Performance of Packed Columns:

Part VIII. Liquid Flow Patterns and Velocities in Packed Beds

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To develop a basis for a better understanding of the behavior of the liquid phase in packed columns, liquid velocities and flow patterns were studied at several typical points in a column packed with 1.0-in. porcelain Raschig rings with a high-speed photographic technique. Liquid velocities were found to fluctuate rapidly with time. Laminar flow predominates, but mixing occurs at junctions between pieces of packing. A complex model is required to describe the behavior of the liquid phase in packed columns.

A very simple model of a packed column was presented in the previous paper of this series (6) to account for the large observed differences between gas phase mass transfer coefficients obtained by vaporization and absorption techniques. This model assumed that the total liquid holdup h_t was made up of two parts, the stagnant pockets corresponding to the static holdup h_s and the liquid which moves rapidly over the packing surface corresponding to the operating holdup h_o. A good and very simple correlation of the experimental data was then obtained by assuming that vaporization can take place from the total surface area, which is proportional to h_t, and that absorption can take place only on the surface area of the operating holdup h_o, because the stagnant pockets become saturated and ineffective. This can be expressed quantitatively as

$$\frac{(k_g a)_{\text{vap}}}{(k_g a)_{\text{abs}}} = \frac{a_{\text{vap}}}{a_{\text{abs}}} = \frac{h_t}{h_o} \qquad (1)$$

Although this correlation and model are adequate for the prediction of mass transfer coefficients for physical absorption and vaporization, they leave much to be desired in studying absorption accompanied by chemical reaction. The concept of completely stagnant pockets does not agree with earlier observations of the behavior of dye solutions reported in this series (7). Motion picture studies of the transfer of dye solutions in and out of pockets indicated that the most stagnant of the pockets turned over completely every 5 to 10 min.

Most investigators of the problems of absorption with chemical reaction have dealt with the liquid phase mass transfer coefficient rather than the gas phase coefficient, and particularly with systems where the absence of the chemical reactant would have resulted in a liquid phase mass transfer controlling system. These systems (such as the absorption of carbon dioxide) are of commercial importance. In addition it had been assumed that for systems where the gas phase mass transfer rate was controlling, there was little to be gained by adding a reactant to the liquid to remove the relatively small liquid phase resistance. The error in this assumption was shown earlier in this series (7) and by the work of Fellinger (2) on ammonia absorption in sulfuric acid and by Secor (5) who absorbed ammonia in boric acid solutions. These observations indicated the gas phase mass transfer coefficients even for normally gas phase controlling systems could be improved up to several hundred percent by the use of a reactant in the liquid phase.

This improvement can be accounted for qualitatively in terms of the turnover in static holdup pockets. As the liquid phase reactant becomes more concentrated, the normal turnover makes the pockets more effective and at high enough concentrations the mass transfer coefficients should approach those equivalent to the high values for vaporization. This prediction is borne out by the experimental data.

Other experimental observations pertaining to the transient behavior of packed columns and the decrease of the gas phase coefficient as the ammonia concentration in the gas phase increases, for absorption in boric acid solutions, as noted by Secor (5) indicate that a quantitative study of these phenomena requires a model based on the actual velocities and flow patterns of the liquid in a packed column.

The present work is an attempt to study the liquid velocities and flow patterns at several typical points in a packed column. It is hoped that observations of this sort can provide the basis for devising mathematical models which will be useful for predicting mass transfer coefficients for absorption accompanied by chemical reaction.

APPARATUS AND PROCEDURE

A variety of methods for measuring liquid phase point velocities and obtaining liquid flow patterns were tested before the methods used were selected. The best method found for measuring the liquid velocity at a point in a packed column involved the use of high-speed motion pictures of very fine particles suspended in water. The technique used consisted of averaging the instantaneous velocities of about fifty particles in one small area to obtain the average point velocity.

The liquid flow patterns which are discussed in a later section come from slow-speed observations of the motion of the particles and also observations of the flow of dye streams introduced into clear water flowing over the packing surface.

The objectives of the study included the measurement of point velocities, observations to determine if the flow was laminar or turbulent, and observations to note the presence and magnitude of eddies which cause local mixing. Typical regions chosen for study include straight film flow over the outside surface of a ring, a junction of several pieces of packing, and several puddles or pockets on the inner surfaces of rings. In all cases the packing photographed had flow patterns established by the presence of at least several inches of packing above the sections observed. The apparatus shown in Figure 1 consists of a well-stirred tank which feeds a particle-water suspension through regulating valves and rotameters through a distributor into a 4-in. diameter column. The suspended particles were ground charcoal which passed through a 200-mesh screen. The column walls are made of open mesh chicken wire to provide a direct,

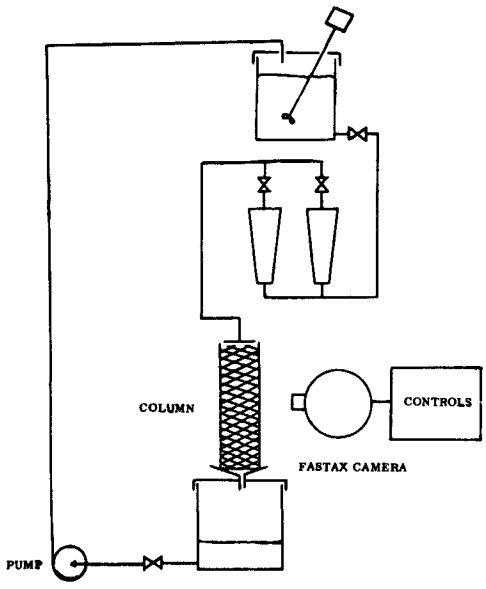

Fig. 1. Schematic diagram of apparatus.

clear view of the 1.0 in. white porcelain Raschig ring packing. The distributor was designed and tested to assure uniform fluid distribution, and the column was aligned vertically by using a level. The fluid draining from the column is collected in a tank and recirculated by means of a pump.

The photographic equipment consists of a Wollensak Fastax K high-speed movie camera capable of taking pictures at rates of from 1,000 to 16,000 frames/sec. The camera could be run from an a.c. power source through a variable transformer or a Wollensak "Goose" control unit. The camera was supplied with an oscillator to put timing marks on the film. The camera was used with extension tubes to take close-up pictures of the packing. Several photoflood lamps were used to provide adequate illumination.

A Vanguard motion analyzer is used to display the films. An important characteristic of this analyzer was the frame advance mechanism which brought each frame to exactly the same position as the preceding frame. In other words, a fixed mark on the object photographed came to the same position on the screen for each frame. By taping tracing paper over the screen, the film could be advanced a given number of frames while the particle paths were traced. The particle paths could be scaled to actual size by comparison with the image of a mark of known length inscribed on a piece of packing in the field of view. The number of frames between timing marks on the film edge multiplied by the oscillator frequency gives the film speed in frames per second. The real particle path length in centimeters multiplied by the film speed in frames per second divided by the number of frames over which the tracing was taken gives the instantaneous particle velocity in centimeters per second. Four to six frames are used for each tracing. Since the 100-ft. roll of 16-mm. photographic film contained approximately 8,000 frames and took about 10 sec. to run through the camera (at the lowest speed used for the liquid pockets), each set of velocities was obtained over about one hundredth of a second. On the liquid film sections faster camera speeds were used so the velocities were obtained over about one thousandth of a second. The velocities may therefore be considered to be relatively instantaneous and not time averages.

Since a plot of the velocities on probability paper could be approximated by a straight line, this method of plotting was used for finding the average velocity at any time. The velocities were ranked in increasing order of magnitude vs. cumulative percent frequency. Fifty was found to be a convenient number of particles to be traced for each average point-velocity determination. The average velocity is then the intersection of the best straight line drawn through the data points with the 50% line. A simple arithmetic average of the fifty velocities gave results which were just about identical to those of the plotting method.

For the dye motion pictures, dye was injected onto and into the water film by gravity flow from a reservoir through a hypodermic needle while the column was in operation.

Details of the equipment, calculation procedures, and data obtained are available elsewhere (*4*).

EXPERIMENTAL RESULTS AND DISCUSSION

High-speed motion picture observations of the motion of suspensions of particles flowing over the packing surface at many points in the column made it obvious that there was an extremely large number of different flow patterns that could be observed. There is no simple scheme for the classification and measurement of the frequency of the patterns. Instead, four different areas in the packing were chosen for detailed observation as representative of the important different types of behavior which could be subjected to velocity measurements. The areas in the packing are shown schematically in Figures 2*A*, 2*B*, 2*C* and 2*D* with several typical particle paths drawn in for each area. The straight line in each area is an inscribed line of known length which served as a reference mark for the particle path length measurements made over known periods of time.

Flow Patterns

Figure 2*A* shows water flow over a relatively flat section of the ring. The particles travel in rather straight smooth lines, and there is no visual evidence of turbulence or eddies. This type of area is representative of a good fraction of the outer wetted surface area of the rings. Dye streams injected into such liquid areas, which will be designated as in film flow hereafter, indicate no appreciable mixing until the liquid leaves the piece of packing under observation. Average velocities are high, in the neighborhood of 40 to 90 cm./sec.

Figure 2*B* represents a semistagnant pool on the inside surface of a ring which shows little motion or a slow rotating type of motion until it is disturbed by a free falling droplet of liquid or by contact with a meandering stream of liquid from an adjacent piece of packing. The disturbance may cause a temporary increase or decrease in the rotating motion usually accompanied by an increase in volume of the pool which is then followed by partial drainage and a return to the original semistagnant condition. Average velocities are low, in the neighborhood of 1 to 4 cm./sec.

Figure 2*C* illustrates the flow of liquid through the interior of an inclined ring. In some cases, such as the one sketched, the pocket of fluid shows two distinctive types of motion. A large part of the fluid passes straight on through in film flow, while a portion of the pocket rotates rapidly as a circulating pool. Average velocities in both sections of the pocket are similar and moderate, in the neighborhood 20 to 50 cm./sec.

Figure 2*D* shows a junction of three rings and is a good example of an area where much mixing takes place. The entire flow pattern changes rapidly with time at the junction, and portions of the liquid exhibit flow patterns similar to the three patterns previously described at different times and in different places. Visual observation frequently shows particles moving in opposite directions or at large

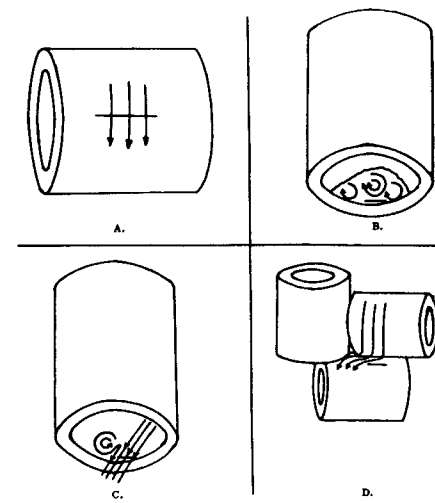

Fig. 2. *A.* Film flow. *B.* A semistagnant pool. *C.* A divided pocket illustrating film flow and a circulating pool. *D.* A ring junction.

TABLE 1. AVERAGE VELOCITY AS A FUNCTION OF LIQUID FLOW RATE

L, lb./(hr.)(sq. ft.)	Average velocity, cm./sec.
2,100	28
2,830	32
2,830	38
3,300	47
4,500	43
4,700	25
6,000	61
7,900	63

angles relative to each other at different depths of the liquid at the same time. The liquid at the different depths seems to be moving in distinct layers. The average velocities at different points vary with time rapidly and cover the entire range of velocities observed, that is, 0 to 100 cm./sec. Dye solutions injected into the upper film flow area indicate thorough mixing at these junctions.

Liquid Velocities

Quantitative average velocity measurements were made in a small area in the neighborhood of the marks inscribed on the surface of the rings. About fifty particle paths were traced for 4 to 6 frames corresponding to time intervals of about 0.001 sec. for high velocities and 0.01 sec. for the low velocities. The fifty measurements were used to determine the average velocity at the point under observation.

The first measurements were made in an attempt to find a relationship between the superficial liquid flow rate and the average velocity at a point in film flow similar to the one sketched in Figure 2*A*. The data in Table 1 indicate that although there is an increase in average velocity with liquid rate in general, there is a large amount of scatter about the best line that can be drawn to represent the data.

In order to avoid coming to false conclusions, an attempt was made to determine how well one of the average point velocities could be duplicated. The liquid rate was set at 4,200 lb./(hr.)(sq. ft.), and five films were taken of the same point at 5-min. intervals. An average velocity was determined near the beginning and end of each film. The ten resulting points are shown in Figure 3. It is obvious that the velocity is varying randomly with time even over the short time interval of 1 sec. required to take each film. Attempts were then made to determine how rapid the velocity fluctuations were on one of the films. Figure 4 shows the results obtained by determining average velocities at 0.1-sec. intervals for the film taken at 10 min. The velocity is still fluctuating rapidly. Figure 5 shows a portion of the same film with velocities at 0.02-sec. intervals and finally, in the inset, at about 0.001-sec. intervals, utilizing very close to adjacent sets of 4 to 6 frames for each average velocity. The vertical lines on each point represent

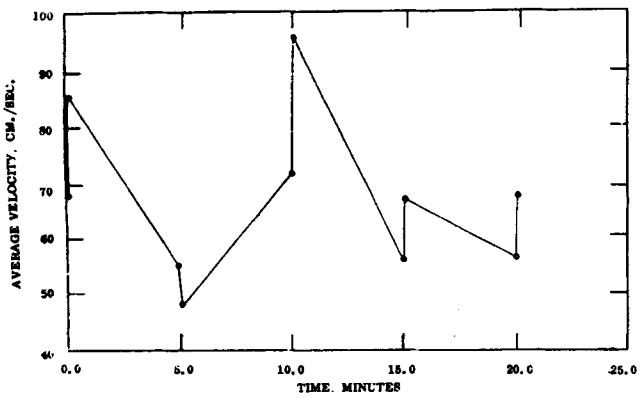

Fig. 3. Film flow over the outside of a 1.0-in. ring. Liquid rate 4,200 lb./(hr.)(sq. ft.).

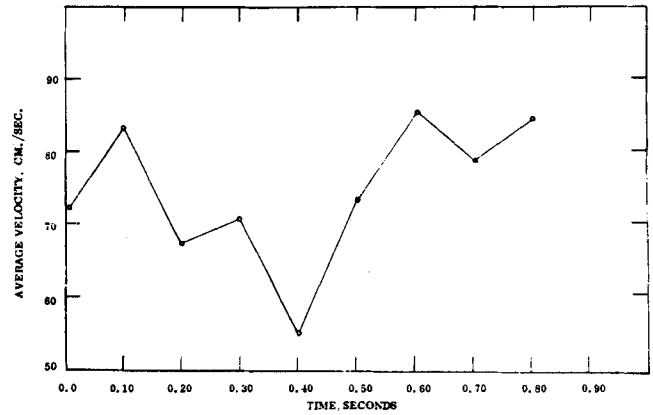

Fig. 4. Film flow over the outside a 1.0-in. ring at 10 min. Liquid rate 4,200 lb./(hr.)(sq.ft.).

the 95% confidence limits for each average velocity which is obtained from about fifty points.

The rapid fluctuations can be explained because the piece of packing under observation is being fed by a combination of liquid streams, free droplets, splashes, etc., coming from many pieces of packing above. The rapid velocity variation is simply a reflection of the many different sources randomly feeding the piece under observation at any moment.

This type of behavior was found at all points in the column for film flow and for pools in contact with moving streams. Figure 6 shows the results obtained for the divided interior pocket illustrated in Figure 2*C*. It can be seen that although the velocity varies rapidly with time, the pool and the film flow section in contact with it show similar variations with time and comparable velocities.

Only the isolated semistagnant pools such as the one in Figure 2*B* have low velocities which do not vary rapidly with time. Figure 7 shows the velocity variation taken from a section of film showing a pool which was disturbed by an external agent such as a droplet or contact with a meandering stream. The velocity which has remained low and fairly constant suddenly decreases and increases again as the pool is disturbed.

Nature of the Film Flow

The visual observations of both the particles and dye streams in film flow indicated no eddies or flow of a turbulent nature. A simple check can be made of the velocity variation at each point to determine if the flow is laminar. Since fifty particle velocities are used to determine the average at each point, it is possible to compare the maximum observed velocity with the average for each set of fifty particles. For true laminar flow of liquid down a wall or tube, a ratio of 1.5 would be expected. For fully de-

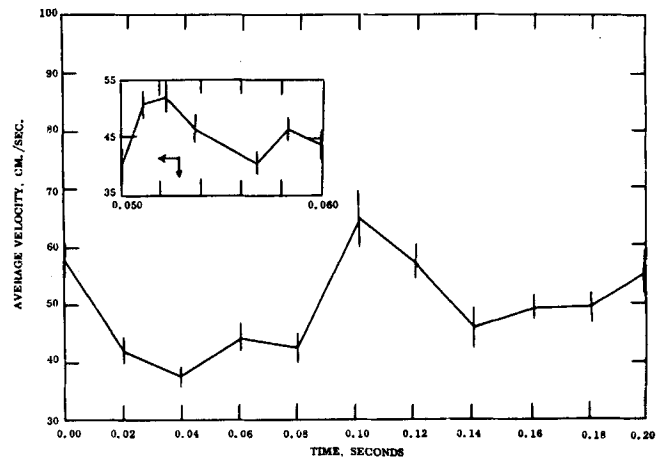

Fig. 5. Film flow over 1.0-in. ring. Liquid rate 4,200 lb./(hr.)(sq. ft.).

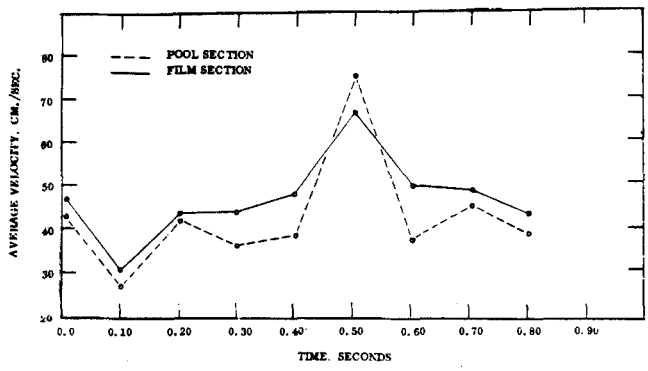

Fig. 6. Divided pocket inside 1.0-in. ring. Liquid rate 4,200 lb./(hr.)(sq. ft.).

veloped turbulent flow the ratio would be lower, at about 1.2 for a flat plate. Table 2 shows the data for several points in the column. For film flow on the outer surface of a ring and on the inside surface the average ratios are 1.4 to 1.5, which is very close to what is expected. The semistagnant pool has low velocities and gives an average ratio of 1.4. The circulating pool section of the divided pocket has an average ratio of 1.6. The rather thoroughly mixed section at the junction of three rings has an average ratio of 1.7.

These ratios indicate that laminar type of flow predominates even when mixing takes place. Ratios over 1.5 probably come from the averaging in of some high velocity particles from an adjacent high velocity region such as is found in the divided pocket and at the junction of three rings.

Comparison with Models

This study indicates that no simple mathematical model can describe the behavior of the liquid phase in a packed column. In addition to the typical areas studied here photographically, there are free droplets and deep, relatively stagnant pockets which could not be examined by these techniques. These portions of the liquid may play important roles in some of the mass transfer problems mentioned earlier.

Perhaps the best approach would be to develop simple models for each major portion of the liquid and then try to combine them to treat the more complex problems. Thus Higbie's (*3*) penetration theory should be adequate for the sections in film flow because laminar flow predominates and velocity measurements make it possible to estimate contact times between the mixing areas at the junction of the pieces of packing.

Dankwerts' (*1*) approach which considers elements of the fluid carried to the active surface and a distribution of exposure times may be suitable for the mixing areas at the

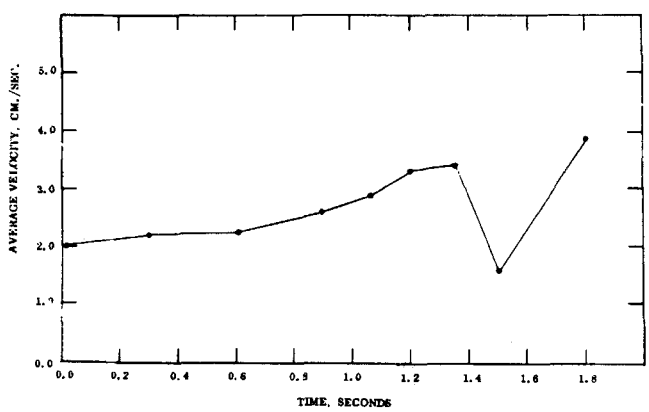

Fig. 7. Semistagnant pool inside 1.0-in. ring. Liquid rate 4,200 lb./(hr.)(sq. ft.).

Table 2. Ranges and Averages of Maximum Velocity, Average Velocity, and Velocity Ratios at Several Points in the Packed Column

Location	Range average vel., cm./sec.	Range max. vel., cm./sec.	Range velocity ratio
Film flow on outer surface of ring	36 to 94	53 to 130	1.20 to 1.72
Average	59.0	82.0	1.4
Film flow on inner surface divided pocket	30 to 65	39 to 92	1.30 to 1.77
Average	43.0	64.0	1.5
Semistagnant pool on inner surface	1.6 to 3.9	2.5 to 5.2	1.26 to 1.54
Average	2.6	3.6	1.4
Pool section of divided pocket	21 to 75	38 to 110	1.30 to 1.81
Average	37.0	59.0	1.6
Junction of three rings	15 to 33	23 to 52	1.31 to 2.19
Average	22.0	38.0	1.7

junctions.

There are many treatments of droplets in the literature, and the deeper pockets may be treated as equivalent to a number of continuous stirred tanks with a distribution of residence times.

Any complex model of the liquid phase would require a comprehensive set of experimental data for the testing of its validity. This would include data for absorption, vaporization, absorption with chemical reaction, and transient behavior, all obtained in the same column with end effects eliminated or corrected. Unfortunately such data are not available at the present time.

CONCLUSIONS

Studies of the liquid velocities and flow patterns in a packed column indicate that point velocities fluctuate very rapidly with time. The liquid moves in laminar flow over the inner and outer surfaces of Raschig rings. Mixing takes place at the junctions of pieces of packing. A complex model, made up of simple models for different portions of the liquid, and a comprehensive set of mass transfer data are required for the analysis of the liquid phase in packed columns.

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NOTATION

a = effective interfacial area, sq. ft./cu. ft.
h_o = operating holdup, cu. ft./cu. ft.
h_s = static holdup, cu. ft./cu. ft.
h_t = total holdup, cu. ft./cu. ft.
k_g = gas phase mass transfer coefficient, lb.-moles/(hr.)(sq. ft.)(atm.)
L = superficial liquid rate, lb./(hr.)(sq. ft.)

Subscripts

abs = physical absorption
vap = vaporization

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