Entrained Particle Collection in Packed Beds

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Small particle collection in packed beds is described by an inertial impaction theory which fits experimental observations. Rings, saddles, spheres, and spherical packings of ½-, 1-, and 1½-in. size were used at air velocities up to 30 ft./sec. for the collection of an oil mist of known size. Particle collection efficiencies up to 50% for 1.0-micron particles were obtained.

Vapor from evaporators, boilers, and stills carries with it small drops of liquid. These drops can be formed by the bursting of bubbles during a boiling process, by the breakup of liquid sheets and ligaments, or by the condensation of saturated vapor. Mist entrained by the vapors causes problems such as corrosion of equipment, decrease in equipment performances, or a loss of the processed material. This same mist may also constitute a public nuisance, a health hazard, or a general air pollution problem.

Many types of mist separators or dust collectors may be used as entrainment separators. Generally, these are especially effective on the larger (10-micron diameter) particles, but have very little effect on particles below a few microns in diameter. A successful entrainment separator must have several essential characteristics: high collection efficiency, very low liquid reentrainment, and low pressure drop.

Towers packed with Raschig rings or coke have been used for many years to collect mists such as phosphorus pentoxide (*1* to *3*). The Tennessee Valley Authority obtained data for mist collection by burning phosphorus in air and passing the resulting gases through a tower irrigated with water or dilute acid. Efficiencies of 90% were obtained only with high velocity–high pressure drop operation. They obtained similar results with a tower packed with small size (1-plus ½ in.) coke. Additional results indicated that in certain cases, a twofold increase in depth produced practically no increase in mist recovery.

Baskerville (*1*), using a pilot scale tower packed with either 1-in. Raschig rings or with coke, studied the effects of gas velocity and bed depth on the recovery (collection) of phosphorus pentoxide. He arrived at a set of semiempirical equations in which many factors such as particle size were omitted. Baskerville claimed, however, that the equations for recovery and pressure drop hold within the limits of accuracy of the data.

Silverman (*4*) has reported on the use of coke boxes for the collection of 0.5- to 3-micron mists in the sulfuric acid industry. Carefully sized and washed coke, ¼ to ⅜ in. in size, were placed between layers of coarser grades of coke and tested at superficial velocities of up to 10 ft./min. with corresponding pressure drops of 1 to 10 in. of water. By using finer coke sizes and lower gas velocities, efficiencies as high as 99% were obtained; increased bed depth caused higher collection efficiencies and higher pressure drops.

Strauss and Thring (*5*, *6*) reported on the use of high-temperature insulating brick (5/16 in. to 7 B.S. mesh), crushed high-temperature fireclay refractories (14 to 24 B.S. mesh), and two types of ceramic filters to clean the fume from hot open-hearth furnace stack gas. From pilot plant studies they report efficiencies of 80 to 90% for the granular refractory, 50% for the fireclay, and 60% for ceramic filters when aerosols containing particles of 0.8 to 6 microns in diameter were used. The granular refractory had the lowest pressure drop. A regression analysis was made to correlate collection efficiency with mass flow rate, temperature, and inlet fume concentration.

THEORETICAL CONSIDERATIONS

Collection efficiency of fibrous filters has been studied by several investigators and is fairly well defined. Collection of particles by larger elements, such as the rings, saddles, spheres, etc., employed in gas absorption and distillation columns, is not as well investigated or as clearly understood.

In general there are five ways of removing particles from a gas stream: settling, inertial impaction, deposition diffusional, agglomeration, and electrostatic deposition. In packed beds, the collection of droplets—larger than a half-micron diameter or so—can be mainly attributed to the mechanism of inertial impaction.

Inertial collection occurs in the following manner. (1) Particles in a gas stream are impacted against the packing surface because of the particle's inertia or inability to follow the gas stream around the packing. (2) After a number of particles have been caught by a packing element surface, they coagulate and tend to flow along the packing surface and out of the collector. Although this draining flow may be partially reentrained and reduce overall efficiency, the effect may be identified separately and is not included in this study.

A particle tends to move in a straight line because of its inertia; therefore, when the suspending fluid flows around an obstacle, the particle tends to keep going toward the obstacle. Collection of a particle by an obstacle, or target, is determined by whether a particle reaches an obstacle or whether the particle is deflected sufficiently by the fluid to by pass or flow around the obstacle. If a particle bounces off from rather than sticks to a surface on impaction, the efficiency will be lower. In this paper the bounce off is assumed zero, although it may be significant for some circumstances.

A mathematical analysis of particle collection may be based on Newton's law of motion and on the assumption that the deceleration force on a particle is given by Stokes' resistance law for laminar flow through a continuous fluid. The probability or efficiency E with which a

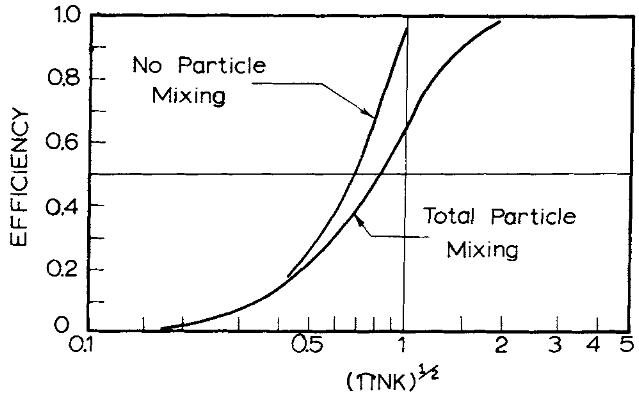

Fig. 1. Collection efficiency vs. inertial parameter.

mist particle in an inertial field is removed from a fluid stream can be expressed as a function of at least three dimensionless parameters. The first of these K is a dimensionless ratio between the inertial force acting on a particle and the force of resistance to its motion relative to the fluid. The parameter K is called the inertial impaction parameter. When Stokes' law does not hold, that is, when the Reynolds number of a particle is more than unity, this Reynolds number must be taken into account. The third parameter is the Reynolds number for flow around the obstacle or collector.

Packed-bed collection efficiencies may be predicted by means of a simplified mathematical model of the collection system. It is first necessary to describe the flow passage and the flow pattern for the fluid. It is then possible to obtain the particle trajectories.

Assume that a packed bed can be represented by a series of bends of equal size and that the gas flows through a number of these passages. In a series of alternating bends the particles are thrown first toward one wall and then the other because of centrifugal forces. Ranz (7) has given an expression for the collection of particles in a sweeping bend: A uniform flow system in which there is no mixing of the particles was assumed. Some of the particles, subject to a collection force, are thrown out in the first half wave. The remainder travel through the system unaffected, as the remaining alternating waves will only cause the particles to move from side to side but will not remove them.

A more realistic way to characterize the collection of particles in a packed bed is to include the effect of turbulent mixing. Assume that mixing occurs either after flow through each bend or that it occurs continuously throughout the flow path. The latter approach will be used here. This effectively means that the particle concentration is constant across any cross section of a bend and that centrifugal sedimentation takes place in a laminar layer adjacent to the packing.

The expression for the collection efficiency E in a sweeping bend which was previously referred to is

$$E = \pi n K \tag{1}$$

The definition for K includes a characteristic linear dimension for the impaction system. For a sweeping bend this dimension was chosen to be the thickness of the gas stream between the walls. The same definition will be used in applying this relationship to packed beds. For a packed bed this width will be called the channel width B, which is a function of the packing diameter. The term n is the number of 360-deg. turns during which the particles may be thrown out of the gas stream.

We may derive a similar expression for the case of turbulent mixing. If Stokes' law applies, then a force balance on the particle leads to

$$U_t = \frac{D_p^2 \rho_p a}{18 \mu_g} \tag{2}$$

The flux of particles of size D_p against the outside wall at $R\theta$ is equal to CU_t. The consideration of the number of particles entering and leaving an element of flow $Rd\theta$ long, B thick, and of unit width gives the differential equation

$$-(V_o B)\, dC = C U_t \, R d\theta \tag{3}$$

where the gas velocity in the circumferential direction is assumed to be V_o everywhere.

By using the boundary condition that $C = C_o$, when $\theta = 0$, the following relationship for C as a function of $R\theta$ is developed:

$$\frac{C}{C_o} = \exp - \left[\left(\frac{U_t}{V_o} \right) \left(\frac{R\theta}{B} \right) \right] \tag{4}$$

The fractional efficiency of impaction for this situation can be defined as the ratio of the number of drops of a certain size removed to the number of drops originally in the stream. That is, $E = (1 - C/C_o)$. The normal acceleration of a stream moving at a velocity V_o on a radius R is (V_o^2/R). If Stokes' law holds, the terminal velocity may now be expressed as

$$U_t = \left(\frac{D_p^2 \rho_p V_o^2}{18 \mu_g R} \right) \tag{5}$$

By substitution

$$\frac{C}{C_o} = \exp - \left[\left(\frac{D_p^2 \rho_p V_o^2}{18 \mu_g R} \right) \left(\frac{R\theta}{B} \right) \right]$$

$$= \exp - \left[\frac{D_p^2 \rho_p V_o \theta}{18 \mu_g B} \right] \tag{6}$$

Since K was previously defined to include the channel width B, the terms inside the inner brackets can be replaced by K giving

$$E = 1 - \exp(-\pi n K) \tag{7}$$

Therefore, there are two distinct assumptions which lead to either of two relationships expressing the collection efficiency as a function of n and K:

For uniform flow $E_o = \pi n K$ (1)

For turbulent flow $E_o = 1 - \exp(-\pi n K)$ (7)

Figure 1 is a plot of collection efficiency vs. the expression $\pi n K$ as predicted by Equations (1) and (7). Figure 2 is a plot of predicted collection efficiency against particle diameter with the gas velocity, packing diameter, and the bed depth as parameters. The channel width B is a function of the packing diameter D and was estimated to be related to the free volume of cubic packed

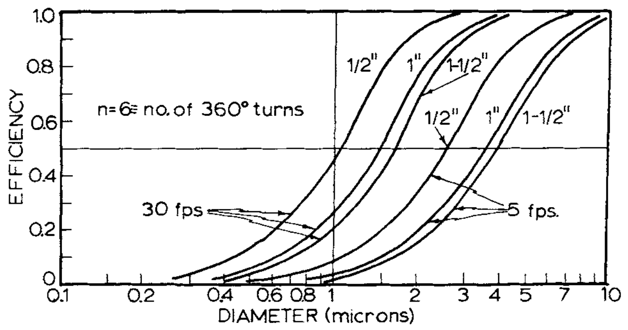

Fig. 2. Predicted efficiency vs. particle size.

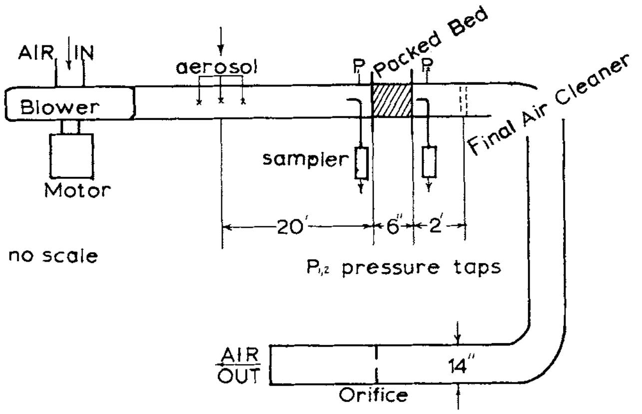

Fig. 3. Schematic diagram of aerosol tunnel.

spheres. The ratio of channel width to the packing diameter is estimated to be a constant:

$$\frac{B}{D} = 0.1 \tag{8}$$

The curves in Figure 2 were developed by using this particular constant ratio.

EXPERIMENT

The experiments were carried out on test apparatus whose main features are shown in Figure 3. The sampling system, a cascade impactor, was used to determine the mass concentration of aerosol mist in each of several particle size fractions. This allowed determination of impaction efficiencies for different ranges of particle sizes.

Operation of the test equipment is as follows. Air is drawn in from outside through a blower and is exhausted into a ducting system. An oil mist is introduced into this air stream and is carried by it to a test section. The air stream is sampled before and after passing through the test section. It then passes through a final air cleaner and is exhausted to the atmosphere.

A test aerosol generator provides a fuel oil mist having a mass median diameter of approximately 6 microns and with a standard deviation of 2.0 at an output flow rate of about 3.6 lb./hr. Fuel oil was chosen because it is relatively nonvolatile, nontoxic, and nonexplosive at the mist concentrations obtained in the test equipment. Important properties of the test oil are: specific gravity 60/60 = 0.83, viscosity at 100°F. = 2.3×10^{-2} poise, surface tension at 70°F. = 24 dynes/cm.

The test aerosol is sampled at positions approximately 6 in. before and after the test section. Samples are drawn from the duct center through a sampling tube connected to a four-stage cascade impactor fitted with a rapid opening plug valve. Following the impactor is a filter unit in which high efficiency filter paper is used to remove all remaining mist particles.

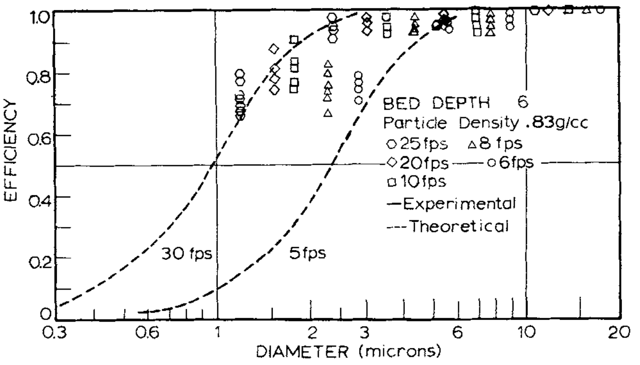

Fig. 5. Experimental collection efficiency. One-half-inch spheres, Berl saddles, and Raschig rings.

Specific details on the systems mentioned are available from the authors.

EXPERIMENTAL PROCEDURE

Tests were carried out at the following approximate superficial velocities: 6, 8, 10, 20, and 25 ft./sec. In a few isolated cases it was also possible to reach 30 ft./sec. For each test condition, test runs were made in triplicate to insure representative efficiencies. Each packing was tested at the above flow rates before changed to another packing.

The test section was constructed from a 6-in.-long section of 14-in. diameter ducting with an inlet and outlet retainer screen of ⅜-in. hardware cloth. After a test bed was packed and the retainer screen fixed in place, the bed was fitted into a horizontal section of the test duct.

Although the mist concentration varied somewhat (minimum and maximum concentrations were 2.7 and 4.2 lb./hr., respectively), it was usually within 5% of 3.6 lb./hr. The aerosol distribution was computed from cascade impactor data and is shown in Figure 4 as a straight line on logarithmic-probability coordinates. A slight error was introduced because of collection on the bend of the sampling tube. By using sample bias provided from previous testing, the raw data can be corrected.

Overall efficiencies were calculated from samples taken before and after the collector being tested. The difference in the total amount collected in the impaction train before and after the collector represents that part of the stream which was removed. When the data were evaluated the weight of material on the first impaction stage was not included. This was done on the assumption that this should be reentrained mist, rather than droplets which have bounced off as the collection for that size range is essentially 100%. In general, this reentrained mist was in the range of 10 to 30 microns, depending upon the superficial velocity of the main stream and is large enough to be easily collected.

The results of these efficiency tests are shown in Figure 5 and 6. The packing size was ½ in. and the packing types were: glass spheres, Berl saddles, Raschig rings, and Intalox

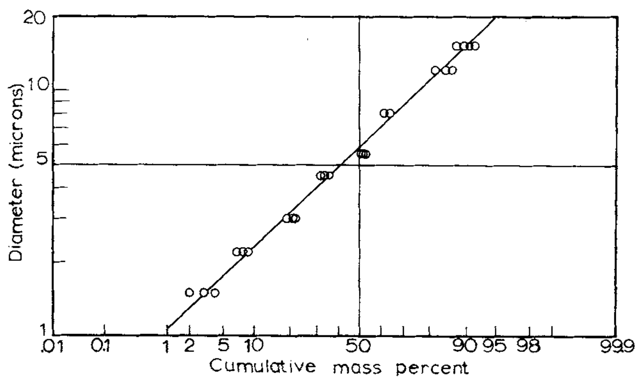

Fig. 4. Size distribution curve; Dm = 6.0 microns; σ = 2.0.

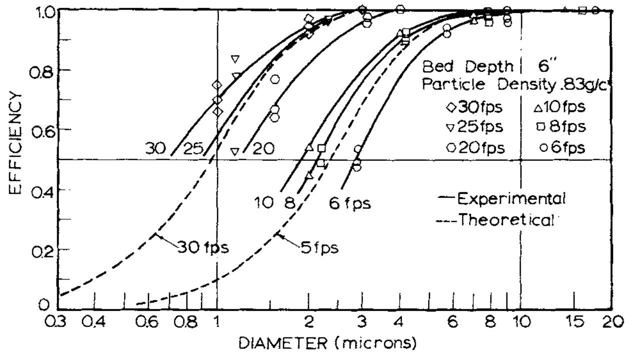

Fig. 6. Experimental collection efficiency. One-half-inch Intalox saddles.

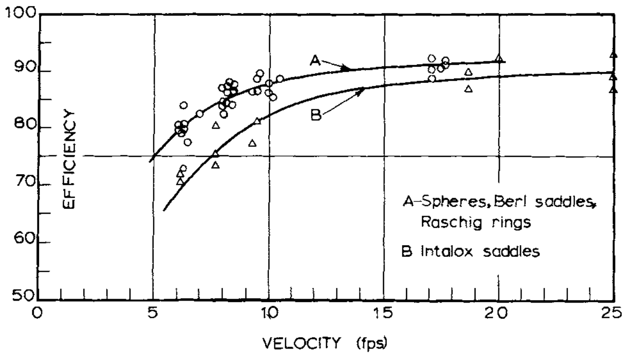

Fig. 7. Overall efficiency vs. superficial velocity.

saddles. The experimental curves in Figure 5 apply to the spheres, the Berl saddles, and the Raschig rings; those in Figure 6 show the results obtained when Intalox saddles were used. Theoretical (predicted) curves for two velocities are also shown on the plots. All the curves, theoretical and experimental, are plots of efficiency vs. particle diameter with velocity as a parameter. In all cases the mass median diameter of the test aerosol was 6 microns (with geometric standard deviation of 2). In the figures the theoretical curves are obtained by applying the turbulent mixing expression, by using n (the number of 360-deg. turns) = 6 as a first approximation.

Overall efficiencies for the entire mist size distribution fed to the horizontal flow bed collector are shown in Figure 7. The curve for the Intalox saddles falls below that for the other types of packings at a lower velocity, but improves at high velocities. The overall efficiencies hide the effect of particle size, but are presented here to give an approximate basis for comparison with other entrainment separators as commonly reported.

On the basis of only the collection efficiency characteristics of the packings used, it would seem that any of the three types previously mentioned—spheres, Berl saddles, Raschig rings—would be superior to the Intalox saddles at the low velocities. Any of the four would be suitable at the higher velocities.

Pressure Drop

The pressure drops which were obtained with this installation ranged from low to moderate. The drop in pressure for the various velocities is shown in Figure 8, which shows that the Intalox saddles have the best operational characteristics. The experimental values for this particular set of tests are 0.5 to 1.0 times those calculated from published correlations (*8*, *9*).

SUMMARY AND CONCLUSIONS

Beds of Raschig rings, Berl saddles, Intalox saddles, and glass spheres are very effective in removing entrained

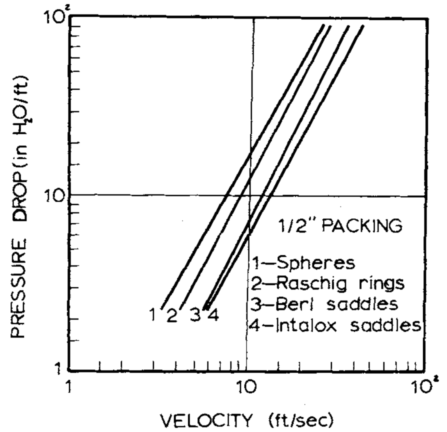

Fig. 8. Pressure drop for ½-in. packings.

liquid droplets down to 2- to 3-micron diameter. Efficiencies up to 50% were obtained for 1.0-micron particles. A turbulent mixing model represents collector performance reasonably well and may be used to predict particle collection by impaction. Subsequent testing on a vertical-flow bed (*11*) has provided additional results which substantiate the model and the use of $n = Z/2D$ as an approximation. In the 6-in. bed used for then , Berl saddles and Raschig rings give the best performance at low velocities. When high velocities were attained, then the lower pressure drop developed in a bed packed with Intalox saddles made it superior. The roles of reentrainment and particle bounce remain to be defined.

ACKNOWLEDGMENT

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NOTATION

a = particle acceleration, cm./sec.^{2}
B = width of flow channel, cm.
C = number of particles of size D_p/unit volume of gas at a distance $R\theta$ from start of turn, No./cc.
C_o = number concentration of particles at R, $\theta = 0$, No./cc.
C_D = drag coefficient = $24\mu_g/(U_t\rho_g D_p)$ for Stokes' law
D = diameter of packing, cm.
D_c = characteristic dimension of inertial impactor, cm.
D_p = diameter of mist particle, cm.
E_o = impaction or collection efficiency
K = inertial parameter = $\rho_p V_o D_p^2/9\mu_g B$
m = mass, g.
n = number of 360-deg. turns swept by gas stream
R = outside radius of bend, cm.
U_t = terminal velocity of a particle relative to the gas stream, cm./sec.
V_o = velocity, cm./sec.
Z = bed depth, cm.

Greek Letters

ρ_g = density of gas stream, g./cc.
ρ_p = density of liquid mist particles, g./cc.
μ_g = absolute viscosity of gas stream, poise
θ = angle, rad.

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