UNIT OPERATIONS FOR GAS-LIQUID MASS TRANSFER IN REDUCED GRAVITY ENVIRONMENTS

N93-14011

Donald R. Pettit
Los Alamos National Laboratory
Los Alamos NM 87545

David T. Allen
Department of Chemical Engineering
University of California
Los Angeles CA 90024

Basic scaling rules are derived for converting Earth-based designs of mass transfer equipment into designs for a reduced gravity environment. Three types of gas-liquid mass transfer operations are considered: bubble columns, spray towers, and packed columns. Application of the scaling rules reveals that the height of a bubble column in lunar- and Mars-based operations would be lower than terrestrial designs by factors of 0.64 and 0.79 respectively. The reduced gravity columns would have greater cross-sectional areas, however, by factors of 2.4 and 1.6 for lunar and martian settings. Similar results were obtained for spray towers. In contrast, packed column height was found to be nearly independent of gravity.

INTRODUCTION

Unit operations are the basic elements of chemical processes to perform mass transfer between gas and liquid phases. Gas-liquid mass transfer is the process of transporting a chemical species from one of the phases into the other. Unit operations for gas-liquid mass transfer have a mature technological base. These terrestrial-based industrial processes range from the manufacture of gasoline and petrochemicals to sewage treatment and the making of pharmaceuticals.

When humans build lunar and martian bases, harsh foreign environments will require a high degree of technical support for development. Technologies will be needed to maintain and recycle life support, process local resources into fuels and construction materials, and to manufacture goods for trade and economic independence. Integral to these processes is the need to perform species separations between gases and liquids, hence the need for unit operations. Several products can be made from indigenous resources for lunar and martian bases (*Mendell,* 1985; *Duke,* 1986). Although chemical processes have been proposed for manufacturing on the Moon and Mars, the details of gas-liquid unit operations have largely been ignored. The volume, mass, and resource consumption rates of the process equipment are crucial in development of overall mission strategies, especially if the equipment is brought from Earth. Estimating equipment mass and volumes directly on Earth-based designs could be erroneous. The purpose of this work is to use simple scaling rules and dimensional analysis to scale an Earth-designed unit operation for use in reduced gravity. It is important to point out that scaling is used to give a first-order design in the absence of actual experimental data taken in low gravity. Until such data are available, scaling gives estimates in the design, and determines equipment volumes and masses.

STANDARD GAS-LIQUID UNIT OPERATIONS

Mass transfer ultimately hinges on diffusional transport of chemical species between the fluid phases and this, in turn, requires a large interfacial surface area. Since diffusion is typically a slow process, the desired path length over which diffusion occurs is made short. Turbulence provides fast convective transport and is usually incorporated to move species from the interior or bulk of the fluid to the interface where molecular diffusion takes place.

There are many ways to achieve the conditions for efficient mass transfer, and the advantages of each method can be matched to the diffusional properties of the species of interest. Dispersing the gas into the liquid as small bubbles in bubble columns provides a large interfacial surface area. Diffusion within the short path length of the bubble brings the species to the interface where the surrounding liquid is well mixed and turbulent, and efficiently transports the species from the interface to the liquid bulk. Liquid can be dispersed into the gas as small droplets in spray towers, providing a large interfacial surface area. Diffusion within the drop brings the species to the interface where turbulence convects it away to the gas bulk. On Earth, convection and related gravitation effects play a significant role in these processes; the effect of lunar and martian gravity is yet to be demonstrated and currently their effects have to be scaled from their known behavior on Earth.

The choice between these two contacting schemes hinges on where the dominant diffusional resistance lies. To counteract dominant resistance in the liquid phase (i.e., a small diffusion coefficient), bubble columns are used where convective transport prevails in the liquid and diffusion is in the gas. Dissolving oxygen into water for aerobic microbial processes falls in this category, hence bubble columns are a standard contacting method. Systems with the dominant resistance in the gas phase benefit by dispersing the liquid as droplets in spray towers where convection is in the gas. Evaporating water into air for humidification and cooling is a system where the dominant resistance lies in the gas phase and spray towers are a standard contact method.

Another standard contacting method is to use a packed column. A containing vessel is packed with small complex-shaped objects that present a large surface area and long tortuous passages. The containing vessel is generally a large vertical pipe; however, much smaller, rotating containment vessels have been used. For the vertical pipe configuration, the liquid is distributed on the top and percolates downward as a thin film that coats the packing material. Gas is blown upward in turbulent flow through the tortuous passages. Efficient mass transfer is achieved because of the large interfacial area, the turbulent convection in the gas, and the thin falling film in the liquid. In rotating contactors, liquid enters at the center of the disk-shaped device and flows radially, due to centrifugal force, to the outer edge of the device. Gas flows either in the same direction as the liquid (cocurrent) or in the opposite direction (countercurrent). These rotating contactors lower resistance in the liquid phase by making the film covering the packing material extremely thin. Either type of packed column is suitable for mass transfer when either or both phases have high resistances.

Other factors are important as well as the efficiency of mass transfer. Some systems tend to foam, so dispersing bubbles in liquid creates a large foamy head and requires centrifugal foam breakers or a large dead space to allow for the head volume. Systems with sediment or fast-growing microorganisms tend to plug the passages in packed columms. Spray towers are often inconveniently high to allow sufficient contact time while the droplets are falling. Choosing the best contacting scheme for a given mass transfer operation involves the consideration of many variables, often resulting in a compromise in mass transfer efficiency to alleviate other troublesome effects. Unit operations that are optimized for Earth can be scaled for use in the reduced gravity environments found on the Moon and Mars and is the subject of this paper. Some thought should be given to ascertain whether a nonstandard contacting method might be better. For example, spray towers that would be impractically high on Earth might be very practical on the Moon due to the $1/6$ gravity slowing the rate of droplet descent.

SCALING FOR REDUCED GRAVITY

These unit operations require gravitational forces to separate the gas and liquid phases. Modifications to the equipment will be necessary for operation in reduced gravity. Two cases are considered: a lunar base with $1/6$ gravity and a martian base with 0.38 gravity. Before a unit operation can be designed, the feed-stream composition, flow rate, and degrees of separation will need to be known. With this, a contacting method is chosen and the design made. Paramount in the design is the unit's cross-sectional area, which governs the throughput of materials, and the column height, which governs the degree of separation. These two factors determine the bulk equipment mass and volume. It is assumed here that feed-stream composition, flow rate, and degree of separation are known for the reduced-gravity setting. Then an Earth-based design is made using standard design techniques. The scaling rules presented here will then enable the Earth-based design to be modified for reduced gravity.

Bubble Columns

There are two general cases for scaling bubble columns: when the liquid is mixed solely from the rising action of the bubbles and when the liquid is mixed using an impeller driven by external shaft work.

When the mixing occurs from the rising action of the bubbles, a fine dispersion of bubbles provides a large interfacial area but poor mixing in the liquid. Conversely, large bubbles provide good mixing but lack surface area. Bubble size is optimized by using a correlation for $\kappa_L a$, where κ_L is the mass-transfer coefficient in the liquid and a is the interfacial area. The interfacial area is approximated by the area of a single bubble times the number of bubbles (for a monodisperse distribution). The number of bubbles for a fixed gas feed is inversely proportional to the bubble diameter cubed. This makes the interfacial area inversely proportional to bubble diameter. Optimization of $\kappa_L a$ is made from a correlation of experimental data using column height, bubble diameter, and gas flow rate (*Welty et al.,* 1976). Determining $\kappa_L a$ in reduced gravity is done by first optimizing the bubble column on Earth and then scaling for reduced gravity. Based on penetration theory, $\kappa_L \propto (V/d)^{1/2}$ for a rising bubble, where V is the rising velocity and d is the bubble diameter. The bubble velocity is found by equating buoyant force to drag force, and results in the scaling equation

$$\frac{V_L}{V_E} = \left(\frac{g_L}{g_E}\right)^{1/2} \left(\frac{d_L}{d_E}\right)^{1/2} \qquad (1)$$

where g is the acceleration due to gravity and the subscripts E and L are for the Earth and the low-gravity setting. The interfacial area, $a \propto 1/d$, used with equation (1) results in the scaling ratio

$$\frac{\kappa_L a|_L}{\kappa_L a|_E} = \left(\frac{d_E}{d_L}\right)^{5/4} \left(\frac{g_L}{g_E}\right)^{1/4} \qquad (2)$$

The details of deriving equations (1) and (2) are given in *Pettit* (1985). To determine the mass-transfer rate for low gravity, first the gas flow rate and Earth tower height are used in the correlation in *Welty et al.* (1976) to optimize $\kappa_L a|_E$ and determine Earth bubble diameter. Equation (2) then determines $\kappa_L a|_L$, which is needed to find the mass transfer rate in low gravity. If bubble diameter is made constant between Earth and low gravity by altering the bubble generator (sparger head), then $\kappa_L a$ is 0.64 and 0.79 times that on Earth for a lunar and martian setting. This decrease in $\kappa_L a$ is due to slower bubble velocity decreasing turbulent mixing.

The amount of mass transferred for a chemical species is $n_i \propto t\kappa_L a$ where n_i is the transferred mass of species i and t is the contact time. Using equation (2) gives the scaling ratio

$$\frac{n_i|_L}{n_i|_E} = \left(\frac{g_L}{g_E}\right)^{1/4} \left(\frac{d_E}{d_L}\right)^{5/4} \frac{t_L}{t_E} \qquad (3)$$

The mass transferred (species separation) is a given design criterion and remains the same between Earth and low gravity. The contact time then scales as

$$\frac{t_L}{t_E} = \left(\frac{g_E}{g_L}\right)^{1/4} \left(\frac{d_L}{d_E}\right)^{5/4} \qquad (4)$$

which for the same size bubble, requires a contact time 1.6 and 1.3 times that on Earth for a lunar and martian setting. A longer contact time is needed to achieve the same mass transfer because of the reduction in $\kappa_L a$.

The column height is scaled knowing $h \propto Vt$ and by using equation (1) and (4), giving

$$\frac{h_L}{h_E} = \left(\frac{g_L}{g_E}\right)^{1/4} \left(\frac{d_L}{d_E}\right)^{7/4} \qquad (5)$$

where h is the column height. For constant bubble diameter, the column height is 0.64 and 0.79 times that on Earth for a lunar and martian setting. Even though the corresponding values of $\kappa_L a$ are lower and the required contact times are greater, the slower bubble velocity more than compensates, giving an overall column height lower than one on Earth.

Column area, A, is proportional to 1/V because the bubble velocity is the rate-limiting constraint on the gas flow rate (*Pettit*, 1985). If the area is insufficient, excessive foaming will result and a large volume expansion will likely cause the column to overflow. The scaling ratio for area is

$$\frac{A_L}{A_E} = \left(\frac{g_E}{g_L}\right)^{1/2} \left(\frac{d_E}{d_L}\right)^{1/2} \qquad (6)$$

where A is the column cross-sectional area. For constant bubble diameter, the column area is 2.4 and 1.6 times that on Earth for a lunar and martian setting. The larger area is needed to accommodate the reduction in bubble velocity.

The bubbles are introduced into the liquid with a sparger, a distributing manifold that contains many small holes from which the bubbles emerge. Small separate bubbles as opposed to semicontinuous bubble chains are desired. Under this flow regime, viscous forces dominate bubble formation at the sparger hole. Using dimensional analysis, the scaling ratio for sparger hole diameter is

$$\left.\frac{Mg}{\sigma D}\right|_E = \left.\frac{Mg}{\sigma D}\right|_L \qquad (7)$$

where M is the bubble mass (which specifies bubble diameter), σ is the gas-liquid surface tension, and D is the hole diameter in the sparger. Once the bubble diameter and sparger hole size have been determined for the Earth design, equation (7) is used to specify the sparger hole size in the low gravity.

A small change in bubble diameter can have a significant effect on the mass transfer. Sparger bubble diameter is actually a distribution of diameters and only approximated by a single diameter in Earth-based design. Designing a sparger for low gravity based on the scaling of equation (7) is approximate at best. The actual bubble diameter may be far enough from the anticipated size to significantly alter the designed mass transfer rate. Only when actual experience is gained in low-gravity mass transfer will this effect be known, and until then, scaling by equation (7) will have to suffice.

When external mixing with an impeller is used, the rising action of the bubbles is not needed to supply the turbulence for efficient mass transfer so the bubbles can be made as small as practical to increase the interfacial area. If the bubbles are too small though, excessive foaming tends to occur and requires a large dead space for volume expansion. The power required to give adequate mixing in the liquid is 1 to 2 W/l (0.5 to 1 hp/100 gal) based on Earth experience. This power level is dominated by viscous dissipation and is not anticipated to significantly change in reduced gravity.

The bubble residence time is complex in a mixed bubble column and is not simply described by a rising velocity over the liquid depth in the column. The turbulence is strong and momentarily overpowers the buoyant forces, causing the bubbles to circulate around and around inside the vessel. When a turbulent eddy brings a collection of bubbles close to the surface, some of them will escape while others will recirculate. Gravity-driven buoyant force is still ultimately responsible for the separation, and for a given level of turbulence and column height, the bubble residence-time distribution remains inversely proportional to bubble rising velocity. In scaling a mixed bubble column for reduced gravity, the effects of gravity on the intensity and eddy size of the liquid-phase turbulence will need to be known to determine κ_L. Since liquid-phase turbulence has small density variations (the liquid being nearly incompressible), the gravitation effects are assumed to be small. If the impeller design and power levels remain constant between Earth and low gravity, the turbulent intensity and eddy sizes should also remain constant. In a mixed bubble column, then, the bubble contact time should keep its inverse proportionality to bubble rising velocity and the mass transfer coefficient should remain a function of the mixing.

In the absence of data on gravity effects of mixing, it would be safest to maintain the same impeller design and power levels used on Earth; thus κ_L is assumed to remain unchanged. Earth-based correlations, then, will specify κ_L. The interfacial area, again for a given gas flow divided among equally sized bubbles is $a \propto 1/d$. The mass transferred is $n_i \propto t\kappa_L a$. The contact time, while complex in a mixed bubble column, is assumed to scale as $t \propto 1/V$ when mixing intensity and column height remain constant. Equation (1) for bubble velocity is used to scale the mass transferred as

$$\frac{n_i|_L}{n_i|_E} = \left(\frac{g_E}{g_L}\right)^{1/2} \left(\frac{d_E}{d_L}\right)^{1/2} \qquad (8)$$

Again, the mass transferred is a given design criterion so equation (8) places the following constraint on the bubble diameter

$$\frac{d_L}{d_E} = \left(\frac{g_E}{g_L}\right)^{1/3} \qquad (9)$$

The present unknowns associated with gravity effects on turbulence require the scaling for mixed bubble columns to keep the impeller design, power level, and column height constant. This, coupled with the given criteria for gas and liquid flow rates and desired mass transfer, places a unique constraint on the bubble diameter as specified by equation (9). Bubble diameter is 1.8 and 1.4 times larger for mixed bubble columns on the Moon and Mars respectively. The column cross-sectional area is given by equation (6) and is 1.8 and 1.4 times larger respectively on the Moon and Mars. Sparger hole diameter is given by equation (7) and, for generating the larger bubbles, surprisingly gives the same hole diameter as on Earth for use on both the Moon and Mars.

Foaming may prove to be an onerous problem in low gravity. Increasing the bubble size may alleviate part of the problem, but systems that tend to foam badly on Earth may require a centrifugal foam breaker in low gravity. The extent of foaming and turbulence will really not be known until low-gravity experience is obtained.

Spray Towers

Dispersions of liquid droplets in a gas for spray-tower design can be scaled for low gravity. The gas and liquid flow rates and degree of chemical species separation are given conditions in the low-gravity environment. These conditions are used to design an Earth-based spray tower where droplet diameter, tower cross-sectional area, and tower height are determined. Scaling relations can then be used to determine the corresponding low-gravity condition. Similar caveats for bubble-tower scaling apply to spray-tower scaling. In the absence of experimental data in low gravity, the scaling rules give a first-order design. Variation in droplet diameter affects interfacial surface area, the mass transfer coeffients, and the contact time, hence the overall operation of the device.

As with bubble towers, interfacial area between low gravity and Earth is $a \propto 1/d$, where d now represent the droplet diameter. The droplet diameter is chosen by the hole diameter in the sprayer nozzle and is scaled according to equation (7). The simplest scaling procedure, although not the only choice, is to maintain the same droplet diameter between low gravity and Earth, which ensures the same interfacial surface area between the two environments. The droplet free-fall velocity is given by a force balance between gravity and drag and gives the same scaling equation as for bubbles in equation (1). A droplet will fall with 0.41 and 0.62 times the velocity on Earth for a lunar and martian setting.

The mass transfer coefficient for the gas phase surrounding the droplets, κ_c, is scaled from its dependence on V and d developed from experimental correlations between a single sphere and surrounding gas. From *Welty et al.* (1976), the correlation shows $\kappa_c \propto (V/d)^{1/2}$, which is not surprising since the same proportionality applies to κ_L for a bubble based on penetration theory as in bubble columns. This yields the scaling ratio

$$\frac{\kappa_c|_L}{\kappa_c|_E} = \left(\frac{g_L}{g_E}\right)^{1/4} \left(\frac{d_E}{d_L}\right)^{1/4} \qquad (10)$$

which gives a mass transfer coefficient 0.64 and 0.79 times that of Earth's when on the Moon and Mars. The lower mass transfer coefficient is the result of a slower free-fall velocity.

The mass transfer for a chemical species is given by $n_i \propto t k_c a$, which is the same for bubble towers. Equations (3) and (4) then will apply to spray towers for scaling contact time.

The tower height is determined from the contact time and the droplet velocity relative to the tower. The gas phase moves upward against the motion of the falling drops, making $h \propto (V-V_g)t$, where h is the tower height and V_g is the gas velocity. The gas velocity is usually some fraction of the droplet velocity, $V_g = cV$, where c ranges from 0.2 to 0.5, which minimizes elutriation of the droplets from entrainment in the gas stream. Using the droplet velocity and contact time of equations (1) and (4) gives scaling for tower height the same as equation (5) for bubble columns. Even though the upward gas velocity is significant in spray towers, its effect cancels out when forming the scaling ratio because of its proportionality to droplet velocity. For constant droplet diameter, the tower height is 0.64 and 0.79 times that on Earth for the Moon and Mars. Even though the corresponding mass transfer coefficient is lower and the required contact time is greater, the slower falling velocity more than compensates, giving an overall tower height significantly lower than a comparable tower on Earth.

The tower cross-sectional area A, is dictated by the gas velocity giving $A \propto 1/V_g \propto 1/cV$. This results in the scaling of tower area given by equation (6). For constant droplet diameter, the tower area is 2.4 and 1.6 times that on Earth for the Moon and Mars. The larger area is needed to reduce the gas velocity in proportion to the reduction in droplet velocity.

Packed Columns

Scaling procedures have previously been developed by *Pettit* (1986) for absorption, stripping, and distillation-column design in low gravity. The scaling packed cross-sectional area is

$$\frac{A_L}{A_E} = \left(\frac{g_E}{g_L}\right)^{1/2} \qquad (11)$$

which is the same result as in bubble and spray towers for constant droplet diameter.

Packed column height is nearly independent of gravity. Column height is dictated by the degree of separation, thermodynamics, the fluid contacting pattern, and geometry. A ratio called the number of transfer units, $m/\kappa_m a$, where m is the flow rate of either the gas or liquid phase and κ_m is the mass transfer coefficient based on m, contains the parameters that are affected by gravity and are needed together with the thermodynamics to specify column height. Varying the level of gravity will certainly affect m, κ_m, and a. These parameters have an interdependence, and correlations of experimental data show that even though a change is made in one of these, the corresponding effects on the other two will cause their ratio to remain nearly constant. In scaling a column for cross-sectional area, the internal flow rates, mass transfer coefficients, and interfacial area will all be affected, but their ratio as the number of transfer units will remain nearly unchanged, hence so will column height.

SUMMARY

Unit operations for gas-liquid mass transfer are standard processes found in industrial-based society. Expansion into the reduced gravity environments found on the Moon and Mars will require similar operations to support the base activities. The standard gas-liquid mass transfer operations require gravitational forces to drive and to separate the fluid phases and have to be appropriately scaled for the reduction in gravity. There are three basic contacting methods for gases and liquids: dispersing the gas as bubbles in liquid in bubble columns; dispersing the liquid as droplets in gas in spray towers; and flowing the liquid and gas in opposite directions through a packed column. In design for reduced gravity on the Moon or Mars, flow rates and degrees of separation for the intended process are used to design the device for use on Earth, then the process is scaled for the reduced gravity setting. The scaling will give overall cross-sectional area and tower height along with some necessary internal design. This in turn will allow equipment volume and mass to be determined, which are needed for transportation arguments when the process is to be shipped from Earth. The scaling procedures shown here are only intended for first-order design in the absence of experimental data from reduced-gravity environments. The scaling rules might be validated experimentally in high-gravity environments produced by rotation on Earth. This would be the next best evaluation short of performing the experiments in reduced gravity.

Acknowledgments. This work was performed under the auspices of the U.S. Department of Energy.

EPILOGUE

Exchanging of Mass

Bubbles in liquid, and droplets in gas
Swirling together to see what will pass
The species will run a diffusional race
Over hill, through dale, and past interface
When liquid and vapor have finished their play
They depart one another, and go their own way

DP 4/88

REFERENCES

Duke M. B. and Keaton P. W., eds. (1986) *Manned Mars Missions,* vols. I and II. NASA M002.

Mendell W. W., ed. (1985) *Lunar Bases and Space Activities of the 21st Century.* Lunar and Planetary Institute, Houston. 865 pp.

Pettit D. R. (1985) Fractional distillation in a lunar environment. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 507-518. Lunar and Planetary Institute, Houston.

Pettit D. R. (1986) Performance of absorption and distillation columns in a lunar environment. *Chem. Engr. Commun., 46,* 111-122.

Welty J. R., Wicks C. E., and Wilson R. E. (1976) *Fundamentals of Momentum, Heat and Mass Transfer,* pp. 634-636, 654-660. Wiley, New York.