Entrainment Removal By A Wire-mesh Separator

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The efficiency of a wire-mesh separator as an entrainment eliminator has been experimentally determined in an evaporator employing a sodium chloride brine to trace the entrainment throughout the system. Superficial linear velocities have been tested with efficiencies ranging from less than 80% at lower velocities up to 99.9% at 17 ft./sec. Higher superficial linear velocities were explored, but the results were erratic, with reentrainment from the separator visually evident. The experimental data have been correlated by the assumption, and development, of a proposed mechanism for the capture of the entrainment particles by the wires in the separator. This mechanism is developed from a theoretical derivation by Langmuir and Blodgett used for correlating the stoppage of mist particles by the leading edges of airplanes and has been found to correlate the experimental data very well, so that predictions in unworked ranges may be made. The separator as applied in this experimental work behaved as an impingement-type, inertial entrainment eliminator.

The use of the presently developed equations permits the recommendation of specifications to be used in the fabrication of a separator for its most efficient performance if the nature of the entrainment and conditions of operation are known.

Carryover, or carry along, of liquid particles (entrainment) in gas and vapor streams has been given much attention. Some of the recent and important studies evaluating the effect of entrainment in fractionating colunms are those of Souders and Brown (*33*); Holbrook and Baker (*16*); Rhodes (*27, 28*); Sherwood and Jenny (*32*); Colburn (*4*); Rhodes and Slachman (*29*); Ashraf, Cubbage and Huntington (*1*); and Eduljee (*6*); and to evaluate the effect of entrainment in evaporators there have been the reports of Cessna and Badger (*3*) and O'Connell and Pettyjohn (*25*).

More recently, however, methods for the removal of entrainment from gas and vapor streams has been the object of most study. These studies have involved the use of standard equipment such as the settling chamber, the cyclone separator, the centrifuge, screens, baffle plates, and their modifications. Typical of such studies are those of Pollak and Work (*26*), observing the performance of various types of cyclone separators; Campbell (*2*) the design and use of a special type of scrubber for the recovery of crude-oil mist from natural gas; Lowrie-Fairs (*23*) the use of the Calder-Fox scrubber; and Houghton and Radford (*17*) the development of a new type of streamlined eliminator for removal of fine liquid droplets containing calcium chloride remaining in the air after local dissipation of natural fog by means of a spray of calcium chloride solution.

Separators consisting of targets of fine wires or fibers upon which the droplets in a stream of entrainment-laden gas or vapors are removed by filming on the filaments, have been found to be very effective. Hammond and Leary (*15*) used a separator of loosely packed Fiberglas in successfully removing the radioactive spray from the scrubbers used in washing the radioactive dusts from the waste air discharged from a laboratory in which radioactive work was being conducted. They reported that this separator showed a pressure drop of 0.67 in. of water/2-in. thickness of packing at a velocity of 150 ft./min. and showed less than 0.05% passage of the spray. York (*35*) reviews the application of the wire-mesh separator as an entrainment eliminator.

Recently Montross (*24*) has extensively reviewed proposed and used equipment and the various mechanisms suggested for entrainment removal.

The present investigation reports the results of experimental work using a knitted-wire-mesh separator as an entrainment eleminator. The theoretical effect of projecting a small water droplet, such as might be present in naturally occurring mist or fog, at a single cylinder oriented with its axis perpendicular to the motion of the droplet approaching from a great distance has been determined by Langmuir and Blodgett (*22*) under a variety of conditions. The results of their theoretical study have been modified and applied to the more complex situation presented by a great many droplets of mixed size range continuously being projected at and reaching the intricate maze of wire comprising the separator. A newly developed equation, derived later in

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this paper, has provided a means for the understanding of the role of wires in the capture of entrainment in a mesh separator and has allowed the setting up of optimum design factors for such separators.

EXPERIMENTAL EQUIPMENT

The basic unit of the equipment is an evaporator having the capacity to vaporize and condense ½ ton of water/hr., which was built for experimental laboratory use by the Vulcan Copper and Supply Company, of Cincinnati, Ohio. The assembly is illustrated schematically in Figure 1. For this work a salt solution was evaporated to supply a vapor stream carrying naturally entrained droplets of salt water. Beginning at the bottom of Figure 1 and working up, section by section, the 30-in.-diam. evaporator consists of a conically shaped reservoir 30-in. high; an internal calandria 31½ in. high having thirty-six 1½-in. I.P.S. tubes in concentric arrangement surrounding a 10-in. downcomer; a disengaging chamber 60 in. high; a second disengaging chamber 33 in. high housing the separator in the orifice of an annular gutter; and, finally, a head connecting with the condenser through a gooseneck vapor-draw-off line.

All condensate streams after the separator are returned to the conical reservoir through a return line in which there are thermometers, conductivity cells, and a nutating disk type of hot-water meter. The amount of entrainment escaping the separator is determined by analysis of samples taken from the return line for salt content.

Entrainment ahead of the separator may be partially settled out in the space (approximately 60 in.) between the surface of the boiling liquid and the separator. Entrainment reaching the separator is determined by analyzing samples of the vapor-entrainment stream collected through a sampling tube extending across the diameter of the evaporator just below the separator. This sampling tube, ⅝ in. in diameter, has six ports through which the vapor-entrainment stream passes; the stream is withdrawn through an external condenser system in which there is a thermometer and a conductivity cell. The ports are small tubes 5/16 in. in diameter, brazed into holes in the underside of the sampling tube. Each port tube extends upward to the axis of the sampling tube so that all vapor entrainment entering the sampling tube will be drained into the external condensing system. All condensate except the negligible amount removed for analysis is returned to the evaporator; and thus the whole operation is carried out as a closed system.

Pressure drop across the separator is measured by a water manometer. Since thermometers are mounted in all vapor and liquid lines, temperatures may be noted at all points; and, since conductivity cells are located in all liquid lines, the approximate salt concentration at any point may be noted by switching the cell circuit through the meter. All vapor chambers and lines are connected to a surge drum in which the pressure is maintained by a rotary type of vacuum pump and controlled by a manostat.

Two wire-mesh separators were used in the experimental work. These were of the standard types available from the various suppliers of such separators specified as York .011R-24CU5-½ No. 8 crmip. One separator, 24½ in. in diameter and 4 in. thick, was mounted in the 24½-in. orifice produced by the annular gutter and was supported by six thin spokes to prevent sagging. A second separator, 5⅞ in. in diameter and 4 in. thick, was mounted in a housing which fitted into the 24½-in. opening and reduced the orifice through which the vapors could pass to a 5⅞-in. opening, thus correspondingly increasing the vapor velocity. The separators were made by rolling a 4-in. ribbon of knitted 0.0113-in. (287 μ)-diam. copper wire, knit to give 96 mesh by 48 needles in a tubular stocking in a knitting machine. The ribbon was flattened to a double thickness, crimped with about 0.05-in. nodes, spaced 0.2 in. apart, and rolled spirally upon itself to form a disk of uniform thickness of the desired diameter. The wire comprising the separator occupied only 2% of the space, so that there was 98% free volume.

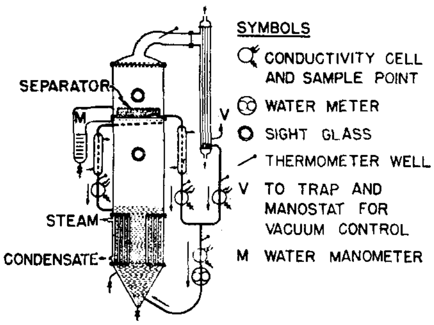

Fig. 1. Schematic flow diagram.

Bypassing of the separator was minimized by purposely fabricating the separator element slightly larger in diameter than the orifice in which it was housed. Owing to the somewhat compressible nature of the separator, intimate contact was obtained between the cylindrical face of the separator and the walls of the enclosing orifice, which completely contained the separator element.

EXPERIMENTAL PROCEDURE

Four sets of experiments were performed: a series of runs with no separator in the 24½-in. orifice, a second series with the 24½-in. separator in place, a third series with no separator in the 5⅞-in. orifice, and a fourth series with the 5⅞-in. separator in place.

In each run a solution of about 5% sodium chloride with 1,000 p.p.m. of sodium chromate as corrosion inhibitor was introduced into the evaporator and the unit was then brought on stream by rapidly introducing process steam to the calandria shell to minimize the tendency of the solution to foam. [*See* the work of O'Connell and Pettyjohn (*25*) on foaming of solutions of sodium chloride in an evaporator and that of Foulk and coworkers (*7, 14*) on their study of foaming in boilers.] Operations were then adjusted to produce a definite and continuing set of recycling conditions as indicated by the steady state of thermometer, manometer, and conductivity-cell readings. While this steady state was continued, samples were taken from the condensate line, which combined to pass to the evaporator all streams after the separator; from the condensate from the sample tube ahead of the separator; and from the boiling solution. These samples were then analyzed for sodium chloride content by the Mohr titration method for chloride ion.

Special note should be made of the method of taking samples in order that they would be representative of the conditions over the period of the run. Flasks were attached to each sampling exit by means of a rubber stopper. A side arm from each flask was attached to a tube leading to the surge drum of the vacuum system and brought to the system pressure. It was then possible to open the stopcock at each sample point and to collect drop by drop during the entire run a representative composite sample. Temperatures and pressures were read. Although the conductivity meter was calibrated, the readings of the cells were noted only to guide in keeping the run on steady conditions.

The data collected in the experimental work were used in compiling the values given in Table 1 and in expressing the experimental results graphically in Figures 2, 3, 4 and 5. Entrainment, as recorded in the tables, is defined as pounds of entrained solution from the main body of the evaporator per million pounds of solvent evaporated.

One may consider any point P after the separator and arrive at the following relation:

$$p = (M \times s)/(M + z_p) \qquad (1)$$

or, by rearranging terms,

TABLE 1.—EXPERIMENTAL DATA

Run	Vapor temp., °F	Specific vol. of sat. steam, cu. ft./lb.	Factor correcting for gas density, (31) and (34) $1/\phi_{\Delta P}$	Mass velocity in orifice lb./(hr.)(sq. ft.) Actual	Mass velocity in orifice lb./(hr.)(sq. ft.) Modified	Superficial linear vel. at flow cond., ft./sec.	Conc. of brine, wt. %	Entrainment, p. p. m. Ahead of separator	Entrainment, p. p. m. Return line	Efficiency %	Pressure drop across orifice ins. of water ft. of separator thickness
	T	v	$\sqrt{0.075v}$	G	$G/\phi_{\Delta P}$	V	s	$(\text{Ent})_Q$	$(\text{Ent})_P$	E_S‖	ΔP
1	2	3	4	5	6*	7†	8‡	9**	10¶	11	12
With 24½-in. Separator											
1	119+	208	3.95	290.9	1149	16.81	4.73	9.48×10^4	4.77×10^1	99.95	0.47
2	139.7	124.01	3.06	165.6	505	5.70	3.75	4.76×10^3	3.12×10^1	99.35	
3	168.5	64.10	2.20	173.8	381	3.09	2.77	1.62×10^3	6.75×10^1	95.84	0.71
4	198−	35.11	1.63	199.5	324	1.95	3.29	4.98×10^2	1.03×10^2	79.29	0.59
5	179.7	50.58	1.94	222.6	433	3.13	3.62	3.00×10^3	9.36×10^1	96.88	
6	181	49.20	1.92	220.3	423	3.01	4.27	9.31×10^2	5.47×10^1	94.12	0.71
7	158	80.84	2.46	208.5	513	4.68	5.59	3.76×10^3	3.98×10^1	98.94	0.71
8	153	90.57	2.60	230.7	601	5.80	5.50	4.37×10^3	4.04×10^1	99.08	0.83
9	126.5	171.91	3.59	282.1	1013	13.47	4.90	5.34×10^4	4.12×10^1	99.92	0.35
10	140	123.01	3.04	107.6	327	3.68	3.17	2.74×10^3	6.93×10^1	97.47	0.12
11	140	123.01	3.04	260.7	792	8.91	4.05	1.42×10^4	3.11×10^1	99.78	0.24
12	132	149.66	3.35	269.7	903	11.21	4.05	2.52×10^4	4.38×10^1	99.83	0.30
24½-in. Orifice without Separator											
13	110	265.4	4.46	257.6	1149	18.99	5.47	4.61×10^4	3.19×10^3	93.09	0.47
14	172.5	58.82	2.10	218.3	458	3.57	5.46	9.68×10^2	6.42×10^2	33.65	0.59
15	144	111.77	2.90	240.8	699	7.48	5.67	5.00×10^3	1.44×10^3	71.13	0.65
16	199.3	34.10	1.60	193.7	309	1.83	5.77	2.64×10^2	1.70×10^2	35.39	0.83
17	130	157.34	3.44	273.7	940	11.96	4.77	2.51×10^4	3.18×10^3	87.32	0.35
18	140	123.01	3.04	247.6	752	8.46	5.24	1.09×10^4	1.62×10^3	85.06	0.12
With 5⅞-in. Separator											
19	212−	26.80	1.42	3,166	4,500	23.6	5.92	1.46×10^3	1.78×10^1	98.78	
20	181.6	48.60	1.91	3,698	7,050	49.9	6.24	1.53×10^3	1.26×10^3	27.62	
21	170	62.06	2.16	1,686	3,640	29.1	6.29	1.26×10^3	5.39×10^1	95.72	
22	160	77.29	2.41	2,677	6,450	57.5	6.22	1.12×10^3	2.17×10^2	80.57	
23	150+	97.0	2.69	2,019	5,450	54.4	7.09	8.70×10^2	7.75×10^1	91.09	5.43
24	150−	97.2	2.70	1,804	4,880	48.7	7.09	1.01×10^3	4.62×10^1	95.41	5.67
25	130	157.34	3.43	2,922	10,000	127.7	7.33	1.32×10^4	1.43×10^3	89.14	15.35
26	146+	106.6	2.83	1,188	3,360	35.2	8.25	4.75×10^2	1.40×10^1	97.04	2.95
27	120	203.27	3.90	869	3,390	49.1	7.72	1.18×10^3	2.10×10^1	98.22	3.94
28	149−	99.4	2.73	2,717	7,420	75.0	7.54	2.13×10^3	5.93×10^2	72.21	9.09
29	130.75	154.42	3.40	2,700	9,180	115.8	7.54	5.16×10^3	6.51×10^2	87.38	13.11
30	153	90.57	2.60	2,112	5,500	53.1	2.46	1.39×10^3	1.27×10^2	90.89	4.96
31	140	123.01	3.03	1,148	3,485	39.2	3.84	1.10×10^3	3.01×10^1	97.26	3.84
32	140	123.01	3.03	1,199	3,645	41.0	3.84	9.32×10^2	3.10×10^1	96.77	1.30
33	140	123.01	3.03	1,720	5,227	58.8	3.84	1.44×10^3	5.73×10^1	96.02	6.14
34	139	126.02	3.08	2,293	7,060	80.3	4.61	1.38×10^4	4.02×10^3	70.77	9.21
35	137	132.30	3.15	2,569	8,070	94.4	4.47	8.38×10^3	1.51×10^3	81.99	11.10
36	137−	132.5	3.15	1,779	5,600	65.5	4.47	1.08×10^4	3.93×10^2	96.36	8.39
37	135	138.95	3.24	1,653	5,340	63.8	4.76	1.52×10^4	2.99×10^2	98.03	7.56
5⅞-in. Orifice without Separator											
38	120	203.27	3.91	1,939	7,580	109.5	4.76	2.54×10^4	1.51×10^4	40.75	1.42
39	130	157.34	3.44	1,649	5,670	72.1	4.66	1.03×10^4	1.88×10^2	98.17	0.94
40	124	183.25	3.71	2,700	10,000	137.4	4.66	4.82×10^3	8.54×10^2	82.28	2.16
41	139−	126.0	3.07	2,385	7,330	83.5	4.66	3.61×10^3	2.34×10^2	93.51	1.38
42	138	129.12	3.11	948	2,950	34.0	4.66	9.29×10^3	6.75×10^2	92.73	0.28
43	119	208.7	3.96	1,945	7,700	112.7	4.41	4.60×10^3	5.57×10^2	87.89	1.58

*Column 4 multiplied by Column 5.
†Product of Columns 3 and 5 divided by 3,600.
‡By Mohr's titration.
**By Mohr's titration and application of Equation (5).
¶By Mohr's tritration and application of Equation (4).
‖Application of Equation (6).

$$z_p = M\,((s/p) - 1) \qquad (2)$$

Entrainment as already defined, may be expressed as follows:

$$\text{Entrainment} = (M)/(z_p/10^6), \text{ or } (M\times10^6)/z_p \qquad (3)$$

If z_p is eliminated between Equations (2) and (3),

$$(\text{entrainment})_P = (p\times10^6)/(s-p) \qquad (4)$$

By analogy, consideration of any other point Q, just ahead of the separator, gives the expression

$$(\text{entrainment})_Q = (q\times10^6)/(s-q) \qquad (5)$$

Efficiency as recorded in the tables represents the effectiveness of removal of entrainment by the separator and is defined as the percentage of the total entrainment just ahead of the separator removed by the separator. An equation to express this definition is

$$Es = \textit{efficiency} = 100\times((\text{ent})_Q - (\text{ent})_P)/((\text{ent})_Q) \qquad (6)$$

where the subscripts Q and P represent points ahead and after the separator, respectively.

EXAMINATION AND DISCUSSION OF EXPERIMENTAL DATA

Efficiency of Separator as an Entrainment Eliminator

Figure 2, which illustrates the percentage of entrainment removed as a function of the linear velocity in feet per second for the 24½-in. separator, shows that the efficiency is very low at the lower linear velocities and increases as the velocity increases. This can be assumed to be caused by the fact that only the smaller droplets pass upward through the settling space to reach the separator at low velocities and that many of these are carried along with the vapor around the wires; but as the velocity increases even the smaller droplets will be less likely to be carried around the wires in the vapor stream lines, owing to the inertial forces overcoming the tendency of these particles to follow the path of the vapor stream lines.

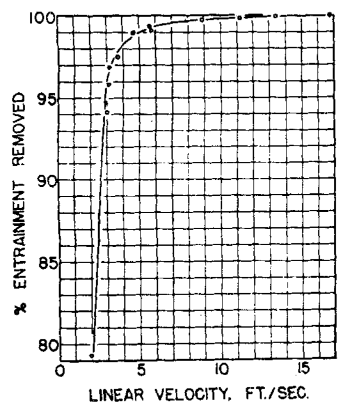

Fig. 2. Experimental efficiency of 24½-in. separator as a function of the superficial linear velocity.

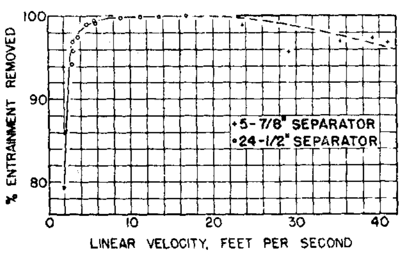

Fig. 3. Experimental efficiency of 24½- and 5⅞-in. separators as a function of the superficial linear velocity.

Then, too, the size of the droplets passing the settling space and reaching the separator will increase with increasing vapor velocity; and, since the large droplets will be less likely to be carried in the vapor stream lines, a larger proportion of them will be captured by collision with the wires. This increase in efficiency continues, reaching nearly 100% between linear velocities of 10 to 20 ft./sec. Above these velocities it was visually observed that free drainage of the separator, under the influence of gravity, is impeded by the rising vapors, and the separator begins to give evidence of liquid buildup or overload on its component wires. At sufficiently high velocities the effect of gravity and surface tension is overcome by the pressure of the rising vapors; and, at least some of the liquid film enveloping the wires comprising the separator and representing entrainment captured by the separator is swept upward to the top layer of the separator and there, when presenting a sufficiently large surface area to the rising vapors, is torn from the wires on the top surface and carried downstream from the separator as reentrainment. Thus reentrainment may be defined as entrainment that, initally removed by the separator, eventually escapes by being torn from the elements or wires of the separator in contrast to entrainment escaping the separator by virtue of its failure to make physical contact with any of these elements or wires of the separator.

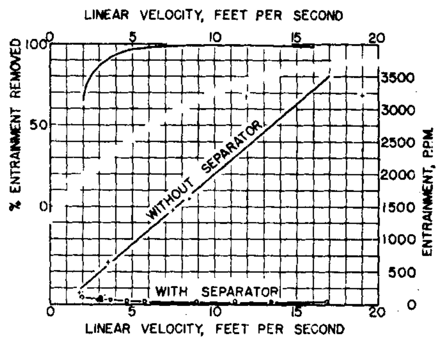

Fig. 4. Entrainment in return line after 24½-in. orifice with and without separator and calculated experimental efficiency, all as a function of the superficial linear velocity.

Reentrainment is clearly indicated in Figure 3 by the extrapolation of the line representing the performance of the 24½-in. separator through the area and into that which represents the performance of the 5⅞-in. separator. It is evident that there is a limited range of vapor velocities where the separator acts with high efficiency. It might be desirable in commercial practice to control the velocity through the separator with changing operating throughputs by partially closing the section weir of the separator with a shield to reduce its cross-sectional area and thus to increase the velocity to an optimum condition. Low separator efficiencies at the lower velocities are due largely to entrainment particles moving with the vapor stream around the wires in the separator, whereas at the higher velocities they are due to liquid build-up or overload on the wires, resulting in reentrainment. The reentrainment as shown by the experimental data was easily confirmed by the visual evidence obtained by looking through the sight glasses.

Figure 4 expresses, as a function of vapor velocity, the amounts of entrainment in the return line with and without the 24½-in. separator. The efficiency of the separator is also expressed in terms of percentage of entrainment removed as a function of the linear velocity. The efficiency of the separator at any velocity is determined by measurement of the difference in entrainment in the return line, as shown by the two lines illustrating the performance with and without the separator at that velocity divided by the entrainment without the separator at the sam velocity. The data thus obtained at several

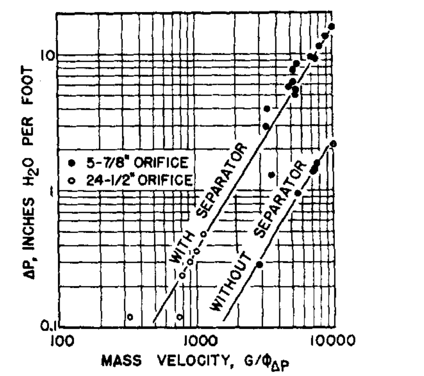

Fig. 5. Pressure drop as a function of mass velocity modified for vapor density.

velocities were then plotted with the result as shown in the curve above the two lines. This curve shows that the efficiency of the separator determined in this manner is in very good agreement with the efficiency given in Figure 2, as determined by Equation (6).

Photographic Examination of the Entrainment

Dappert(5) made a photographic study of the size and distribution of the entrainment particles in some of the runs. His photographs showed that sizes of the particles before the separator varied widely and that the reentrained particles above the separator were large. The formation and growth of the reentrained particles could be seen as they collected on the top side of the separator and finally as they were torn off and projected upward into the vapor stream.

Pressure Drop

The upper line in Figure 5 represents the pressure drop in inches of water per foot of separator thickness; and the lower line shows the pressure drop between the same two points without the separator in place as a function of the mass velocity, as corrected for vapor density (*31, 34*). The actual pressure drop due to the separator at any selected velocity can be directly determined by noting the difference between the two lines at that velocity. The pressure drop caused by the separator is small and varies from about 0.1 to 13 in. of water/ft. of separator thickness as the corrected mass velocity varies from 400 to 10,000 lb. of vapor/(hr.)(sq.ft.). At the higher pressure drops shown in Figure 5 the separator was reentraining severely. However, when no visual reentrainment was observed at corrected mass velocities of 1,000 or less, the pressure drop was found to be less than 0.5 in. of water/ft. of thickness of separator. It should be noted that the pressure-drop curve is continuous, without a break, an indication that under the conditions of operation there was no tendency for the separator to "flood," in the sense of a packed column, even when reentrainment was severe.

MECHANISM OF THE CAPTURE OF ENTRAINMENT BY THE SEPARATOR

The geometry of a knitted-wire-mesh separator is very complex compared with that of a single unbent component wire. However, there is a certain degree of regularity in a knitted-wire-mesh separator resulting from the uniform and more or less parallel spacing of wires by means of equally spaced knitting needles used in the fabrication of the tubular stocking described earlier. Furthermore, the crimping also gives a regularity, if not a parallelity, to the spatial arrangement. Incidentally, others [Lapple (*21*) and Houghton and Radford (*17*)] say that the efficiency of a multiplicity of targets (wires) may be a derived function of the efficiency of single target (wire).

Langmuir and Blodgett (*22*) in their study for the Air Technical Service Command of the Army Air Forces were concerned with the formation of ice on the leading edge of the wing of an airplane; and since these leading edges are cylindrical (24 in. or more in diameter) they considered the effect of projecting water droplets at a cylinder oriented with its axis perpendicular to the motion of the droplet approaching from a great distance. With the aid of the General Electric differential analyzer, the trajectories of such droplets were traced as they approached the cylinder, and their deflection around or removal by filming on the cylinder was determined. This concept of the mechanism of the capture of a particle by a cylindrical surface of comparatively tremendous size has been considered with the necessary modifications which have been developed relating to a maze of very small cylindrical surfaces in the interpretation of the present experimental data.

The evaluation of the maximum total efficiency of deposition of particles on a cylinder was in terms of the ratio of the droplets impinging under the conditions of operation to the droplets that would impinge if the drops were to travel in straight lines without deflection by the vapor stream lines around the cylinder. This maximum total efficiency of deposition of particles, E_M, is dependent upon the vapor velocity, drop velocity, vapor viscosity, vapor density, drop density, drop radius, and cylinder radius.

It was thus desired to find whether the fundamental work of Langmuir and Blodgett on single cylindrical surfaces as targets is applicable to the performance of a separator of very small cylindrical surfaces as targets in layers and groups of layers.

The knitted-wire-mesh separator may be considered to consist of a number of more or less parallel layers of wire formed by interlocked wire loops. When a knitted-wire-mesh stocking is flattened to form a ribbon and this ribbon of double thickness is then crimped and rolled spirally upon itself to form such a separator, a considerable amount of the total wire in the separator opposes the passage of entrainment through the separator, even though only about 2% of the total volume is occupied by wire; and the space between the wires is very large compared with the size of the entrainment particles. The remaining wire in the separator, which is not particularly effective in opposing the passage of entrainment, acts as the spacer elements maintaining the layers of wire opposing the passage of entrainment a uniform distance apart. It is possible to vary the distances between layers during fabrication of a separator. By nature of the knitting process the average distance between layers in the separator used was about 0.1 in. although the actual distances between layers were alternately about 0.05, 0.15, 0.05, 0.15, etc., in., respectively. For the purpose of this analysis it has been assumed that the alternately close and wide separations between layers, averaging about 0.1 in., are relatively large by comparison with the diameters of the entrainment particles passing into the interior of the separator or through the separator without capture, so that the entrainment progressively redistributes itself uniformly among the layers of wire during its carry through the separator by the vapor itself.

Since the wires in the separator are cylindrical, it is possible to set up an expression including the conditions of the experiment and the maximum total efficiency of deposition, E_M, as previously determined for a single cylinder. From this expression the efficiency of the separator can be predicted for the conditions of (*a*) uniform particle size, (*b*) no reentrainment, (*c*) no build-up of liquid in the separator during the experiment, and (*d*) uniform redistribution of particles between layers. (These will be called hereinafter the four basic conditions.) The basis of such an expression is the assumption that each layer in the separator has the same entrainment-removal efficiency. Then the fraction of entrainment escaping a single layer may be expressed as

$$(1 - E_M/c) \qquad (7)$$

where E_M = maximum total efficiency of deposition of particles for a single filament of the separator, fraction recovered, for conditions of operation and c = modifying characteristics of the separator.

Since it has been assumed that each layer in the separator has the same entrainment removal efficiency, it follows that the fraction of entrainment escaping the separator is equal to the fraction of entrainment escaping a single layer raised to a power equivalent to the number of parallel layers in the separator:

$$(1-E_S') = (1-E_M/c)^N \text{ or } E_S' = 1 - (1-E_M/c)^N \qquad (8)^*$$

where c, the modifying characteristic of the separator, is a function of the effective area of the separator in each layer and is expressed as the fraction of the total flow cross section obstructed by wire in a single layer:

$$c = N/kF \qquad (9)$$

The modifying characteristic of the separator, c, used in this research has been evaluated from its physical properties as follows:

N = forty-eight layers in separator perpendicular to flow

F = 0.67, the fraction of the total wire in an effective position as evaluated by inspection of the separator and measurement of the length of wire in the separator perpendicular to and parallel to the superficial flow through the separator

k = 10.601 is evaluated by combining the cross-sectional area of the 24½-in. orifice of 3.2739 sq. ft. with the 0.0113-in. (9.4167×10^{-4} ft.).-diam. wire and the estimated wire length of 36,856 ft. (0.0113-in.-diam. copper wire of 556.88 lb./cu.ft. density weighing a total of 14.3 lb.) to give

$$k = \frac{36{,}856 \times 9.4167 \times 10^{-4/3}}{3.2739} = 10.601$$

then

$$c = 48/(10.601 \times 0.67) = 6.748$$

from substitution in Equation (9).

Equation (8) may be used to predict theoretically the efficiency of a separator when N, c, and E_M are known and the four basic conditions hold. It will be noted that Equation (8) predicts a straight-line correlation for a logarithmic plot of entrainment escaping a single layer of the separator vs. the entrainment escaping the entire separator. The slope of such a plot represents the number of layers in the blanket.

N and c depend upon the physical configuration of the blanket. E_M is evaluated by the wire radius, particle radius, and conditions of operation. Langmuir and Blodgett prepared tables of K, ϕ, and E_M and plotted K vs. E_M, with ϕ as the other parameter, for single cylinders (Figure 6), where

$$K = 2d_l\, Ua^2/9\eta C \qquad (10)$$

$$\varphi = 18\,(d_v)^2\, CU/\eta\, d_l \qquad (11)$$

are dimensionless ratios in which

a = radius of liquid drop, cm.

C = radius of cylinder (wire), cm.

d_l = density of liquid drop, g./cc.

d_v = density of vapor, g./cc.

η = viscosity of vapor, poises, g./cm.sec.

U = vapor velocity, cm./sec.

The theoretical efficiencies of the separator have been calculated by means of Equations (8), (9), (10), and (11) for the four basic operating conditions with 6-, 7-, and 8-μ-diam. particles, and these theoretical efficiencies have been tabulated in Table 2*, together with the experimentally determined efficiencies. These efficiencies are graphically represented in Figure 7 as a function of the linear velocities. Examination of the lines shows them to be smooth curves and demonstrates that the efficiency of the separator should increase in all cases with increase in velocity until 100% is reached.

COMPARISON OF THEORETICAL WITH EXPERIMENTALLY DETERMINED EFFICIENCY OF THE SEPARATOR

The experimentally determined efficiencies plotted against linear vapor velocities are represented in Figure 7 by small circles; a smooth line is drawn through them.

Examination of the theoretical curves in Figure 7 shows a wide divergence in efficiencies for particles of 6-. 7-, and 8-μ-diam. at low vapor velocities, but at higher vapor velocities the curves or efficiencies all merge and closely agree, irrespective of size in this range. It is also to be noted that the separator operates better for larger than for smaller particles at low vapor velocities. Comparison of the experimental curve with the theoretical curves indicates that the entrainment encountered in the experiments at low vapor velocities is made up of particles of small diameters; but as the vapor velocity increases, the average diameter of particles reaching the separator increases—finally indicating an average of more than 8 μ.

Examination of the experimental curve shows that the efficiency of the separator for removal of particles of many sizes increases as the vapor velocity increases, which is in agreement with the theoretical curves for a single particle size. The particles reaching the actual separator constantly increase in size as the vapor velocity increases, because at lower velocities the large particles settle out below the entrainment separator. This accounts for the steep slope of the curve at the low vapor velocities where not only the velocity but the size of particles is an important factor in influencing the efficiency of the separator.

Study of the curves, both theoretical and experimental, suggests that particle size is the main influence in determining the efficiency of any particular separator at low vapor velocities, while vapor velocity has a much greater influence in determining the efficiency of the separator at the higher vapor velocities. When, however, the theoretically or the experimentally determined efficiency approaches 100%, there seems to be little change in the efficiency either by change in size of particles or in vapor velocity; i.e., the spread between curves of different particle size is not great and the curves are quite flat near 100%. This high efficiency continues with increase in velocity until the separator becomes overloaded and reentrainment in significant amount takes place.

The experimental evidence is in agreement with the theoretical prediction based on the mechanism of capture of particles by a single cylinder and adapted to the performance of the complex, multiwire maze comprising the knitted-wire-mesh separator. This evidence supports the assumption that the wires of the separator furnish targets with which the particles must collide in order to be captured as a result of the envelopment of the separator wires with a thin liquid film which may then be drained free from the separator and recovered. The separator as used in this experimental work behaved as an impingement-type, inertial entrainment eliminator.

An interesting application of this type of entrainment elimination is illustrated by the work of Hough-

This equation is in agreement with an expression given by Houghton and Radford(17)*.

ton and Radford in the design of their streamlined unit with staggered arrangement of the targets for removal of large particles, average 40 μ and some as large as 60 μ.

Another recent application of the staggering principle is the use of the random arrangement of small fibers of a glass-wool separator for removal of the very fine mists which fail to be trapped by other eliminators [cf. the report by Hammond and Leary (*15*)]. These glass-wool separators, like the knitted-wire-mesh separators, cause very little pressure drop. Rodebush (*30*) in speaking of filters for aerosol particles points out that when the mesh consists of "loosely aggregated fibers, and to avoid excessive resistance to the flow of air, the mesh of the filter must be large compared to the size of the particle to be removed" and that "the particles most difficult to remove by filtration are those in the range of 0.1 to 1 μ. . . . In order to obtain efficient filtration without excessive resistance the filter must contain

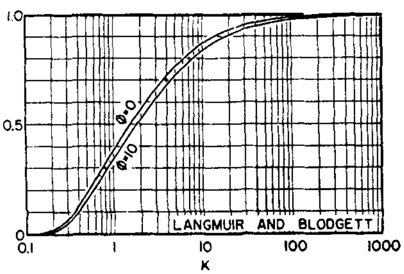

Fig. 6. Efficiency of deposition on cylinders, E_M, with ideal fluid flow (*22*).
$K = 2d_lUa^2/9\eta C$ and $\phi = 18(d_v)^2 CU/\eta d_l$

fibers of small diameter approaching that of the particles themselves."

THEORETICAL DETERMINATION OF THE INFLUENCE OF THE EFFICIENCY OF THE SEPARATOR BY DECREASE IN WIRE DIAMETER

The evidence already presented has emphasized how vapor velocity and particle size affects the efficiency of the separator as an entrainment eliminator when the four basic conditions hold. Examination of the equations used in developing the theory of the mechanism by which particles are captured shows that there may be made mechanical modifications of the separator which would improve its efficiency. Examination of the previously used equations

$$K = 2d_l\,Ua^2/9\eta C \qquad (10)$$

$$\phi = 18\,(d_v)^2\,CU/\eta d_l \qquad (11)$$

shows that any change in C, the radius of the wire, would directly change the values of both K and ϕ. For illustration, if C is divided by 2, K is doubled and ϕ is halved.

As an example, the effect on K may be considered when the diameter is divided by 2 and the length of the wire is multiplied by 2 in order to keep the target area constant. If $K = 1$ and 2, respectively, the effect upon E_M, the maximum total efficiency of deposition, for a single cylinder can be determined by reference to Figure 6 for any given value of the parameter (ϕ).

It will be noted that a change in K produces a marked change in E_M over a wide range of values for K. For the parameter $\phi = 0$ when $K = 1$, $E_M = 0.386$, and when $K = 2$, $E_M = 0.565$, there is an increase in target efficiency of 46.4%. If the values are substituted in Equation (8),

$$E_S' = 1 - (1 - (E_M/c))^N \quad (8)$$

the expression developed to give the theoretical efficiency of the separator where c is the modifying characteristic of the separator and has been calculated as 6.748 for the separator used in this research $E'_S = 0.9408$ for $K = 1$ and $E'_S = 0.9850$ for $K = 2$ for forty-eight target layers ($N = 48$). This represents an increase in the separator efficiency of 4.7%. Inspection of Figure 6 shows a similar effect if the parameter (ϕ) selected is 10. The parameter (ϕ) for the separator is about 0.0888, the average of column 7, Table 2.*

Interpreting these values for E'_S by reference to the curves in Figure 7 shows that for the 8-μ curve an increase in efficiency from 94.08 to 98.50% would be obtained by changing the vapor velocity from 1.8 to 3.2 ft./sec., for the 7-μ curve from 2.2 to 4.0 ft./sec., for the 6-μ curve from 2.9 to 5.4 ft./sec., and for the experimental curve from 2.8 to 4.4 ft./sec.

If the same total projected area of target is maintained, there are other consequences resulting from decreasing the wire diameter with a corresponding increase in wire length or from increasing the frequency of wires:

1. In the case just considered there would be twice as many target wires in each layer; and although the total target area of the wire and the interstices for the passage of vapor remains constant, each interstice would be just half as wide as the original.

2. Since the wire is one half the original diameter and only twice as long, the total volume occupied by the wire is only one half that of the volume of the original wire and therefore requires only one half the weight of metal.

3. Since the wire is one half the diameter, the distance between the layers is slightly increased, and the total free space in the blanket would be increased from 98 to 99%.

In general, to decrease the diameter of the target wire n times and multiply its length n times, while maintaining the same total projected area of target, would increase the number of targets in each layer n times and reduce the weight of metal required to $(1/n)$th of the original conditions.

Possibility of such an improvement in the theoretical efficiency of the separator by changing the diameter of the wire depends upon the physical properties of the wire which would permit the drawing of the wire to a smaller diameter and its fabrication in a knitting machine. Separators made of stainless steel wire of much smaller diameter than was used in these experiments have been successfully fabricated and used.

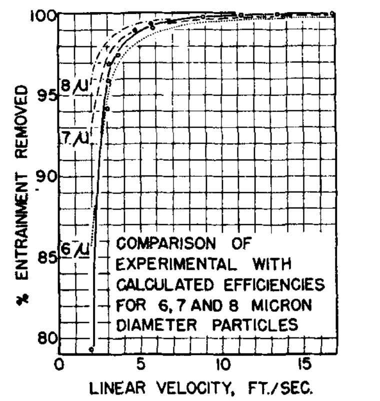

Fig. 7. Theoretical efficiency without reentrainment of 24½-in. separator as a function of the superficial linear velocity for 6-, 7-, and 8-μ diameter particles as compared with the experimental results.

THEORETICAL DETERMINATION OF THE INFLUENCE OF THE THICKNESS OF THE SEPARATOR ON ITS EFFICIENCY

Since the theoretical efficiency of the separator, based on the assumptions above, can be calculated

$$E_S' = 1 - (1 - (E_M/c))^N \quad (8)$$

from the expression where N is the number of target layers in the

*Available as document 4733 from the Photoduplication Service, American Documentation Institute, Library of Congress, Washington 25, D. C., for $1.25 for microfilm or photoprints.

separator, the expression can be solved for separators having any chosen number of target layers by substituting for N any number desired. For example, it is possible to predict the efficiency of a wire-mesh separator for three, six, twelve, twenty-four, forty-eight, and ninety-six target layers, separator thicknesses of ¼, ½, 1, 2, 4 and 8 in., respectively, for any size of particles when the four basic conditions hold. The total projected area of wire in the separator opposing the passage of entrainment is directly proportional to the number of target layers or thickness of the separator.

E_M and E'_S have already been calculated for particles of 8-μ diam. as recorded in columns 10 and 13 of Table 2*; c is a constant, and $1/c = 0.14819$ for the separator used in these experiments. The theoretical efficiency, E'_S, of separators with three, six, twelve, twenty-four, forty-eight, and ninety-six target layers as eliminators for particles 8 μ in diameter for the conditions of each of the runs have been calculated and recorded in Table 3*; and E'_S is plotted for each thickness of separator against linear velocity in Figure 8.

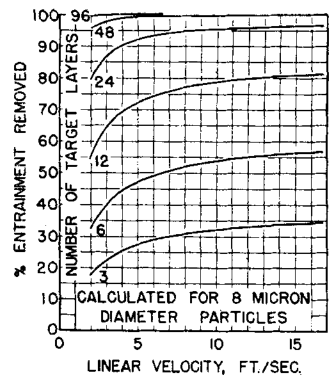

Fig. 8. Theoretical effect of number of target layers on efficiency without reentrainment of 24½-in. separator as a function of the superficial linear velocity for 8-μ diameter particles.

Examination of the curves in Figure 8 shows the effect of the number of target layers or separator thickness, or, therefore, the total projected area of the wires opposing the passage of entrainment through the separator, on the efficiency of the separator for particles having a diameter of 8 μ. The separator used in the experimental work had forty-eight target layers, and it is seen from Figure 8 that except at velocities below 4 or 5 ft./sec. there would be little advantage to be gained in doubling the number of target layers to ninety-six. It is also seen that high efficiencies could not be expected with fewer than twenty-four target layers.

*See footnote on page 555.

DESIGN FACTORS OF A KNITTED-WIRE-MESH SEPARATOR

In order best to recommend the fabrication of a knitted-wire-mesh separator of the type used in the present experimental work, as much as possible should be known about the size of the particles and the vapor velocities carrying the entrainment to be removed. For example, reference to Figure 8 shows that a forty-eight-target-layer separator has an efficiency of about 95.5% at a linear velocity of 2 ft./sec. for conditions of operation used in the experimental work. The same figure indicates that an efficiency of about 99.8% could be realized under the same conditions of operation if the number of target layers were to be doubled to ninety-six, thus requiring double the weight of metal and thereby providing twice the total projected area of wire opposing the passage of entrainment as in the forty-eight-layer separator. However, if a forty-eight-layer separator having double the length of wire of one half the diameter, were used, so that the same total projected area of the forty-eight-target-layer separator used in the experimental work might be maintained, it is calculated that an efficiency of 98.8% would be realized.

Thus almost the same improvement in efficiency may be obtained by reducing the diameter of the wire to one half and simultaneously doubling its length as can be obtained by doubling the thickness of the separator. It would therefore require four times as much wire, by weight, to fabricate the ninety-six-layer separator as to fabricate the forty-eight-layer separator from a wire one half the diameter of the wire used in the ninety-six-target-layer separator. The percentage of efficiency improvement is about the same in either case (3.5 vs. 4.5%) although doubling the separator thickness is somewhat more effective.

In general, the greatest improvement which may be made with a separator having a given total projected area of the component wires would be to reduce the diameter of the wire as much as possible and increase the vapor velocity as long as inertial effects rather than diffusional effects are controlling. The reduction in the wire diameter would be the most effective improvement for capture of small particles, but the physical properties of the material used in making the wire and fabricating it in a machine will control the extent to which a reduction in wire diameter becomes possible or practical. The particle-size range where diffusional and inertial effects are in transition is a function of the system. In the steam-brine system employed under the conditions of operation in this study it is theoretically indicated that the threshold where diffusional forces take over is in the range of particle diameters less than 1 to 3 μ. In the air-water system the threshold range would be for particle diameters somewhat larger owing primarily to the greater viscosity of air than of steam.

CONCLUSIONS

The results showed that the wire-mesh separator used in these experiments was a poor eliminator of the entrainment carried in the vapor stream above a boiling solution in an evaporator at low vapor velocities, but its effectiveness increased very rapidly as the vapor velocity increased. At linear velocities of 2, 9, and 17 ft./sec., 79, 99.8, and 99.9%, respectively, was removed. This high efficiency continued until the velocities approached 20 ft./sec. It was in this area that the separator became overloaded and reentrainment took place.

There was developed an equation

$$E_S = 1 - (1 - (E_M/c))^N \quad (8)$$

which correlated very well the actual experimental performance of the separator used for the capture of entrainment particles of mixed size in a vapor stream. The assumptions were (a) uniform particle size, (b) no reentrainment, (c) no modifying build up of liquid, and (d) constant entrainment-removal efficiency in each layer of the separator by virtue of uniform redistribution of particles after passage through each layer. This redistribution assumption is reasonable since the distances between layers in the separator were relatively large compared with the diameters of the particles not removed in the first layer of the separator which passed into the interior of the separator before capture or through the separator without capture.

The efficiency of the separator as predicted by Equation (8) agreed very favorably with the experimentally determined performance. It is therefore possible to predict the area wherein 100% removal is approached for this type of separator with the aid of Equation (8) and to recommend specifications for the fabrication of a separator for the most effective performance when the nature of the entrainment and the conditions of operation are known.

ACKNOWLEDGMENT

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NOTATION

a = radius of liquid drop, cm.
c = modifying characteristic of separator, defined by Equation (9), the fraction of the total flow cross section obstructed by wire in a single layer
C = radius of cylinder (wire), cm.
d_l = density of liquid drop, g./cc.
d_v = density of vapor, g./cc.
E_M = maximum total efficiency of deposition of particles for a single filament of the separator, fraction recovered, for conditions of operation
E'_S = theoretical efficiency of separator, fraction recovered, for the four basic conditions of operation, defined by Equation (8)
E_S = experimental efficiency of separator, defined by Equation (6)
F = fraction of total separator wire in effective position
G = mass velocity in orifice, lb./(hr.) (sq.ft.)
k = dimensionless ratio; product of diameter and length of wire in N layers of the separator divided by the area occupied by the separator perpendicular to the flow—used in evaluating c, the modifying characteristic of the separator
K = dimensionless ratio due to Langmuir and Blodgett (*22*), defined by Equation (10)
M = pounds of main body of evaporating liquid reaching point P as entrainment
n = an arbitrary number
N = number of layers in the separator perpendicular to the flow through the packing.
p = concentration of sodium chloride present in the entrained liquid together with the vapor associated with the entrained liquid at any point P after the separator in pounds sodium chloride per pound of vapor plus entrainment. (When vapor is condensed this becomes pounds sodium chloride per pound of solution.)
P = any point after the separator, i.e., evaporator recycle stream
q = concentration of sodium chloride present in the entrained liquid together with the vapor associated with the entrained liquid at any point Q just ahead of the separator in pounds sodium chloride per pound of vapor plus entrainment. (When vapor is condensed this becomes pounds sodium chloride per pound of solution)
Q = any point ahead of the separator, i.e., just preceding separator
s = concentration of sodium chloride in main body of evaporator in pounds sodium chloride per pound of solution
U = vapor velocity, cm./sec.
v = specific volume of saturated steam, cu.ft./lb.
V = superficial linear velocity at flow conditions, ft./sec.
z_p = pounds solvent reaching point P as vapor

Greek Letters

η = viscosity of vapor, poises (g./cm.sec.)
ϕ = dimensionless ratio due to Langmuir and Boldgett (*22*), defined by Equation (11)
$\phi\Delta_P = (0.075v)^{-\frac{1}{2}}$ factor correcting for gas density for pressure-drop correlation
μ = micron, 1 micron = 10^{-6} meter

Subscripts

P = after separator
Q = before separator

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