Process Tomography: An Option for the Enhancement of Packed Vapor−Liquid Contactor Model Development

Carolyn E. Schmit, Dwight Cartmel, and R. Bruce Eldridge*

The Separations Research Program, The University of Texas, Austin, Texas 78758

A multitude of packed vapor−liquid contactor mass-transfer and hydraulic models exist in the literature. With few exceptions, the development of these models has been based on a very limited understanding of the microscale hydraulic phenomena inside the contacting column. Recently, the use of X-ray tomography has been shown to be an effective technique for imaging flow patterns in multiphase contactors. This paper describes the potential benefits that X-ray tomography analysis can bring to the understanding and modeling of the vapor−liquid contacting process. The technology has significant potential for enhancing the prediction of both mass-transfer efficiency and packing pressure drop of commercial packed columns.

Introduction

Distillation is the dominant unit operation in the chemical process industry. Despite the classification of distillation as a mature technology, improvements in the design of contacting devices, especially packings, continue to be made. The development of structured and random packing is an ongoing effort that consumes significant financial resources each year. As the development of new devices has taken place, significant advances in the modeling of the vapor−liquid mass-transfer process have occurred. Researchers at The University of Texas Separations Research Program (UT-SRP) have conducted a large percentage of this modeling effort. The efforts in mass-transfer model development have utilized commercial- and pilot-scale mass-transfer and pressure drop data, supplemented to some degree with bench-scale experiments. While this approach has produced reasonable models, a more detailed understanding of the mass transfer and hydraulics is needed to yield truly predictive models and to accelerate further advances in column internals design. The authors believe process tomography can yield the information required to significantly enhance the development of vapor−liquid contactor models.

Many models for predicting packed-column mass-transfer efficiencies and hydraulic characteristics have been proposed. With few exceptions, these models incorporate variables derived from macroscopic properties of the entire column (composition profiles, exit stream concentrations, pressure drop, gross liquid holdup, height equivalent to a theoretical plate (HETP), temperature profiles, etc.). Values of HETP and pressure drop are currently predicted using models that are semiempirical and do not rigorously represent the underlying momentum, heat, and mass-transfer processes. Typical models for determining hydraulic characteristics include those of Stichlmair et al.[1] for random packing and Rocha et al.[2] for structured packing. Models to predict mass-transfer performance (HETP) include those of Wagner et al.[3] for random packing and Rocha et al.[4] for structured packing.

* To whom correspondence should be addressed. Mailing address: 10100 Burnet Road, Mail Code R7100, Austin, TX 78758-4497. E-mail: rbeldr@che.utexas.edu. Phone: (512) 471-7067. Fax: (512) 471-1720.

For a detailed review of process tomography, the reader is referred to Chaouki et al.;[5,6] a brief introduction is given below. Process tomography is a method of determining the spatial distribution of a material within a process vessel. It includes techniques that use radiation, such as γ-rays and X-rays; acoustic techniques, such as ultrasound; techniques that measure electrical properties, such as capacitance, resistance, and inductance; and nuclear magnetic resonance imaging (NMRI). Many of these methods have been developed for, and used in, medical imaging and nondestructive testing. Existing tomography technology can be applied to gain additional insight into the operation of vapor−liquid devices. This new application could produce exceptional advances in the area of distillation, by enhancing of the current state-of-the-art performance models and improving packing design methodology.

Transmission tomography, which is the focus of this paper, involves the use of a beam of either X-rays or γ-rays. The beam is directed toward the object of interest. As the beam of radiation passes through the object, it is attenuated by mass along its path. The greater the mass, the greater the attenuation. Detectors are used to measure the intensity of the beam after it passes through the object. The ratio of the initial to final radiation intensity is indicative of the average density along the path of the beam. After many measurements are obtained along different paths through the object, the density at each point in the cross section can be mapped using a reconstruction algorithm.

Tomography Applications

Process tomography has been applied with increasing frequency to measure noninvasively the characteristics of flow in a process vessel. The technique used depends on the requirements for measurement time and spatial resolution. Several applications of transmission tomography are described below to illustrate the successes of process tomography applied to multiphase columns; these applications are summarized in Table 1. Of particular interest for the enhancement of vapor−liquid packed-column models is the quantification of liquid holdup, liquid distribution, and effective mass-transfer area.

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Table 1. Selected Applications of Transmission Tomography for Multiphase Flow Systems

type of column (diameter)	phases present	variables measured	reference
industrial reactor risers and packed beds	process fluids and solids	fluid distribution	Bowman[7]
industrial-sized packed column (3 ft)	water, solid packing	liquid distribution, liquid holdup	Xu and Kennedy[8]
trickle beds (square column, 6.03×6.03 cm^2)	water with barium bromide or water−ethanol mixture, glass spheres	liquid distribution	Lutran et al.[9]
trickle bed (4.5 cm)	water, glass beads	liquid holdup	Kantzas[10]
fluidized bed (10 cm)	gas, glass beads, or polyethylene particles	gas holdup	Kantzas[10]
trickling filters (0.6 m)	water, random polypropylene packing	liquid holdup	Toye et al.[11]
trickling filters (0.6 m)	water, random polypropylene packing	flow regime characteristics	Toye et al.[12]
trickling filters (0.6 m)	water, random polypropylene packing	liquid distribution, liquid holdup	Toye et al.[13]
trickling filters (0.6 m)	water, random polypropylene packing	bed void fraction, liquid holdup	Toye et al.[14]
packed column (20 cm)	water, ceramic spheres, or metal structured packing	liquid distribution, liquid holdup, water film thickness	Schmitz et al.[15,16]

γ-ray Tomography for Industrial Columns. A commercial industrial γ-ray computed tomography (CT) technique for reactor risers and packed beds has been developed by Tru-Tec Services, Inc., LaPorte, TX. The technique is an extension of one-dimensional γ-ray measurements. The scan line orientations consist of either 7 or 13 source and detector locations, spaced evenly around the column circumference.[7] The number of data points limits the resolution of the resulting density map. The industrial limitations include the accessibility of the vessel from all of the desired source and detector locations. The γ-ray CT technique was applied to a packed-bed column to determine the density contour map. The results showed variations in the density of the packed-bed cross section. A region of low density indicated that the vapor flow was biased toward that section of the column. The maldistribution was also identified with transmission measurements along four perpendicular, equal-length paths; the advantage of the CT approach was to quantify the pattern of maldistribution. Some forms of maldistribution, such as concentric annular flow, would not be identified by the simpler method but would be identified and quantified with the use of CT.

An application of γ-ray CT, in which liquid distribution and liquid holdup were quantified for an industrial-sized packed column, was reported by Xu and Kennedy.[8] Density maps were produced based upon γ-ray absorption measurements in a 3-ft-diameter Plexiglas column that contained 5 ft of random packing. The column operated with water as the liquid flow but with no vapor flow. During the γ-ray measurements, the liquid distribution was determined by measuring the amount of exiting liquid in a segmented liquid collector. The γ-ray source was located at nine locations evenly spaced around the column, 6 in. above the bottom of the bed. For each source location, nine detectors were used to measure γ-ray intensity. A fourth-order equation with x and y representing positions in the column was regressed to determine the density map, based upon Bartholomew and Casagrande.[16] The liquid distribution based upon this expression compared favorably to the experimental values. The liquid volume fraction (holdup) for any specific area was obtained by integrating the difference between the operating bed density distribution and the dry bed density distribution. Therefore, γ-ray CT can be used to represent the large-scale phenomena within an industrial column. However, this technique does not have the desired image resolution for yielding data for use in the development of a rigorous hydraulic model. It does have value for validating such a model on industrial columns.

Liquid Distribution Studies in Trickle Beds. The liquid distribution in trickle beds was the focus of studies by Lutran and co-workers[9] that used a medical X-ray CT system. The objective of the work was to achieve three-dimensional flow visualization within a packed column. A 30.48-cm-tall Plexiglas column with a square cross section was used. The inside width was 6.03 cm, while the outside width was 7.30 cm. The column contained a 19-cm-tall bed of either 3-mm- or 6-mm-diameter glass spheres, supported by wire gauze. Water, with barium bromide added to increase the absorption index for better contrast with the glass spheres, was distributed using a plate in which 25 holes were drilled in a 5×5 square pattern. In addition, the effect of surface tension on the flow pattern was investigated with the use of a water−ethanol mixture. A square liquid tank was located at the bottom of the column, where the liquid collected before it was recycled. Three liquid flow rates were used: 11.5 mL/s (11386 kg/m^2·h), 23 mL/s (22752 kg/m^2·h), and 33 mL/s (32672 kg/m^2·h). Gas flow was not incorporated. The uniformity of the liquid distribution was measured in the empty column by collecting liquid in 16 equal-sized square zones at the exit.

As a result of the medical scanner geometry, the images obtained were vertical slices through the column and the image area was a circular region, in which the entire column was viewed. The column and recycle pump were placed on the conveyor belt and moved through the imaging plane. Vertical scans, which required 26 s to complete, were taken every 3 mm. Images of the dry column were obtained. Images were obtained at each flow rate in an increasing order, and again while decreasing the flow rate, to determine the effect of prewetting on flow distribution. For these experiments, the spatial resolution was approximately 0.5 mm, determined because 1-mm objects could be resolved according to the authors.

The initial images analyzed were of flow through the column packed with 3-mm spheres. The liquid was observed to travel as tortuous filaments down the column. As the flow rate was increased, the filaments were observed to branch into a few new filaments. At the high flow rate (33 mL/s) the column was observed to flood. The images obtained after the bed was prewetted were quite different from those obtained before. In these images, the liquid was scattered throughout the bed, with liquid pockets forming. When the bed was prewetted, it was discovered that the liquid flow rate did not have as much influence on the flow pattern. When the 6-mm spheres were used within the column, changes were noted in the flow patterns. After switched from the low flow rate to the medium flow rate, new filaments appeared, as opposed to the branches that were identified for the 3-mm spheres.

The liquid distributor was modified to determine the contribution of each individual inlet to the flow pattern. The distribution patterns used were (1) one row of five

holes down the middle of the column and (2) one inlet hole at the center of the distributor. For these configurations the liquid flow rate per inlet hole was unchanged. The liquid flowed down the column primarily as films. With the one inlet configuration, prewetting the bed reduced the liquid maldistribution in the column. The water−ethanol mixture used for determining surface tension effects had a surface tension of 49.7 dyn/cm and a viscosity of 1.6 cP. The column was packed with the 3-mm spheres, and the line distribution scheme was used. The liquid flow rate was 4.6 mL/s, corresponding to the medium water flow rate with uniform distribution. With the reduced surface tension, the flow filaments seemed less tortuous, because the flow paths remained in the center of the column near the distribution line. The authors assumed the effect of viscosity was small enough to neglect.

Significant observations were made regarding the flow of the liquid in the square column, using a medical CT scanner. Similar measurements, using column internals used for distillation, would provide needed insight into the flow patterns. The studies of Lutran and co-workers[9] show that the effects of initial liquid distribution can be identified; therefore, the effects of packing features on flow patterns in a column should also be identifiable.

Holdup Measurements for Fluidized and Trickle Beds. A modified medical X-ray CT scanner was used by Kantzas[10] to determine the holdup in fluidized and trickle beds. The scanner was capable of imaging objects, up to a 32-cm diameter, oriented either horizontally or vertically. During a scan, components of the scanner rotate around the object to be scanned. The duration of a scan, 3 s, is longer than the dynamics of the flows; thus, the images are time-averaged representations of the flow.

The trickle bed column imaged was 4.5 cm in diameter and 0.45 m in height and was constructed of Plexiglas. It contained glass beads of size 0.4−0.6 mm. Water flowed downward at a rate of 1.57 cm^3/s. A total of 150 scans were performed to obtain images with a resolution of $0.4 \times 0.4 \times 3.0$ mm^3. The fluid holdup in the column was found to be nonuniform, despite the uniform packing.

The fluidized bed imaged was 15 cm in height, within a 10-cm-diameter, 100-cm-height column. The bed contained either 20−30-mesh glass beads or 0.4-cm polyethylene particles. A sequence of images was obtained to represent the entire fluidized bed. From the images, the holdup were calculated for each $0.4 \times 0.4 \times 5.0$ mm^3 volume element. A plot of the average gas holdup as a function of bed elevation indicated that there was a relatively constant holdup throughout the column. However, there was considerable radial variation in these values. The author concluded that a one-dimensional description of the holdup behavior would be an oversimplification. An additional study of the time-varying holdup was performed, by imaging one slice of the bed continuously for 30 min. The holdup values calculated for this series of images were all within a 0.04 range. Spatial variation of the density was observed across the cross section.

The imaging experiments of Kantzas[10] illustrate how the use of tomography can lead to a better understanding of the flow characteristics than could be determined from macroscopic column measurements. In addition, it was shown that even though the flow dynamics were not captured, changes in the time-averaged representations are measurable.

Liquid Holdup and Liquid Distribution in a Packed Column. X-ray CT was applied to trickling filters by Toye and co-workers.[11] A trickling filter is distinguished from a trickle bed by the lack of co-current vapor phase flow. The application of the trickling filters was in the treatment of wastewater, where the packing local properties and liquid distribution are important in determining the area on which a biofilm can form. In addition, it is important to know the distribution of the three phases (gas, liquid, and solid) in the filter to develop an accurate model for performance. X-ray CT was selected because it offered a true noninvasive technique, spatial resolution of 1−2 mm with a 2.5-min measurement time, and the ability to provide information on local packing morphology and local liquid flow. The X-ray CT system used was built from available constitutive elements. It is capable of scanning objects up to 0.8 m in diameter and 2 m tall. The X-ray source produces a 40° fan beam of X-rays of energy between 0 and 160 kV. The detector is a linear array of 1024 photodiodes. The motion of the source and detectors around the object is synchronized in the axial and radial directions.

The trickling filter imaged was constructed of polyethylene and was 2 m tall with a 0.6-m inner diameter. The fixed bed consisted of random polypropylene packing—Etapak 210 (diameter 0.05 m, void fraction 95%, and specific area 220 m^2/m^3). The liquid used was pure water, distributed at the top of the column by a multiple-point distributor. Images were obtained for dry packing and under flow conditions. The geometry of the individual packing elements could be seen clearly in the images of dry packing. Also evident was the nonuniform distribution of the packing elements across the cross section at a given elevation. The void fraction was calculated using the gray-scale images for the dry packing; the value matched the 95% claimed by the manufacturer. For the flow conditions, an image representing the liquid only was obtained, by subtracting the drained column raw data from the irrigated system raw data prior to image reconstruction. The values calculated for liquid holdup compared favorably with holdup determined by a tracer technique.

Further experiments by Toye and co-workers[12] with the same column and X-ray system were used to identify characteristics of the flow regime. As before, the projection signals from the drained column were subtracted from those of the irrigated column. The image, representing the local dynamic liquid holdup, indicated that the liquid flow was comprised of rivulets on the surface of the packing elements. Therefore, the liquid flow distribution should be correlated with the solid-phase distribution. A conclusion reached by the authors was that in trickling filters the packing heterogeneity is one of the essential causes for liquid flow maldistribution.

Cascade Mini-Ring 1A packing (diameter 0.044 m, height 0.016 m, specific surface area 185 m^2/m^3, and void fraction 92%) was the random packing used by Toye and co-workers[13] to evaluate the liquid distribution in a packed column. The same X-ray CT system was used. Tomographic images were obtained at two elevations of the column, with and without flow. Subtraction of the projection data was performed before reconstruction of the images, to obtain images representing the dynamic liquid holdup only. The local holdup values were ob-

tained by averaging a 6 × 6 pixel region of the image. A stochastic partial wetting model was used to compare the computed holdup values with a predicted value. It was reported by Toye et al.[14] that the water flowed mainly in films and rivulets on the surface of the Cascade Mini-Ring 1A packing elements.

The results obtained from the various experiments by Toye and co-workers[11−14] are indicative of the capabilities of X-ray tomography. Quantification of the area on which a film forms, which was mentioned as a goal for wastewater treatment applications, has not yet been reported. Successful measurement of the liquid holdup and of the distribution of the liquid in the column has been shown. Classification of the liquid flow as rivulet flow is important in determining the approach to take for model development. The scan time of this work was significantly longer (2.5 min vs 3 s) than the work of Kantzas;[10] however, the time-averaged images were still valuable for evaluating flow characteristics.

Liquid Holdup, Liquid Distribution, and Film Thickness Measurements. Schmitz and co-workers[15,16] evaluated the liquid-phase distribution for random and structured packing with the use of X-ray CT. The X-ray scanner consisted of a fixed X-ray tube source and an array of 15 detectors. The X-ray source was set to 360 keV and a current of 4 mA. The source provided a fan beam of collimated X-rays, with 40° aperture and 2 mm thickness. A filter consisting of 2-mm aluminum and 3-mm copper was attached to the front of the X-ray tube to prevent beam hardening effects. The spatial resolution of the scanner was set to 0.4 × 0.4 mm^2, with an imaging time of 15 min/image. The column was constructed of acrylic glass with a thickness of 5 mm, a diameter of 200 mm, and a height of 250 mm. The random packing was ceramic spheres of 10-mm diameter, and the structured packing was Mellapak 250Y, from Sulzer. Mellapak 250Y is a folded-metal structured packing with 0.1-mm thickness. Water was distributed at the top of the column with the use of a perforated plate distributor. The distributor contained 177 holes of 1-mm diameter each. The maximum liquid flow rate was 30 $m^3/(m^2\ h)$ (12.3 gpm/ft^2).

Images were obtained of both dry and wetted packing. To obtain the liquid distribution, the images of dry packing were subtracted from the images of wetted packing. Liquid holdup was calculated for both types of packing. For the ceramic spheres, water was distributed irregularly with the water flowing mainly in regions with a high density of ceramic spheres. The authors attributed this to the high attraction of the spheres for water. In some regions, there was no water. Axially, there was a significant change in the distribution of the liquid after a 2-mm displacement. The authors concluded that liquid distribution measurements made at the outlet of the column are not representative of the distribution throughout the column. For the structured metal packing, a film of water was found over all packing surfaces. The thickness of the water varied with the position of the metal elements. Films on upward-facing surfaces were 3−4 times thicker than films on the underside of the packing. Water was also found to accumulate where the metal sheets of packing were close to each other. The variation in the axial direction was not observed for the structured packing. The holdup compared favorably with Suess and Spiegel.[18] Schmitz and co-workers[16] noted that maldistribution was reduced when a gas phase was introduced through the packing in countercurrent flow.

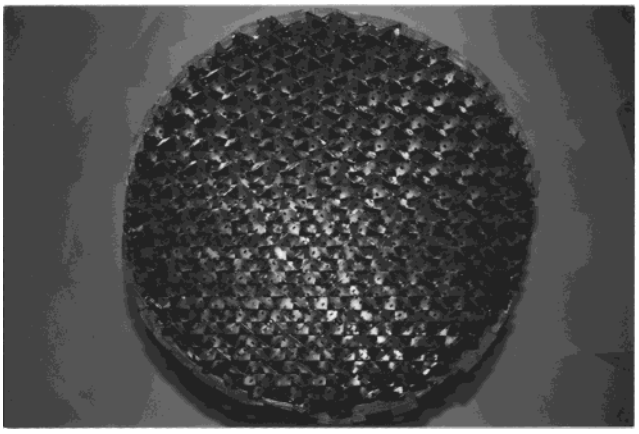

Figure 1. Top view of a structured packing element.

This application of tomography advanced the understanding of the flow characteristics in both structured and random packing. Imaging of structured packing constructed of metal, within a column of 200-mm diameter, was feasible with the high-energy X-ray source. The method of holdup calculation differed from the method used by Toye and co-workers;[11−13] the reconstructed images, rather than the projection data, were subtracted. The successful calculation of film thickness on structured packing is a step toward quantifying interfacial area.

Potential of Tomography in Modeling Vapor−Liquid Contactors

Measurements in a packed column using X-ray tomography can be used to improve the accuracy of predictive models. The hydraulic and mass-transfer models of Rocha−Bravo−Fair[2,4] for gas−liquid flows in structured packing will be reviewed to illustrate information gaps that could be addressed by X-ray tomography. Lockett[19] concluded that these models were the most rigorously sound of those available in the open literature. While this discussion will only address structured packing, a similar argument could be made for random packing based on the model of Wagner et al.[3] A typical structured packing element is shown in Figure 1. The packing consists of a series of ordered sheets aligned vertically. In theory, this uniform geometry should simplify model development.

Hydraulic Performance. The hydraulic model of Rocha et al.[2] is based upon a mechanistic approach and is used to predict pressure drop and maximum flow capacity (the flood point) in columns containing structured packing. It is limited to structured packing of the corrugated sheet geometry. The model predicts liquid holdup in order to develop a more rigorous and thus more general model. The first step in model development was to determine the total holdup for the column. The effective gravity acting on the liquid film flowing on the packing surface was determined using a force balance. The static holdup for the structured packing was calculated using a semiempirical relationship. With the effective gravity and static holdup determined, the total holdup correlation was determined (eq 1). The

$$h_t = \left(4\frac{F_t}{S}\right)^{2/3}\left(\frac{3\mu_L U_{LS}}{\rho_L(\sin\theta)\epsilon g_{eff}}\right)^{1/3} \quad (1)$$

$$\frac{a_e}{a_p} = F_{SE}\frac{29.12(We_L Fr_L)^{0.15}S^{0.359}}{Re_L{}^{0.2}\epsilon^{0.6}(1-0.93\cos\gamma)(\sin\theta)^{0.3}} \quad (2)$$

correction factor for total holdup due to effective area, F_t, incorporates the correlation of Shi and Mersmann[20] described by eq 2, which accounts for available interfacial area.

The hydraulic model uses a channel model as the basis for the pressure drop correlation. The dry pressure drop required in the model is calculated with the use of a friction factor equation. The dry pressure drop prediction is independent of the liquid behavior. The irrigated pressure drop expression, shown in eq 3, was correlated using experimental data. The irrigated pressure drop

$$\frac{\Delta P}{\Delta Z} = \frac{\Delta P_d}{\Delta Z}\left[\frac{1}{1-K_2 h_L}\right]^5 \quad (3)$$

is predicted based upon the dry pressure drop. With the expressions for dry pressure drop and liquid holdup fixed, the correlation constant, K_2, was determined to have a linear dependence on the packing size. The use of this model to predict pressure drop and flooding point requires iterative calculations.

Mass Transfer. The mass-transfer model of Rocha et al.[4] is based upon the two-resistance theory, with the assumption of equilibrium at the phase interface. The main parameters are the individual phase mass-transfer coefficients and the effective interfacial area. The gas-phase mass-transfer coefficient was determined using wetted wall theory, which involves correlation of dimensionless groups; three parameters were determined to best fit the database. The liquid-phase mass-transfer coefficient was based on penetration theory. The exposure time was based on liquid flow across one corrugated face of the packing. A semiempirical equation developed by Shi and Mersmann[20] was applied to determine the effective area for sheet metal structured packings. The expression for calculating the effective area is shown by eq 2.

For gauze packing surfaces, a correlation based on packing area, packing dimensions, and liquid flow rate was applied to determine the effective area. The three parameters of gas-phase mass-transfer coefficient, liquid-phase mass-transfer coefficient, and effective interfacial area were used to calculate height equivalent to a theoretical plate (HETP), according to eq 4.

$$\mathrm{HETP} = H_{OG}\frac{\ln\lambda}{\lambda-1} = \left(\frac{U_{gs}}{k_g a_e} + \lambda\frac{U_{Ls}}{k_L a_e}\right)\frac{\ln\lambda}{\lambda-1} \quad (4)$$

Model Limitations. The prediction of the hydraulic and mass-transfer performance using the Rocha−Bravo−Fair models depends strongly upon the Shi−Mersmann expression for determining the effective interfacial area. Figure 2 shows where this term, which is based upon the packing void fraction, packing geometry, superficial liquid velocity, and physical properties of the liquid, appears in the hydraulic and mass-transfer models. As a result of these dependencies, inaccuracies in the theory to develop the effective interfacial area directly and indirectly affect the accuracy of the mass-transfer model.

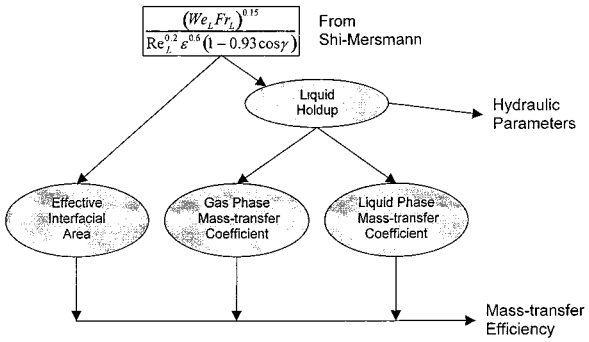

Figure 2. Dependencies of the Rocha−Bravo−Fair model upon the Shi−Mersmann calculation for the effective interfacial area.

The effective interfacial area in the Rocha-Bravo-Fair model, described by eq 2, is dependent upon the packing void fraction, packing geometry, superficial liquid velocity, and physical properties of the liquid. Variations in mass-transfer area that result from uneven liquid distribution are not included. In addition, the effects that vapor flow properties have on the flow patterns through the column are not incorporated. With the use of X-ray tomography, it is anticipated that the interfacial area can be quantified. The validity of the current expression can be evaluated for a range of operating conditions. The effects of distribution, vapor flow properties, and vapor flow rates may also be evaluated. Improvements to the accuracy of the interfacial area may result with the use of area calculated from tomographic data.

Both the liquid holdup in the hydraulic model and the effective interfacial area in the mass-transfer model depend on the expression cited in Figure 2. This expression is used to calculate the correction factor for total holdup due to the effective area, F_t, used in eq 1. This correction factor accounts for the impact of the effective area on liquid-phase holdup. Any inaccuracy in the form of the effective interfacial area expression influences the accuracy of the hydraulic model through the calculation of liquid holdup.

Inaccuracies in the effective interfacial area model also influence the calculation of individual-phase mass-transfer coefficients. The calculation of the gas-phase mass-transfer coefficient, which appears in eq 4, is based on wetted wall theory. The effective vapor and liquid velocities are used to calculate a Reynolds number for the system. The effective velocities are dependent upon the liquid holdup, which depends on the effective area correction. Thus, as depicted in Figure 2, the gas-phase mass-transfer coefficient depends indirectly upon the expression from Shi−Mersmann. Also depicted is the indirect dependence of the liquid-phase mass-transfer coefficient. The calculation of the liquid-phase mass-transfer coefficient, which also appears in eq 4, is based upon the penetration theory. The exposure time depends on the effective velocity of the liquid. Again, the calculation of the correction for interfacial area, in the hydraulic model, is important in accurately determining the individual-phase mass-transfer coefficient.

Nontomographic Measurement Limitations. The typical experimental method for obtaining dynamic holdup values involves shutting off flow to an operating tower and collecting the liquid that drains from the packing. The experiments are typically done using an air−water system. Such an approach yields an average measurement over the entire tower, for an air−water

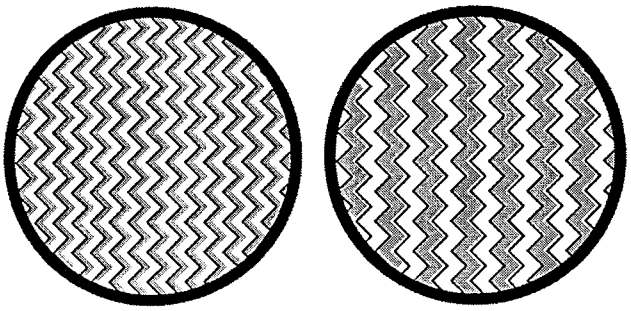

Figure 3. Illustration of two types of flow through structured packing, with equivalent liquid holdup. On the left, liquid is evenly distributed on the packing surface. On the right, the liquid is flowing in every other channel. The effective interfacial area is significantly different for the two flows.

system only, and does not account for axial or radial holdup variations. It also cannot distinguish between various flow forms in the column. Equivalent holdup values could be obtained for a column exhibiting large liquid streamlines or small, widely dispersed streams. In Figure 3, two possible types of flow through structured packing are illustrated. The cross section on the left contains a constant film thickness on each packing surface. The cross section on the right contains fluid in every other channel. The liquid holdup in both cross sections is identical. This difference would not be identified with a measurement of the total column holdup but would be identified with X-ray tomography.

Potthoff[21] used temperature measurements, an invasive technique, to evaluate liquid distribution in packed columns. The studies incorporated random and structured packings of various height beds and several distributor designs within two columns. The fluids were hot water and dry air. The temperature was measured at 19 points at each of 10 elevations (190 total measurements) for the smaller column (0.14-m diameter) and 61 points at each of 7 elevations (427 total measurements) for the larger column (0.63-m diameter). A numerical model was developed for a packed column with maldistribution, and the calculated three-dimensional temperature profile was compared to the experimental values.

The measurement technique used by Potthoff[21] produced profiles that represent the liquid distribution within the column. The number of measurements used is not sufficient to obtain the information required to quantify interfacial area; X-ray tomography has the potential to noninvasively do so. None of the imaging results to date indicate success in precisely determining the area of the liquid films and drops in a packed column. However, measurement of the film thickness was accomplished by Schmitz et al.[15,16] Successful measurement of the thickness of films on the structured packing surface provides encouragement that measurement of the mass-transfer area is feasible. While a quantitative measure of the interfacial area continues to be a goal, a qualitative measurement or an improved semiempirical expression could be incorporated into mass-transfer models.

The true flood point, and the cause of flooding, can potentially be identified with the use of process tomography. Images of the column just prior to flood can identify where the flooding begins. More accurate measures of the flood point can be incorporated into the hydraulic model. In addition to improved modeling, a potential result of identifying the cause of flooding is improved column internals that address capacity limitations.

Mass-transfer efficiency has been measured at the UT-SRP primarily with the use of top and bottom, and in some cases intermediate, concentrations. A recent study showed that changes in the packed-bed height can influence the HETP for a given packing, as shown in Figure 4. This theoretical height equivalent is expected to be independent of bed height. The differences in HETP observed for the 10- and 14-ft beds are attributed to changes in the fluid hydraulics, such as the liquid distribution. The packing was a random type, but a similar phenomenon is expected for structured packing.

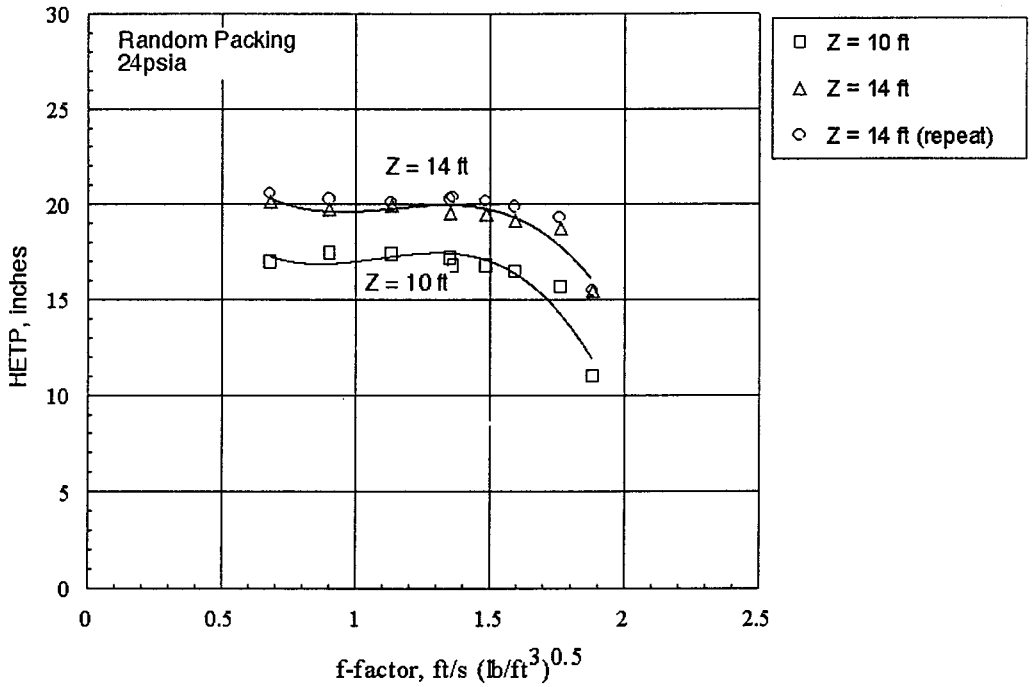

Figure 4. Variation in HETP measured for packed-bed heights of 14 and 10 ft.

A tomographic technique to image the fluid distribution in a 14-ft packed bed, at elevations of less than 10 ft and between 10 and 14 ft, would be valuable to quantify the difference in flow patterns.

Summary and Conclusions

Noninvasive imaging techniques have the potential to provide insight into the flow patterns throughout the column, across the cross section and at various elevations. When the operating conditions, packing type, and fluid properties are varied, the effects these parameters have on column operation can be observed. In addition, X-ray tomography has the potential to identify how packing features cause changes in liquid distribution. Application of X-ray tomography to a packed vapor−liquid contactor will provide additional understanding that will lead to a more rigorous modeling approach.

The distribution and quantity of liquid across the column cross section must be adequately described to improve hydraulic and mass-transfer models and to produce an accurate column design methodology. No models to predict structured packing performance explicitly address the liquid distribution. Advanced imaging offers the potential to supply distribution information, as a function of radial or axial position. The use of X-ray tomography will allow the complex interactions the various column parameters have on both liquid holdup and interfacial area to be measured simultaneously. The use of process tomography to quantify the liquid holdup, liquid distribution, and mass-transfer area will allow for the development of a more rigorous model for column performance.

A good basis exists for advancing vapor−liquid model development through the use of imaging technologies. The fundamental barrier to applying X-ray tomography may be the tradeoff between image resolution and acquisition speed. To effectively determine flowing liquid behavior, the image must be "captured" quickly. Unfortunately, for radiation-based methods, quick acquisition will produce limited resolution of small-scale features. While electrically based methods have high imaging speed, they do not have the necessary resolution to identify the effects of the packing characteristics in vapor−liquid contactor applications. Whether an optimized X-ray approach can be developed which identifies liquid behavior quickly enough to yield data for interfacial area and film flow is still in question.

The belief of the authors is that X-ray tomography has significant potential for yielding the microscale data required for the development of rigorous packed-column hydraulic and mass-transfer models. While the gamma ray technique described will continue to be used for large-scale industrial applications, it does not provide the resolution required for the investigation of local vapor−liquid phenomena. Much can be learned by coupling laboratory and pilot-scale mass-transfer and hydraulic studies with X-ray tomography. Work is ongoing at the University of Texas Separations Research Program to take full advantage of this powerful new analytical tool. The ultimate goal is to develop accurate predictive models and a fundamental understanding of vapor−liquid behavior in a packed tower. This understanding will dramatically enhance the industry's ability to optimize both packing design and column performance.

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Nomenclature

a_e = effective area (1/m)
a_p = packing surface area (1/m)
F_{SE} = factor for surface enhancement
F_t = correction factor for total holdup due to the effective wetted area
Fr_L = liquid-phase Froude number
g_{eff} = effective gravity (m/s^2)
h_L = liquid holdup
h_t = total liquid holdup
H_{OG} = height of an overall transfer unit, gas-phase basis (m)
HETP = height equivalent to a theoretical plate (m)
k_g = mass-transfer coefficient gas phase (m/s)
k_L = mass-transfer coefficient, liquid phase (m/s)
K_2 = correlation constant, eq 3
ΔP = pressure drop (Pa)
ΔP_d = dry pressure drop (Pa)
Re_L = liquid-phase Reynolds number
S = side dimension of corrugation (m)
U_{gs} = superficial gas velocity (m/s)
U_{LS} = superficial liquid velocity (m/s)
We_L = liquid-phase Weber numbe
ΔZ = incremental height (m)

Greek Letters

γ = contact angle between liquid film and solid surface (deg)
ϵ = void fraction of the packing (dimensionless)
θ = angle with horizontal for falling film or corrugation channel (deg)
λ = ratio of slopes, operating line to equilibrium line (dimensionless)
μ_L = liquid viscosity (kg/ms)
ρ_L = liquid density (kg/m^3)

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