Award Lecture . . .

INTERFACIAL TRANSPORT PROCESSES AND RHEOLOGY

Structure and Dynamics of Thin Liquid Films

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Thanks, ASEE. I consider myself fortunate to join the roster of twenty-eight distinguished chemical engineers who are previous recipients of the 3M Lectureship Award. It is noteworthy that many of them have gone on to receive even greater accolades in their professional careers after their achievements were first recognized by the ASEE Chemical Engineering Division by this award.

I also consider myself most fortunate to have received my academic training at two of the most prestigious chemical engineering departments in the world: first as an undergraduate student at the University of Illinois at Urbana-Champaign where I studied under Tom Hanratty, John Quinn, Jim Westwater, Daniel Perlmutter, Harold Johnstone, and Max Peters (chairman at the time), and second as a doctoral student at the University of California at Berkeley under Andy Acrivos, John Prausnitz, C. Judson King, Charlie Tobias, Eugene Petersen, Don Hanson, and Charlie Wilke (my supervisor). I thank these outstanding educators for not only preparing me for the subsequent academic career but also for providing me with their friendship for the past thirty years.

I also want to thank my professional colleagues, Howard Brenner (MIT), Norman Li (Allied-Signal Corporation), Bill Krantz (Colorado), Dinesh Shah (Florida), and Bob Kintner, Ralph Peck, Dimitri Gidaspow, and Richard Beissinger (IIT), with whom I have worked and shared several graduate students and postdoctoral fellows.

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Interfacial Transport Processes represent a rapidly growing field of scientific research with applications ranging from chemical engineering separation processes to engineered materials and development of energy, food, and environmental technologies. In particular, interfacial transport processes are of specific importance in those multiphase fluid systems possessing a large specific surface, *i.e.*, whose surface-to-volume ratio is large and which utilize substances (*e.g.*, surfactants) that are interfacially active.[1] Applications of interfacial transport processes where such conditions are met include: separation processes such as distillation, flotation, and liquid membranes; processing/flow/stability of emulsions; processing/flow/stability of foams; processing/flow/stability of particle dispersions; ink-jet printing; coatings; wetting; *etc*. In most of these applications, thin liquid films are found to arise. The thickness of these films is typically on the order of the long-range intermolecular forces ($< 0.1\ \mu m$).

One of my major areas of research over the last two decades has been the structuring and dynamics of thin liquid films, focusing particularly upon the importance of interfacial transport processes and rheology. A critical thrust of our research program has been the development of instrumental techniques for measuring rheological or flow properties of fluid-fluid interfaces containing surfactants and polymeric macromolecules. Two of our instruments (the Interfacial Viscometer and the Expanding Drop Tensiometer) have been commercialized and are now used as the primary tools in emulsion and foam-stability research work. We have pursued the development of reliable measurement techniques for dynamic surface properties through a series of studies, both experimental and theoretical, which are aimed at understanding the role of interfacial rheological properties such as surface viscosities and elasticities or tension-gradients in the stabilization of liquid surfactant films and thereby in the stabilization of colloidal dispersions such as emulsions and foams. This work has been summarized in a recent text book.[2]

A new era of research on thin liquid film phenomena was opened when we discovered a new mechanism for the film stability induced by the formation of "ordered" surfactant micelle structures inside the film over distances of the order of 100 nm or 1,000Å. Recently, we have shown that the phenomenon of multilayered structuring or stratification (*i.e.,* internal layering of micelles) in thinning films is much more universal and can also be observed with concentrated submicron particle suspensions with narrow size distribution and prevailing repulsive forces.[3-7] The study of thin films of self-organizing microstructures has applications to such diverse areas as ceramics processing, coatings, magnetic tapes and discs, and emulsion and foam systems.

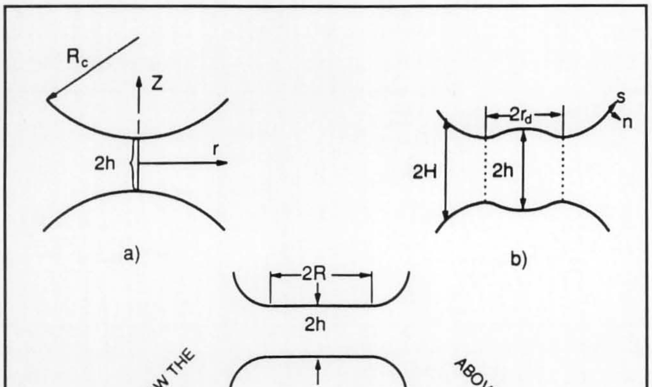

Figure 1. *Main stages in the evolution of a thin film.*

THIN LIQUID FILM PHENOMENA

Thin films have been the focus of scientific interest since Hooke's report in 1672 to the Royal Society regarding "holes" within stable soap films (later understood by Newton and Gibbs to be film regions sufficiently thin to prevent the interference of light rays reflected from upper and lower film surfaces). Thin film formation, structure, and stability are controlled by the hydrodynamic and thermodynamic interactions between the two film surfaces. The hydrodynamic interactions dominate at film thicknesses more than 100 nm or 1,000Å and are greatly influenced by the deformation and mobility of the surfaces. These, in turn, are greatly influenced by the presence of surface-active species or surfactants adsorbed at the film surfaces. Once a film has thinned to less than 100nm, thermodynamic interactions caused by van der Waals', steric, electrostatic, and structural forces begin to dominate.

The main stages in the formation and evolution of the thin liquid film between two approaching drops or bubbles, as shown in Figure 1, are:

a. Two drops approach each other, resulting in their hydrodynamic interaction;

b. Deformation of the drops leading to a bell-shaped formation which is called a "dimple";

c. The dimple gradually disappears and a plane-parallel film of radius, R, is formed. The film drains under the combined action of suction at Plateau borders and the disjoining pressure; subsequent thinning of the film depends on the surfactant concentration;

d. At low surfactant concentrations (*i.e.,* below the critical micelle concentration, CMC), when the disjoining pressure gradient is negative, it favors the growth of corrugations at the film surfaces and at a critical thickness, h_{cr}, either the film ruptures or a jump transition in thickness occurs, leading to a stable or metastable structure. This process of transition to stable or metastable state is known as "black spot formation" since at these thicknesses the film appears to be grey or black;

e. The black spots increase in size and cover the whole film;

f. The formation of an equilibrium film whose lifetime can be virtually unlimited and is dependent upon the magnitude of the capillary pressure;

g. At high surfactant concentrations (*i.e.,* above CMC), when the structural component of the disjoining pressure is positive, a long-range colloid crystal-like structure is formed due to the internal layering of micelles inside the film;

h. The thinning film exhibits a number of metastable states and its thickness changes in a stepwise fashion; the stratification depends on the micellar concentration and film size;

i. The film attains an equilibrium state with no more stepwise changes, and the resulting film is stable, thick, and contains micelles.

The stability and structure of emulsions or foams are determined primarily by the relative rates of two major breakdown processes, *i.e.,* coalescence and flocculation of the dispersed droplets or gas bubbles. Coalescence is controlled by the thinning and rupture of the thin liquid films formed between two droplets or between a single droplet and its bulk homogeneous phase as the droplet approaches the surface. Hence, if the colliding droplets have axial symmetry, the process of coalescence can be split into **(a)** mutual approach of two droplets to form a plane-parallel film, and **(b)** thinning of the film to such a thickness so that rupture can occur, followed by **(c)** rupture itself when a hole is formed. Stages (a) and (c) occur immeasurably fast so that the lifetime of the intervening film is essentially given by stage (b). Experimental observations suggest that the stability of thin liquid films is determined primarily by the rate of thinning rather than by the rupture process. Thus, the lifetime of the intervening film is an important characteristic of dispersed systems such as foams and emulsions and is directly related to their stability.

The forces of interaction that govern the lifetime of thin liquid films are the capillary pressure (suction at the Plateau borders) and the disjoining pressure. The thermodynamic properties of thin liquid films are different from those of the bulk surfactant solutions. These films possess an excess chemical potential that is manifested as an excess pressure. Derjaguin coined the term "disjoining pressure" to characterize this excess pressure. Generally, the disjoining pressure consists of the electrostatic repulsion forces between ions on the two surface layers, the attractive van der Waals' forces among all the molecules of the film, and the steric forces due to steric hindrance in closely packed monolayers.

FILM DRAINAGE MODEL

The approach of two drops or bubbles under the capillary pressure acting normal to the surfaces causes liquid to be squeezed out of the film into the Plateau borders. This liquid flow results in the convective flux of surfactant in the sublayer (see Figure 2). Therefore, the surfactant concentration at the surface is increased in the direction of the flow. The nonuniform surfactant distribution leads to surface flow which, in turn, gives rise to surface stresses. The difference in concentration along the surface results in a difference of the local values of surface tension which produces a force (equal per unit length to the gradient of surface tension) opposite to liquid flow (Marangoni-Gibbs effect). In addition, the surfactant monolayer may undergo dilating and shearing deformations which also produce surface stresses. The sum of the above stresses must counterbalance

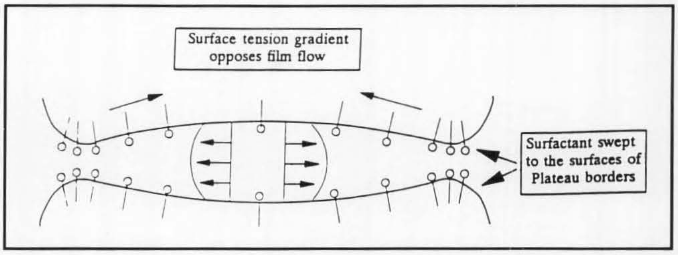

Figure 2. *Marangoni-Gibbs effect in the thin film drainage process. Surfactant is swept to the Plateau borders by flow in the film and droplet phases, thereby creating surface concentration gradients which engender surface tension gradients.*

The ASEE Chemical Engineering Division Lecturer for 1991 is Darsh Wasan of the Illinois Institute of Technology. The purpose of this award, for which the 3M Company provides financial support, is to recognize outstanding achievement in an important field of ChE theory or practice.

Darsh Wasan, a native of Bombay, India, came to the U.S. in 1957. He obtained a BS in chemical engineering from the University of Illinois at Urbana (1960) and a PhD. in chemical engineering from the University of California at Berkeley (1965). At Berkeley, he worked with Charles R. Wilke in the field of mass transfer in turbulent flow, and his doctoral thesis work was the subject matter of the 3M Annual Lecture that Charles Wilke delivered at the 1964 ASEE meeting. Darsh joined the faculty at the Illinois Institute of Technology as an assistant professor in 1964, was promoted to full professor in 1970, and was appointed chairman of the department in 1971, where he remained until 1987. After serving twice as interim dean of the college of engineering, he was made Vice President for Research and Technology at IIT and its Research Institute in 1988, and in 1991 was appointed Provost and Vice President.

Darsh's research activities span a number of separate but interrelated fields focusing particularly upon the importance of interfacial transport processes and rheology. This research, which has resulted in over two hundred publications, including seven research monographs, twelve book chapters, and three U.S. patents, has been summarized in his recent textbook, *Interfacial Transport Processes and Rheology,* written with his doctoral student, David Edwards, and Professor Howard Brenner at MIT. He has directed forty-five PhD and fifty-five MS students.

The novel instrumentation developed by his group for thin film research and interfacial rheological measurements has been adopted by industry. He is the first engineering scientist to ever receive the NSF Special Creativity Award twice. An AIChE Fellow, his other honors include the ASEE Western Electric Fund Award, the AIChE Chicago Section Ernest W. Thiele Award, Syracuse University's Donald Gage Stevens Distinguished Lectureship Award, and the Bulgarian Academy of Sciences Asen Zlatarov National Award. He is also well known for his service to the professional societies.

the tangential bulk stress from the film liquid which causes surface flow.

Reynolds was the first to study the rate of approach between surfaces separated by a draining film. His analysis assumed that the two surfaces were both flat and rigid. As pointed out by many researchers, Reynolds' equation represents a most conservative prediction; it underestimates the velocity of thinning and hence overestimates the film drainage time. Both theoretical and experimental research have shown that drainage between two liquid film surfaces is generally much more rapid due in part to a fluidic mobility within the boundary surfaces of the film. In fact, much of the thin-film drainage research in the past four decades has focused on quantifying the relevant parameters within thin film which determine whether the film will drain rapidly (promote instability of the emulsion or foam) or slowly (promote stability), largely on the basis of the mobility of the boundary surfaces. We have recently developed a generalized model which accounts for the effect of the mobility of the surfaces on film thinning phenomena by considering the kinetics of adsorption-desorption of surfactants, surface and bulk diffusion, surface rheological properties, and flow in both film and bulk phases.[8]

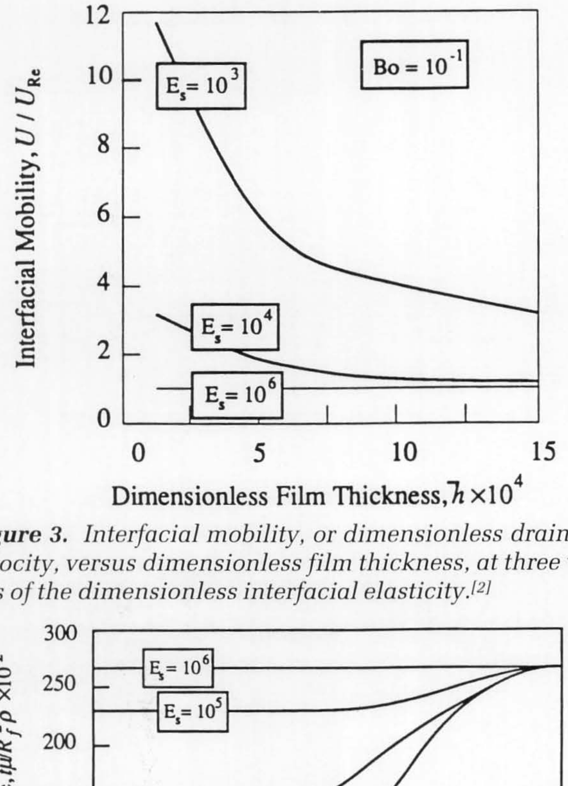

Figure 3. *Interfacial mobility, or dimensionless drainage velocity, versus dimensionless film thickness, at three values of the dimensionless interfacial elasticity.*[2]

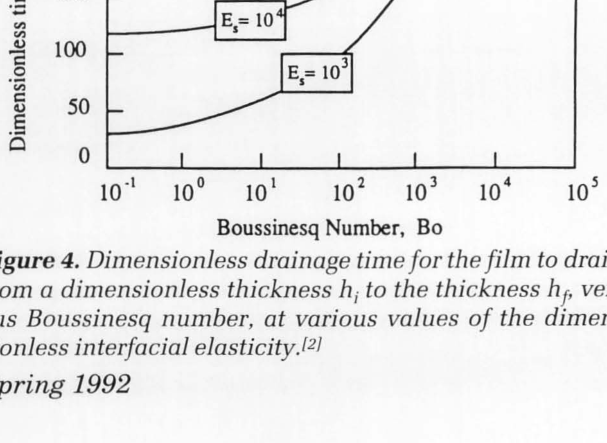

Figure 4. *Dimensionless drainage time for the film to drain from a dimensionless thickness h_i to the thickness h_f, versus Boussinesq number, at various values of the dimensionless interfacial elasticity.*[2]

In Figure 3, the effect of the surface tension gradient upon surface mobility is shown in terms of the dimensionless elasticity number E_s. The surface-tension gradient in the thinning film is created by the efflux of liquid from the film and the sweeping of surfactant along the film surfaces to the Plateau borders, as depicted in Figure 2. This creates a surface-tension gradient that opposes film drainage, creating immobile film surfaces.

The effect of surface tension gradient on the film drainage time is depicted in Figure 4. At high values of tension gradient, *i.e.,* high E_s, bulk and surface diffusion cannot counterbalance the surface tension gradient (the Marangoni-Gibbs effect) and hence, the velocity of thinning (or the drainage time) is essentially given by the Reynolds' equation. However, for small values of E_s, even at a moderate surface viscosity (*i.e.,* moderate Boussinesq number, Bo), the thinning or approach velocity is several times greater than Reynolds' velocity. An increase in surface viscosity results in decreased surface mobility and hence, higher drainage time. Thus, the thin film drainage model predicts that at low surface viscosity (*i.e.,* Boussinesq number less than 10), the Marangoni-Gibbs effect will impart the more significant influence on film drainage and, thereby, on the drop or bubble-coalescence rate. Therefore, these theoretical findings clearly suggest that differences between estimated drainage times for films with mobile surfaces (*i.e.,* no surfactant and therefore no surface rheological stress) and immobile surfaces (*i.e.,* very large surface rheological stresses leading to a solid-like surface behavior) may be several fold. It has also been reported that surface rheological properties may also considerably stabilize a thin film by imparting a rigidity to liquid film surfaces. The differences between estimated rupture times for films with mobile surfaces and immobile surfaces may also be several fold.[9-10]

Several factors may influence both the drainage time and stability of thin liquid films, including film viscosity, film thickness, surface diffusion and surfactant adsorption, and surface shear and dilatational viscosities and elasticities.[2]

The theoretical findings of a thin film drainage model, as discussed above, clearly suggest the important role that surface viscosities and elasticities play in foam and emulsion stability. Indeed, correlations between the surface shear viscosity and surface dilatational elasticity and emulsion or foam stability have been reported by many investigators.

Surface rheological properties also possess a direct significance to the bulk rheology of emulsions and foams. This may be attributed both to the presence of surfactants adsorbed to the surfaces within foams or emulsions and their large specific surface. The relationship between the macroscopic foam, rheological behavior and surface dilatational viscosity and surface-tension gradients, as well as thin foam film parameters such as disjoining pressure, was recently considered.[2] We showed that for monodisperse, spatially periodic foams possessing a finite foam film contact angle and relatively low disperse phase volume fraction, the dilatational viscosity of the foam depends primarily upon interfacial stresses owing to the large surface-to-volume ratio of the foam and is localized within the Plateau border zones of the local foam structure. Interfacial viscosities were shown to be most important for "wet" foam (*i.e.*, relatively low dispersed phase volume fraction). However, the Gibbs elasticity (*i.e.*, the interfacial tension gradient) was shown to be most important for the "dry" foam (*i.e.*, dispersed phase volume fraction approaching one). The foam dilatational viscosity for both wet and dry systems was found to be inversely proportional to film thickness.

It may be concluded that the surface rheological properties, such as surface elasticity or tension gradients and surface viscosities, play most important roles in thin film drainage and stability and thereby in both emulsion and foam stability, and in their bulk rheological behavior at surfactant concentrations near or below the critical micelle concentration (CMC).

ORDERED MICROSTRUCTURES KEY TO THIN LIQUID FILM BEHAVIOR

At high surfactant concentrations (*i.e.*, much above CMC), it has been observed that thin liquid films become thinner in a stepwise fashion—that is to say that thinning foam or emulsion films formed from micellar surfactant solutions exhibit a number of metastable states before attaining an equilibrium film thickness.

Figure 5 depicts an interferogram of films formed from surfactant micellar solutions. We used the microinterferometric method to investigate thin film behavior, as described in recent papers.[3-6] Using a film formed from a micellar surfactant solution, we observed the following:

- As soon as the film forms, it starts to decrease in thickness.
- After it is thinner than 104nm, *i.e.*, 1040Å (the last interferential maximum corresponding to the monochromatic 546nm light reflected from the film), the film thickness changes in steps (*i.e.*, stratification—see Figure 5).

Thinning film shows ordered structure

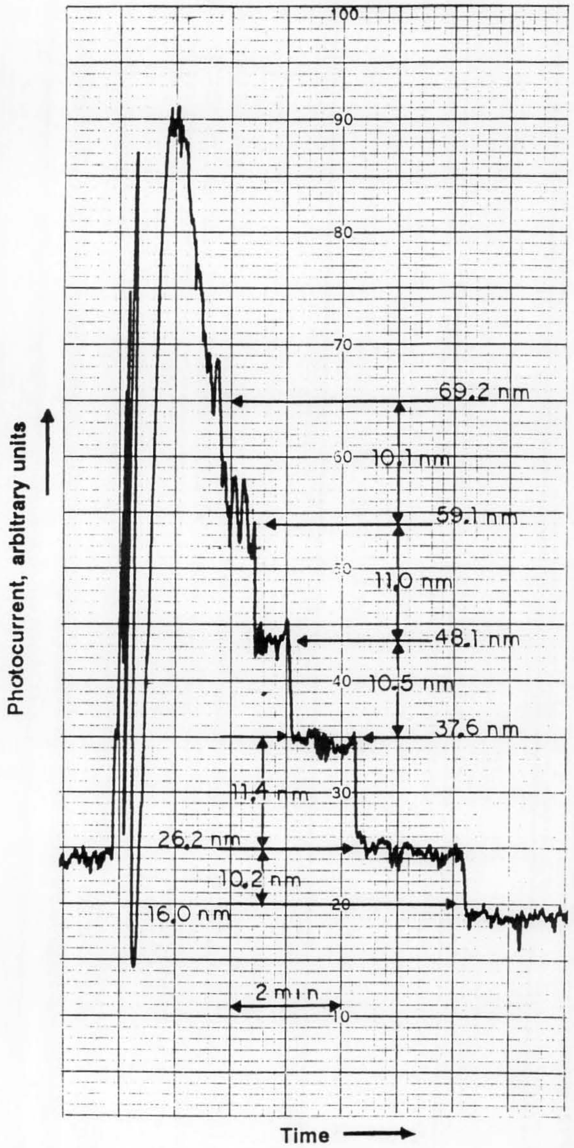

Figure 5. *Interferogram of film formed from solution of nonionic detergent (Enordet AE 1215-30, 0.052 mol/l). As film thins, less light is reflected. Formation of metastable states of uniform thickness is revealed by "steps." Height of step corresponds to thickness of film. Vertical distance between steps corresponds to micelle diameter, about 10nm. Width of steps is proportional to lifetimes of respective metastable states.*

- The film rests for a few seconds in a metastable, uniformly thick state.
- Then, dark spots (with smaller thickness than the remaining part of the film) appear and gradually increase in size (see Figure 6A).
- The spots cover the entire film and the film "rests" for a time in a new metastable state.
- Then, even darker spots appear and, after their expansion, a subsequent metastable state ensues.

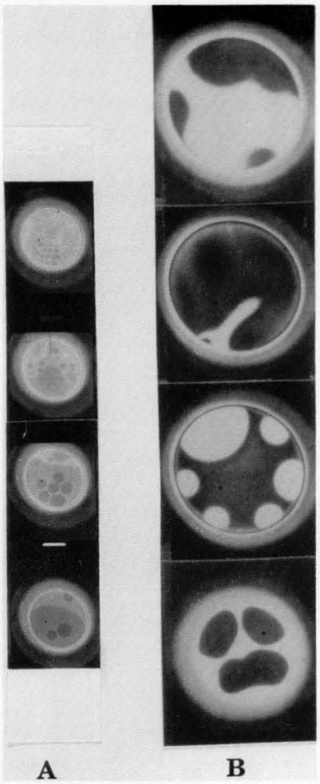

Figure 6. Stratification of films:
A. *0.1 mol/l sodium dodecylsulfate surfactant solution.*
B. *30 wt% latex suspension with a particle diameter of 91 nm.*

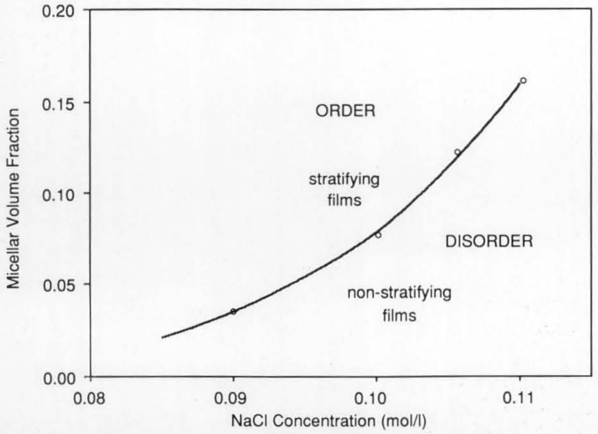

Figure 7. *Phase diagram of order/disorder transition. Volume fraction of micelles versus concentration of added NaCl. The curve represents the threshold concentration separating the regions with and without stratification in thinning foam films.*

This process continues until the film finally reaches a stable state with no more stepwise changes. The metastable state of the film appears in the interferogram as a step-wise width in proportion to the lifetime of the respective state. The calculated height of the steps is also shown in Figure 5, and the magnitude is approximately constant for all steps (about 10.6nm), which corresponds to micelle diameter, about 10nm. For ionic surfactants, the effective micellar diameter includes the Debye diameter of the surrounding electric double layer.

Some other findings: Foam films formed from concentrated suspensions of polystyrene latexes (see Figure 6B) and silica particles stratify in similar fashion.[7] But there is one difference: Because the particles are much larger than surfactant micelles, with diameters exceeding the thickness of the last interferential maximum, there can be constructive as well as obstructive interference, and the thinner spots sometimes appear brighter rather than darker than the remaining thicker film. When the repulsive force is electrostatic (as in latexes and micellar solutions of ionic surfactants), adding salt to the mixture suppresses stratification; above a threshold salt concentration, no stepwise transitions occur (see Figure 7). When the repulsion is the result of steric forces (the case with nonionic surfactants) stratification is temperature-sensitive.[6]

All the experimental data for stratifying films and theoretical analysis of these data[5] show that stratification is a universal phenomenon and is due to the formation of a long-range crystal-like structure within the liquid film and a layer-by-layer thinning of such an ordered structure.

The driving force for the step-wise thinning of the film is the gradient of the chemical potential of the micelles at the film's periphery, as discussed in our recent paper.[11] This ordering occurs because surfactant micelles or colloidal particles with narrow size distribution interact via repulsive forces and are forced into the restricted volume of the film.

Another way to demonstrate the presence of ordered structure inside a stratifying film is to form a large film (2.5cm diameter) in a vertical frame inside a glass cylinder (see Figure 8). With foam films formed from polystyrene suspensions, one observes a series of stripes of different, uniform colors at the upper, thinner part of the film. The different colors are due to interference of the common (polychromatic) light reflected by the surface of the different, uniform thickness stripes. The boundaries between the stripes are very sharp, a consequence of the stepwise profile of the film in this region, and the liquid meniscus below the film appears as a region with gradually changing colors where the order/disorder transition region is observed. The different thicknesses of the stripes as determined by the difference in reflectivity are marked on this figure. According to the colloid crystal-like model, the different color stripes contain different numbers of particle layers. Figure 8 also shows the almost circular spots in the order/disorder region. The colored spots of lesser thickness than the surrounding film move upward in the lower stripes and, eventually, fuse with the corresponding upper stripe. By measuring the velocities and size (radii) of these spots, one can estimate the effective dynamic viscosity of the ordered structure inside the film.

We observed similar sharply defined stripes with foam films formed from micellar solutions of nonionic surfactant (*e.g.*, ethoxylated alcohol, with 30 ethoxy groups and 12-15 carbon chains) with a micellar diameter of about 10nm. However, all stripes were very grey in color, though with different intensities, because the diameter of the micelles is small.

As discussed in a recent paper,[5] we have developed the theoretical model to explain the stratification in foam films of micellar solutions of ionic surfactants. The micelles interact via screened electrostatic repulsion forming an ordered structure due to the restricted volume of the film. The model permits, for the first time, calculation of the structural contribution to the disjoining pressure of the

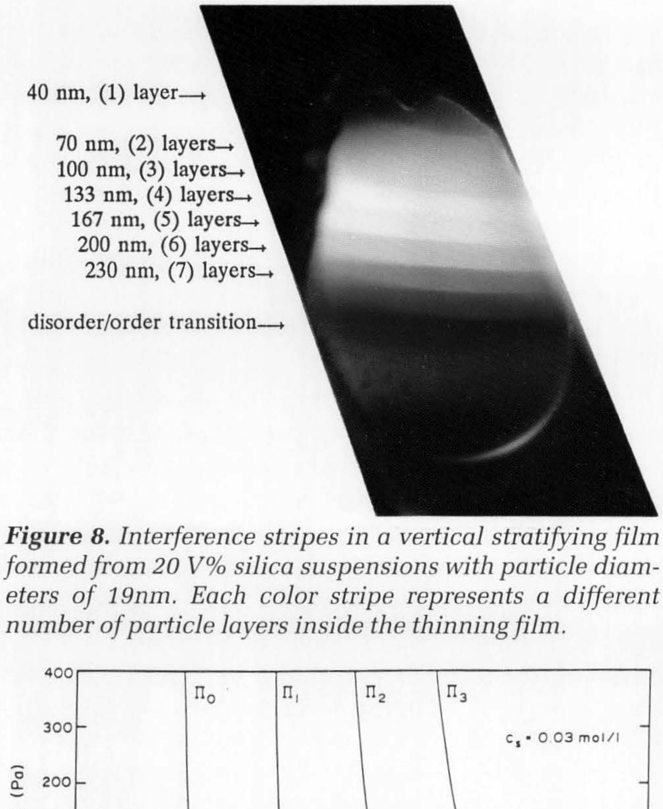

Figure 8. *Interference stripes in a vertical stratifying film formed from 20 V% silica suspensions with particle diameters of 19nm. Each color stripe represents a different number of particle layers inside the thinning film.*

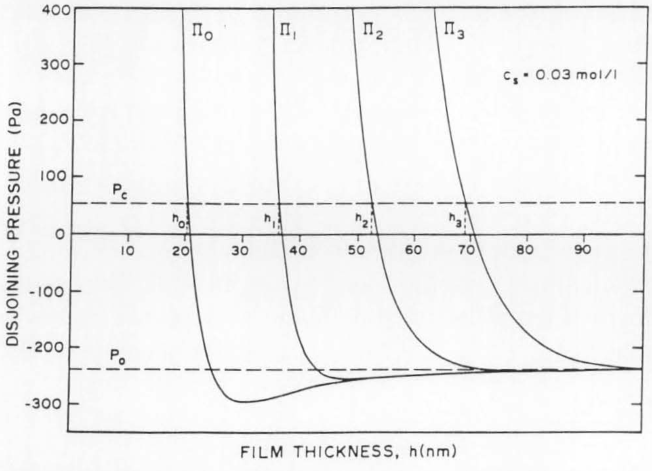

Figure 9 *Calculated disjoining isotherms $\Pi_n(h)$ for thin films with n micellar layers inside (h_n = 0,1,2,3).*[5]

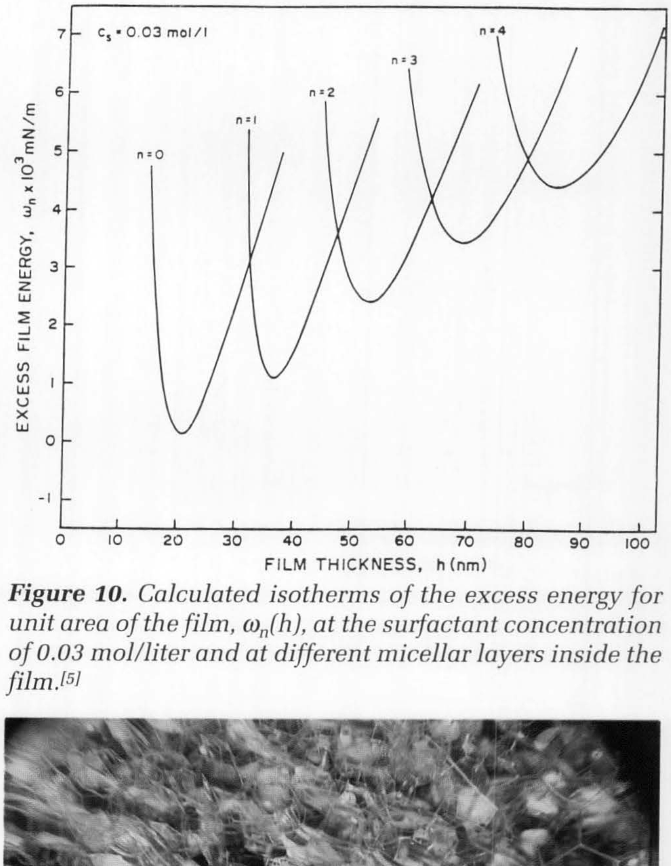

Figure 10. *Calculated isotherms of the excess energy for unit area of the film, $\omega_n(h)$, at the surfactant concentration of 0.03 mol/liter and at different micellar layers inside the film.*[5]

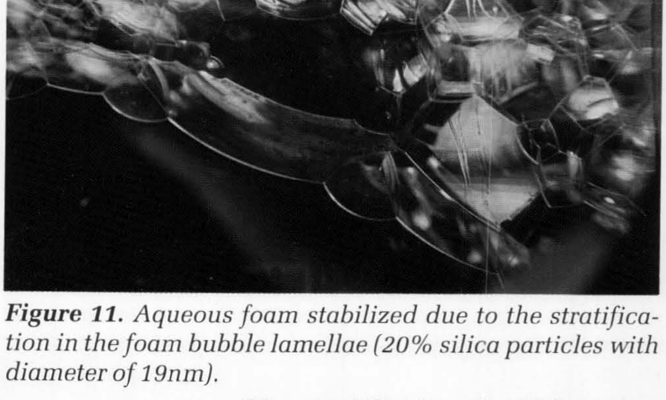

Figure 11. *Aqueous foam stabilized due to the stratification in the foam bubble lamellae (20% silica particles with diameter of 19nm).*

film that arises from the presence of micellar structure within the films.

Figure 9 shows the disjoining pressure isotherm calculated from our theoretical model[5] for 0.03 mol/l concentration of sodium dodecyl sulfate. By integration of disjoining pressure with respect to the film thickness, we derived the expression for the interaction free energy. The curves for the excess free energy (see Figure 10) exhibit the structural stability of films due to the inner multi-layering of micelles. The curves exhibit minima, which correspond to the metastable state (n = 1,2,3,...) and to the final stable state (n = 0) of the film. A stepwise film thickness transition can be interpreted as a transition from a given metastable state to the next one. The experimental values of the film thickness are in good agreement with the ones calculated from the theoretical model. The shape of these energy curves also properly reflect the phenomenon of stratification; the energy of the metastable state decreases with the decrease in film thickness, and consequently, the film stability increases. Work is in progress in our laboratory to delineate effects of several factors such as surfactant micellar concentration, electrolyte, temperature, and film curvature on the film stratification phenomenon using our newly developed surface force balance apparatus for films with fluid surfaces.

TABLE 1
Technological Impact of Thin Film Research

- Coalescence of drops and bubbles as in **Emulsions and Foams**
- **Tertiary Oil Recovery** and other processes concerned with multiphase flow in porous media
- Spreading of liquids on solid surfaces as in **Coating** processes
- **Magnetic Tapes and Discs** involving deposition of thin films of colloidal magnetic particles which must be well-bound to the support surface
- **Tribology**, the science of lubrication and wear, reveals the importance of thin film lubricating layers whose properties can be significantly different from those of the parent bulk material
- **Space Technology** has created a demand for thin film coatings to make processing container wall selectively wetting to certain fluids
- **Biotechnology** which can provide economic pathways to chemical feedstocks and novel products which require a basic understanding of the lipid thin film layers which constitute the cell walls
- **Ceramics** processing, the intervening thin liquid films between powder particles determine the stability of colloidal dispersions and thereby influence the properties of the engineered materials
- Formation of new materials such as **Biochips** with prescribed microstructures
- **Microelectronics** industry employs a variety of deformable films to selectively etch, form, and protect chips, microsensors, and other types of microcircuitry

CONCLUDING REMARKS

The formation of long-range ordered structures inside thin films has many implications of both fundamental and practical significance. For example, the dynamic process of stratification or multilayer microstructuring in sub-micron thin liquid films can serve as an important tool for probing the long-range structural or interaction forces in concentrated particle suspensions and colloidal dispersions. The rheology of such dispersions containing stratifying films will be quite different. We have recently attempted to determine the dynamic viscosity of the stratifying foam film as depicted in Figure 8. Such measurements are detailed elsewhere.[12] The dynamic viscosity of the stratifying foam film was found to be much higher than that of the pure solvent.

From a practical point of view, we have identified a new mechanism for the stabilization of foam and emulsion films via the presence of such ordered microstructures inside the films. The lifetimes of foams or emulsions with stratifying films are observed to be much longer.

Figure 11 clearly shows, for the first time, a photograph of an aqueous foam system stabilized due to the stratification in the foam bubble lamellae.[13]

Finally, at a recent NSF Workshop on "Interfacial Phenomena in the New and Emerging Technologies," thin film science has been identified as one of the pivotal areas of basic research which is needed to strengthen the competitiveness of U.S. science and technology.[14] Thin liquid films are gaining large scientific and industrial applications, as outlined in Table 1.

ACKNOWLEDGEMENT

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ChE book review

PROCESS SYSTEMS ANALYSIS AND CONTROL, *2nd edition*

by D. Coughanowr

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Reviewed by

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I learned process concepts from the first edition of this book when I was a student at the University of Arkansas. The clarity of its presentation and the effectiveness of the instructor (Carl Griffis) have been the main reasons for my sustained interest in process control for the last twenty years.

Much of the material from the first edition has been retained in the second edition, but there are additional new chapters on advanced control strategies, process identification, sampled-data control, state-space representation, multivariable control, and computers in process control applications.

In advanced control, Professor Coughanowr covers cascade and feedforward control, ratio control, dead-time compensation, and internal model control. In the chapters on sampled-data systems the author discusses sampling operations, Z-transforms, design of sampled data controllers, and stability. The chapter on state space method is a good introduction to the subject, as is the chapter on multivariable control.

In the chapter on computer simulation, the author discusses the use of TUTSIM and its potential applications to process control problems. TUTSIM uses an analog computing type of logic and is easy to learn and use. In the last chapter the student is introduced to distributed control concepts. The new material is well written and clear. However, in many instances the level of detail is so small that it is not of much practical use. (But, in a first course in process control, how many topics can be covered?) Also, there does not appear to be enough examples and problems in some of the chapters.

Having made a phenomenal impact on improving quality (and therefore competitiveness) in discrete manufacturing industries, Statistical Quality Control (SQC) concepts have arrived on the scene in continuous industries as well. Statisticians are routinely consulted on issues of quality, but the control engineer is on the sidelines, often unable to make an impact on process operations. Control technologies which can be shown to have a direct impact on quality are needed. This text, as well as others on the market (including ours), does not appear to provide these perspectives to the student.

In closing, the second edition is a good addition to the collection of textbooks on undergraduate process control, subject to the comments in this review. Students and instructors alike will enjoy learning and teaching from this book. ❐

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how it might have been avoided, and how it can be prevented in the future.

There are sample problems throughout the text, and each chapter has problems and questions at the end. Most of the sample problems are clear and easily followed. A manual containing solutions for most of the problems is available. A few of the solutions are incorrect, but the errors are mostly minor and easily found. There are some errors in printing, again mostly minor, and mostly identified in an errata list available from the authors. The errors distract little from the presentation of the material.

I find the text to be a welcome addition; it presents more than enough material for an undergraduate course in chemical process safety. It contains sufficient references that considerable additional material can be found, either for incorporation by the instructor or for additional study by the student. The book can also serve the practicing engineer by providing a basic background for understanding other information that is available. The most important accomplishment of the text may be that it provides the basis for including the study of chemical process safety in the curriculum for chemical engineers. That is something we need to have emphasized more strongly if we are to be professionally competent. ❐