = 0.91$.

The values of the other parameters are $v = 9.7 \text{ ms}^{-1}$, $D = 1.0 \text{ cm}$ and $L = 34 \text{ cm}$ ($w/v = 1.8 \times 10^{-2}$). The geometric properties of the polyurethane reticulated foam used to construct the TFP were as follows: strand diameter $D_f = 70 \times 10^{-6} \text{ m}$, average pore size about 0.5 mm, porosity $(1 - \beta) = 0.97$. It is assumed that the average depth of penetration of the eddies into the collection region consisting of foam is $\ell = D/2 = 0.5 \text{ cm}$. It is also assumed that the mean approach velocity v_∞ of the mist particles to the collecting strands is equal to v' . Using the above values of the pertinent parameters in a combination of Equations (3c) and (10) there results:

$$\varepsilon v' = 0.1687 \text{ ms}^{-1} \quad (11)$$

The well-known filtration equation, i.e.:

$$E = 1 - \exp\{-\eta L_f \beta / D_f (1 - \beta)\} \quad (12)$$

contains the collection efficiency of a single fibre imbedded in the filter, η . L_f is the depth of the filter and D_f is fibre diameter. Using the values of the pertinent parameters in Equation (12) there results:

$$\eta L_f = 5.45 \times 10^{-3} \text{ m} \quad (13)$$

Noting that $L_f = n \ell$, combination of Equations (8) and (13) yields the result:

$$\eta v' = 5.45 \times 10^{-3} \frac{Dv}{4 L \ell} \quad (14)$$

whence substitution of values for D , v , L and ℓ yields:

$$\eta v' = 7.71 \times 10^{-2} \text{ ms}^{-1} \quad (15)$$

Combination of Equations (11) and (15) results in:

$$\varepsilon / \eta = 2.187 \quad (16)$$

There exists a considerable uncertainty as to the correct way of calculating η , the collection efficiency of a single fibre or strand, imbedded in a foam. The flow pattern in the pores of the foam is unknown and there is no known model of collection mechanism that could be expected to apply to the collection of the particulates by the strands present in the collection region of the foam. As experimental evidence indicates that particulates are collected by the strands in the entire collection region very efficiently, for the purpose of these calculations an empirical relationship, given by Subramanyam and Kuloor [4], i.e.:

$$\eta_I = \frac{\Psi}{\Psi + 1.15} \quad (17)$$

is used to calculate η_I , the collection efficiency of a single strand by inertial impaction.

Here Ψ is the inertia parameter, i.e.:

$$\Psi = \frac{C \rho_p v_\infty d^2}{18 \mu D_f} \quad (18)$$

with C the Cunningham correction factor, ρ_p particle mass density, d particle diameter and μ gas viscosity. The collection efficiency by inertial impaction of a single strand imbedded in the reticulated foam, $\eta_{I\beta}$, is calculated by the empirical formula given by Dorman [5], i.e.:

$$\eta_{I\beta} = \eta_I (1 + 110 \beta) \quad (19)$$

The collection efficiency of a single strand by interception η , is calculated by the formula given by Ranz and Wong [6] for potential flow, i.e.:

$$\eta_c = (1 + R) - \frac{1}{1 + R} \quad (20)$$

where $R = d/D_f$. The collection efficiency by interception of a single strand imbedded in a reticulated foam, $\eta_{c\beta}$, is calculated by the empirical formula given by Dorman [5], i.e.:

$$\eta_{c\beta} = \eta_c(1 + 30\beta) \quad (21)$$

The total collection efficiency of a single strand imbedded in the reticulated foam, η , is calculated in the customary approximation as follows:

$$\eta = 1 - (1 - \eta_{I\beta})(1 - \eta_{c\beta}) \quad (22)$$

Substitution of the values $C = 1.15$, $\rho_p = 800 \text{ kgm}^{-3}$, $\mu = 1.8 \times 10^{-5} \text{ Pa}\cdot\text{s}$ into Equation (18) there results:

$$\Psi = 4 \times 10^{-2} v_\infty \quad (23)$$

Substituting this result into Equation (17) we have:

$$\eta_I = \frac{4 \times 10^{-2} v_\infty}{4 \times 10^{-2} v_\infty + 1.15} \quad (24)$$

Combining Equation (24) with Equation (19) gives:

$$\eta_{I\beta} = 4.3 \frac{4 \times 10^{-2} v_\infty}{4 \times 10^{-2} v_\infty + 1.15} \quad (25)$$

where $\beta = 0.03$ has been used.

By Equation (20), we have:

$$\eta_c = 0.028 \quad (26)$$

whence, using Equation (21):

$$\eta_{c\beta} = 0.0532 \quad (27)$$

and, after introduction of Equations (25) and (27) into Equation (22), there results the following expression for η :

$$\eta = \frac{0.165 v_\infty + 0.0612}{4 \times 10^{-2} v_\infty + 1.15} \quad (28)$$

Combining Equation (28) with Equation (16) yields the following equation for ε , the particle removal efficiency of

the collection region in one exchange step of the gas between a flow passage and the adjacent collection region:

$$\varepsilon = \frac{0.361 v_\infty + 0.134}{4 \times 10^{-2} v_\infty + 1.15} \quad (29)$$

Using the assumption of $v' = v_\infty$ in Equation (11) and substituting the result into Equation (29), there results:

$$\varepsilon = \frac{0.0609/\varepsilon + 0.134}{6.75 \times 10^{-3}/\varepsilon + 1.15} \quad (30)$$

Solving this quadratic equation for ε we have:

$$\varepsilon = 0.29 \quad (31)$$

whence by Equation (11):

$$v' = v_\infty = 0.578 \text{ ms}^{-1} \quad (32)$$

The ratio $v'/v = 0.578/9.7 \cong 0.06$ is not at all unreasonable. As any conceivable model of particulate collection by inertial or turbulent deposition mechanism will predict an increased fibre collection efficiency, η , and hence an increased, ε , with increasing v_∞ , there can exist only a limited range of possible solutions for v' and ε that satisfy the condition that their product must be equal to the measured value $w = 0.1687 \text{ ms}^{-1}$.

By Equation (8), there results the following value for n , the number of times the gas is exchanged between the gas flow passage and the adjacent collection region, i.e. the reticulated foam:

$$n = 8.25 \quad (33)$$

i.e., there is predicted a complete exchange of gas for every 4 cm length of a flow passage, and the residence time of the gas in the TFP is predicted to be about 8 times the residence time t_r calculated by Equation (5).

3 EXAMPLES OF REALIZATIONS OF THE TFP

3.1 Plate-Type TFP

The first TFP that was built and was subsequently tested quite extensively was the plate-type TFP, shown in Figure 1. The cross-sectional dimensions of the housing was 30.5 cm by 30.5 cm and the height of the gas passage was varied from 7.6 cm to 1.3 cm. The plates were spaced 2 cm apart. The test dust was kaolin (ASP 200) of a mass median diameter of about 2.5 micron, determined with the help of an Andersen cascade impactor.

Most of the dust deposition was on the front faces of the plates in the form of a band extending over a distance of about 2 cm next to the top edges of the plates. There was dust deposition also in the form of spots over the entire front face and particularly the entire back face of the plates. When packing the spaces between the plates with fibres there was some dust deposition on the fibres all the way to the bottom of the housing.

The test procedure used consisted of isokinetic sampling according to the *Source Testing Code of the Ontario Ministry of the Environment (OME 1973)* [7]. The experimental data were analyzed in terms of a three-factor design, using linear regression. The effective migration velocity, w , was computed, using Equation (3a), from measured values of E , L , S and v . It was assumed to be a linear combination of L , S and v :

$$w = Av + BS + CL + D \quad (34)$$

Linear regression yielded the following estimates of the parameters and the 95% confidence intervals:

$$\begin{aligned} A &= 1.34 \pm 0.224 \\ B &= 0.319 \pm 1.045 \\ C &= -2.856 \pm 3.586 \\ D &= 21.355 \pm 16.3 \end{aligned}$$

It is evident that w is statistically independent of S and L , but is statistically the following linear function of v :

$$w \text{ (cm/s)} = 0.0134 v \text{ (cm/s)} + 21.35 \text{ (cm/s)} \quad (35)$$

(The value of v was varied from 13 m/s to 57 m/s in these tests.)

It is apparent from Equation (40) that the value of the “intrinsic efficiency” w/v increased from 1.7×10^{-2} to 3×10^{-2} as the value of v was lowered from 57 m/s to 13 m/s. A possible reason for this trend is that there was in all the tests a small amount of entrainment of dust that was deposited right at the top edge of the plates and this decreased as the velocity was lowered. Fractional dust removal efficiencies were determined by means of an Andersen cascade impactor. The parameters in these tests had the following values: $L = 2.7$ m, $S = 3$ cm and $v = 42$ m/s. The results of these tests are shown in Figure 2.

The following are some comments on the performance and the limitations of the plate-type TFP. The maximum overall removal efficiency of the kaolin dust in these tests was about 87%. High efficiencies require large L and/or small S . Small S entails small, i.e. unfavourable value of the ratio of flow passage cross-section to TFP cross-section. For large gas flows many TFP’s are required and because the position of the plates must be vertical, TFP’s must be also arranged in layers one above the other, resulting in complications in construction. Hence, plate-type TFP’s are limited to gas flows ranging up to about 5000 to 10 000 Nm³/h.

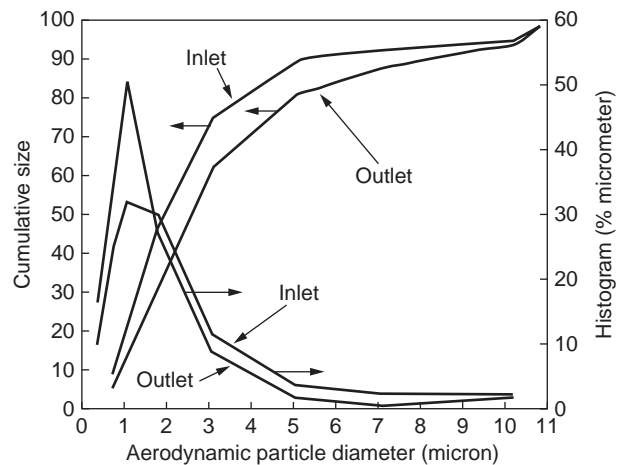


Figure 2

Fractional collection efficiencies of kaolin dust by plate-type TFP.

3.2 Vertical Tubular Fibrous Mat-Type TFP

This TFP is shown schematically in Figure 3. In this prototype, the collection region consists of the spaces between next-neighbour fibres in a fibrous mat. A 10 cm thick fibreglass or polyester mat was wrapped around a 20 cm diameter tubular wire cage of 236 cm length and then the assembly was fitted into a 40 cm i.d. tube. The fibrous mats consisted of about 30 micron diameter fibres and its average porosity was about 0.996. The average distance between next neighbour fibres was estimated at about 1 mm. Kaolin dust deposition in the tests, conducted by using the same procedure as in the case of the plate-type TFP, was observed visually throughout the entire 10 cm depth of the fibrous mats. Whereas in the case of the plate-type TFP the dust, after deposition on the plates, sloughed off the plates by only the action of gravity, the dust deposited on the fibres had to be dislodged by intermittently shaking the assembly, using a quick-return mechanism that moved the assembly up-and-down in the tube in a reciprocating action, with the fast (short) stroke pointing in the downward direction. The gas flow and the dust feeding were discontinued while operating the shaker. The gas velocity was varied from 13 m/s to 20 m/s. There was no noticeable trend of efficiency with gas velocity and the average collection efficiency was about 68%. By Equation (3c) the value of the intrinsic efficiency w/v is found to be 2.5×10^{-2} which is comparable with the value obtained for the plate-type TFP at $v = 20$ cm/s.

Comparing the plate-type and the tubular fibrous mat-type TFP’s of the same lengths L at the same collection efficiency levels, because w/v is the same value in both prototypes, there follows from Equations (3a) and (3c) that $D/4 = S$. Assuming that there is the same gas flow Q , m³/ℓ, in these

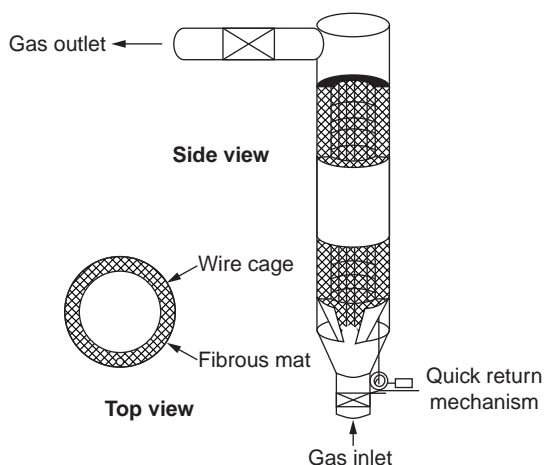


Figure 3
Tubular fibrous mat-type TFP.

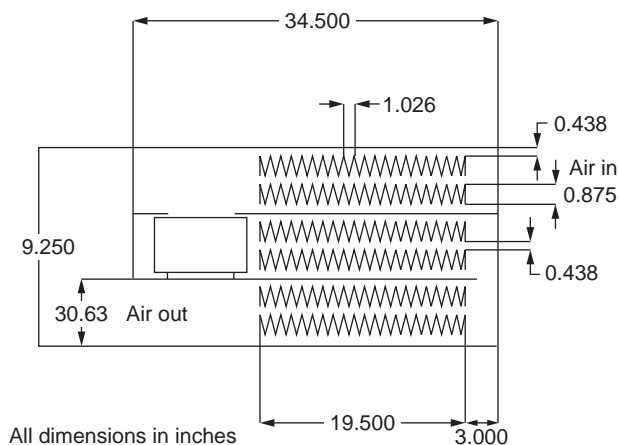


Figure 4
Schematic of structure of residential TFP.

two prototypes, there follows that the ratio of the velocities is $v_p/v_t = 20\pi \text{ cm}/30.5 \text{ cm} \approx 2$ (v_p and v_t are the velocities in the plate-type and the tubular TFP's respectively).

The ratio of the pressure losses in these two TFP prototypes is, therefore, predicted to be about $2^2 = 4$, showing considerably lower operating expenses for the tubular-type TFP. A constructional advantage of this prototype is that it permits the treatment of arbitrarily large gas flows by using many fibrous mat tubes standing side-by-side with a discharge into one or several hoppers positioned below the TFP. A disadvantage is the great thickness of the fibrous mat required for maximum effectiveness. For the achievement of higher dust removal efficiency it is not practical to use flow passages of a smaller diameter because, if the fibrous mat thickness is kept undiminished, the equipment cross-section required for the treatment of a given gas flow increases.

3.3 Pleated Filter-Type Residential TFP

This TFP has been on the market for four years and it has been a commercial success. Its design has been improved several times, mainly with the objective of reducing the manufacturing cost without affecting the performance. The current design, marketed in North America, is shown schematically in Figure 4. The residential TFP can be installed on furnace ducting or HRV ducting or it can be free-standing. In order to meet the requirements of small size, competitive air flow, pressure loss and removal efficiency of room air dust of very small aerodynamic diameter, commercially available pleated furnace filters have been used to form both the gas flow passages, defined by the peaks of the pleats and the spaces between the peaks, and the collection region which consists of the spaces formed by the grooves in the pleated filters. The pleat height and the pitch of the filters are 2.22 cm and 2.61 cm respectively, which corresponds to a pleat angle of about 61° ,

or about 86% grade, which is very close to the 100% grade of the plates in the plate-type TFP. In the plate-type TFP, however, the plate height is almost ten times greater than the pleat height in the residential TFP. The effectiveness lost by the relatively low pleat height is more than compensated for by using pleated filters with permanent electrostatic charges. The charges draw the submicron dust particles which are carried by the turbulent eddies close to a fibre but not close enough for deposition, all the way to the fibre surface. The furnace filters are 0.5 m by 0.5 m frames. In the current design, shown in the figure, there are six filter frames arranged in three channels which are in series with each other, with two filter frames arranged side-by-side in each channel, resulting in a total flow passage length $L = 1.5 \text{ m}$. In each channel there are three parallel flow passages formed by the filters, two of which have only side facing a collection region, i.e. a pleated filter, whereas the flow passage in the middle faces two collection regions, i.e. a pleated filter on each side. In an attempt to produce equal air flows in all three parallel passages, the passage gap widths have been chosen to be of the same size of about $S = 9.5 \text{ mm}$. Using Equations (3a) and (3b), along with a measured collection efficiency of $E = 0.88$ of room air dust of 1 micron optical diameter the value $w/v = 1.08 \times 10^{-2}$ is obtained for the "intrinsic efficiency" of the TFP for room air dust of 1 micron optical diameter. Introducing this value in the following equation:

$$E = 1 - \exp\{-Lw/S_{eff}v\} \quad (36)$$

along with $E = 0.88$ and $L = 1.5 \text{ m}$, the value $S_{eff} = 7.64 \text{ mm}$ is obtained. The range of air flow rates covered by the residential TFP is about 150 to 200 Nm^3/h . The pressure drop is not greater than 250 Pa. The initial dust removal efficiencies as determined by an independent laboratory are listed in Table 1.

It is noted that the optical diameter of room air dust, reported here, which is determined by scattering of a laser beam, is estimated to be an order of magnitude greater than the aerodynamic diameter which is the relevant size parameter for capturing a particle. The reason for this discrepancy is the very low density of room air dust that is a loose agglomerate consisting of very fine fibrous matter.

TABLE 1
Removal efficiencies of room air dust by lifebreath TFP air cleaner vs. optical particle size ranges

Particle size ranges (micron)	Initial removal efficiency (%)
0.3-0.4	73.77
0.4-0.5	77.36
0.5-0.6	81.03
0.6-0.8	83.96
0.8-1.0	86.69
1.0-1.5	89.60
1.5-2.0	93.55
2.0-3.0	95.65

3.4 Reticulated Foam-Based TFPs

The latest development in TFP technology is represented by reticulated foam-based TFPs. In these the collection region consists of the spaces, or pores, formed by next neighbour strands in a reticulated foam, and the boundaries of the flow passages are defined by peripheral strands and the spaces between these strands.

The construction of a foam-based TFP may comprise punching identical circular holes into sheets of a reticulated foam, the same hole pattern in every sheet, and then assembling the sheets in such a manner that the holes in all the sheets are perfectly aligned and form identical, parallel, straight, unobstructed flow passages. For best utilization of space the holes may be arranged on a triangular pattern with a center-to-center distance equal to two hole diameters, or as shown schematically in Figure 5a, on a square pattern.

Reticulated foams are characterized by the number of pores per unit length along a straight line, and is expressed at ppi (pores per inch), ranging from 10 ppi to about 100 ppi.

Reticulated foams made of polyurethane, polyurethane coated with PVC, various ceramics, vitreous carbon, nickel, etc. are commercially available.

TFPs using approximately 50 PPI polyurethane foam, with flow passages of about 1 cm diameter and a length of about 34 cm sketched in Figure 5b are on the market for the removal from air of ultra-fine oil mist produced from oil which is used as coolant for very high rpm metal working machine tools. Typical droplet size distribution of an oil mist is shown in Table 2, along with the fractional removal efficiencies obtained with the TFP.

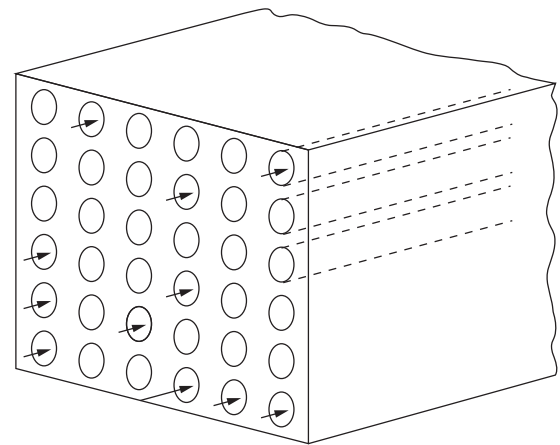


Figure 5a
Foam-based TFP.

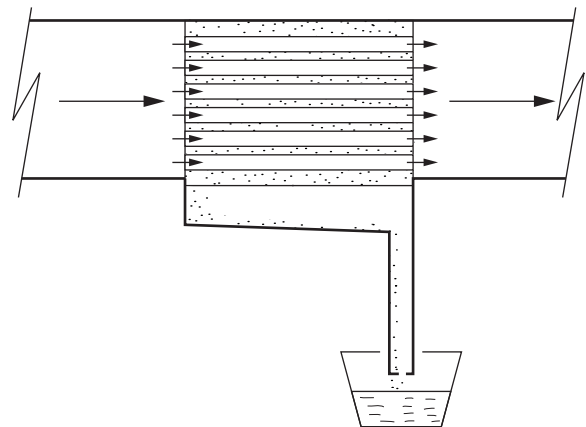


Figure 5b
Foam-based oil mist eliminator TFP.

TABLE 2
Size distribution of test oil mist and removal efficiencies by TFP

Size range (micron)	Weight percent	Removal efficiency (%)
11.4	0	-
7.1	traces	-
4.8	traces	-
3.3	2.6	99.8
2.1	26.4	99.8
1.0	50.6	97.8
0.64	13.5	88.6
0.43	3.0	78.5
< 0.43	2.4	92.0

The overall removal efficiency of the oil unit by the TFP is about 96%. The “intrinsic efficiency” w/v is about 2.4×10^{-2} . Typical air passage velocities in the TFP are about 10 m/s and the pressure losses are about 1 kPa or less. The efficiency was found to increase with velocity which indicates a virtual absence of reentrainment of oil from the foam. The oil is held in the pores of the foam by capillary forces. It drains continuously from the foam and is discharged from the TFP as sketched in Figure 5b. The same polyurethane foam-based TFP was found to remove 99.98% of 30 micron mean diameter atomized water spray from air.

A TFP made of 10 ppi polyurethane foam, containing 1.6 cm diameter, vertical, circular flow passages of 46 cm length gave an initial removal efficiency of ASP 200 (kaolin) dust of about 87%, corresponding to an “intrinsic collection efficiency” of $w/v = 1.8 \times 10^{-2}$. The tests were run at about $v = 5$ m/s gas passage velocity.

The same TFP, run at about $v = 5.5$ m/s gas passage velocity gave a removal efficiency of about 97% ($w/v = 3 \times 10^{-2}$) of FCC catalyst dust of the particle size distribution determined by means of an Andersen cascade impactor, shown in Table 3.

TABLE 3
Particle size distribution of FCC catalyst dust

Particle size (micron)	Weight percent
11.4	25.8
7.1	36.7
4.8	15.3
3.3	8.0
2.1	8.6
1.0	3.4
0.64	1.4
0.43	traces
< 0.43	traces

A TFP made of 20 ppi reticulated ceramic foam with circular vertical flow passages of 1.3 diameter and 46 cm length gave an initial removal efficiency of the FCC catalyst dust of about 90% at a gas passage velocity of about 7 m/s. Raising the velocity to about 9 m/s resulted in a drop of efficiency to about 83%, presumably due to reentrainment of already deposited dust from peripheral strands of the ceramic foam that are on the boundary of a flow passage. After continuous injection of an amount of dust equivalent to 30 kg dust per m^3 TFP volume, the initial efficiency decreased from 90% to about 84%.

Subdividing the above TFP into three separate TFPs, connected in series, each of 15.33 cm flow passage length, the removal efficiency of the FCC catalyst dust, at $v = 7$ m/s, was higher than in the single TFP and it was still 94% after injecting an equivalent of 45 kg dust per m^3 of TFP volume.

This improvement is due to the collection in the second TFP of dust reentrained from the first TFP and collection in the third TFP of dust reentrained from the preceding TFPs.

For very large gas flows three separate TFPs require almost three times more metal to construct than only one TFP of the same passage length as the sum of the passage lengths of the three TFPs, because the cross-sectional area of a TFP is directly proportional to the gas flow, whereas the passage length is independent of the gas flow. Therefore, it was of interest to explore whether or not it is also possible to reduce reentrainment by subdividing the TFP into three equal parts in series connection, each of 15.33 length, with all three parts in the same housing, with 15.33 cm wide gaps between each two adjacent parts. In these tests, run at $v = 7$ m/s, after injecting an amount of dust equivalent to 40 kg dust per m^3 of TFP volume the removal efficiency was about 86%, showing only a small improvement over 84% (the initial efficiency was about 90%).

The total passage length of the same TFP discussed above was increased to 68.6 cm. It was subdivided into three equal parts in series connection, each of a length of 22.4 cm, separated by gaps of 7.6 cm width. This TFP was tested with the flow passages oriented both vertically and horizontally. After injecting an equivalent amount of about 40 kg dust per m^3 of TFP volume the efficiency was about 93%. The initial efficiencies were about 95% and 93% in the horizontal and in the vertical orientations, respectively. In all the TFPs made of a reticulated foam the dust deposited in the foam can be dislodged by vibrating the TFP. During this operation the gas flow is disconnected.

Reticulated foam-type TFPs have virtually unlimited applications for any conceivable gas flow and also under conditions of very high temperatures and/or corrosive atmospheres.

CONCLUSIONS

The turbulent flow precipitator (TFP) has evolved from 1991, the year when the idea underlying its operation was conceived, to the present date into a commercial success. The Lifebreath Residential Air Cleaner is constructed of pleated cloth carrying permanent electrostatic charges, the Nutech Mist Eliminator TFP is constructed of perforated sheets of reticulated polyurethane foam, the Nutech Thermal Sand Separator utilizes a plate-type TFP. Reticulated foams, made of a large variety of different materials, some of which can resist very high temperatures and/or corrosive atmospheres, offer the widest range of opportunities for applications of TFPs.

The performance of a TFP can be accounted for by a consistent application of three mathematical models: a material balance, a residence time model and a filtration model.

ACKNOWLEDGMENTS

The author wishes to acknowledge the invaluable technical help received by him over the years from his wife Ann, from Mr Will Kwan and others, and the interest shown in this project by both the *Institut francais du pétrole* and *Nutech Energy Systems, Inc.*, London, Ontario, Canada, without which no TFP of a practical value could have been developed.

REFERENCES

- 1 Dullien, F.A.L. and Collins, A. (1992) *2nd European Symposium: Separation of Particles from Gases*, Nuremberg, 85-96.
- 2 Dullien, F.A.L., Kwan, W. and Collins, A. (1993) *Gas Cleaning at High Temperatures*, Blackie Academic & Professional, 41-56.
- 3 Friedlander, S.K. and Johnstone, A.F. (1957) *Ind. Eng. Chem.*, **49**, 1151-1155.
- 4 Subramanyam, W.V. and Kuloor, N.R. (1969) *Ann. Occup. Hyg.*, **12**, 9-15.
- 5 Dorman, R.G. (1964) *High Efficiency Air Filtration*, Butterworth, London.
- 6 Ranz, W.E. and Wong, J.B. (1952) *Ind. Eng. Chem.*, **44**, 1371-1381.
- 7 OME (1973) Source Testing Code, Measurement of Emission of Particulates from Stationary Sources, *EPS-1-AP-74-1*.

Final manuscript received in July 1999