

**E.T.S. D'ENGINYERS INDUSTRIALS DE BARCELONA**

*Departament d'enginyeria química de la UPC*

**CINÉTICA, EQUILIBRIO Y  
TRANSPORTE DE MATERIA EN  
LA HIDRATACIÓN CATALÍTICA  
DIRECTA DE isoBUTENO A  
*ter*-BUTANOL**

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## BIBLIOGRAFIA

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- Ahtchi-Ali, B., and Pedersen, H. "Very Large Lattice Model of Liquid Mixing in Trickle Beds" *Ind. Eng. Chem. Fundam.* **25**, 108 (1986).
- Anderson, E. (ed.) "New Raw-Material Source Looms for Fast-Rising Octane Boosters" *Chem. Eng. News*, July 18, 9 (1983).
- ARCO Chemical Europe *Oxinol Technical Bulletin*, England (1985).
- Baker, O. "Simultaneous flow of oil and gas" *Oil Gas J.* **53**, 185 (1954).
- Bakos, M., and Charpentier, J.C. "Taux de Rétention pour des Écoulements Gaz-Liquide à Co-Courant vers le Bas dans les Colonnes à Garnissage Arrosé et Noyé" *Chem. Eng. Sci.* **25**, 1822 (1970).
- Baldi, G. "Heat Transfer in Gas-Liquid-Solid Reactors" NATO Institute on Multi-Phase Chemical Reactors, Vineiro, Portugal (1980).
- Barron, C.H.Jr., Chaty, J.C., González, R.A., and Eldridge J.W. "Thermodynamic Properties of Isobutylene" *J. Chem. Eng. Data* **7**, 394 (1962).
- BASF A.G.: Merger, F., Volkamer, K., Nestler, G., and Schubert, E. *tert-Butanol*. West German Patent 2,538,036 (1977).
- Beaudry, E.G., Duduković, M.P., and Mills, P.L. "Trickle-Bed Reactors: Liquid Diffusional Effects in a Gas-Limited Reaction" *AIChE J.* **33**, 1435 (1987).
- Beaudry, E.G., Mills, P.L., and Duduković, M.P. "Gas-Liquid Downflow, Upflow and Countercurrent Flow in Packed Beds: Reactor Performance for a Gas-Limiting Reaction" *Proceed. World Congress III Chem. Eng.* Tokyo, Vol. IV, 173 (1986).
- Beeckman, J.W., and Froment, G.F. "Deactivation of Catalyst by Coke Formation in the Presence of Internal Diffusional Limitation" *Ind. Eng. Chem. Fund.* **21**, 243 (1982).
- Bernasconi, F. "Value of Oxygenates to the Refiner for Gasoline Blending" *Proceed. VII Int. Symp. on Alcohol Fuels*, 475 (1986).
- Bird, R.B., Stewart, W.E., and Lightfoot, E.N. *Transport Phenomena*. Wiley, New York (1960).
- Biscaia, E.C., and Cid, E.A. "Isothermal Trickle-Bed Reactor Modeling for Reactions with a Gas-Phase Limitant Reactant" *Proceed. World Congress III Chem. Eng.* Tokyo, Vol. IV, 784 (1986).
- Bischoff, K.B. "An Extension of the General Criterion for Importance of Pore Diffusion with Chemical Reactions" *Chem. Eng. Sci.* **22**, 525 (1967).
- Bondi, A. "Handling Kinetics from Trickle-Phase Reactors" *Chem. Tech.* 185 (March, 1971)
- Boyd, R.H., Taft, R.W. Jr., Wold, A.P., and Christman, D.R. *J. Am. Chem. Soc.* **82**, 4729 (1960).
- Buffham, B.A., and Rathor, M.N. "The Influence of Viscosity on Axial Mixing in Trickle Flow in Packed Bed" *Tr. Inst. Chem. Engrs.* **56**, 266 (1978).
- Cáceres, E., Puigjaner, L., and Recasens, F. "A Trickle-Bed Process for Hydration of isoButene to tert-Butyl Alcohol: a Study of Reactor Performance" *Chem. Eng. J.* **37**, 43 (1988).
- Chao, Y.-C., Chang, J.-S., and Huang, H.-P. "Set Point Optimization of an Adiabatic Trickle-Bed Reactor System" *Can. J. Chem. Eng.* **68**, 139 (1990).
- Charpentier, J.C. "Mass Transfer in Packed Beds" *Chem. Eng. J.* **11**, 161 (1976).
- Charpentier, J.C., and Favier, M. "Some Liquid Holdup Experimental Data in Trickle-Bed Reactors for Foaming and Non-Foaming Hydrocarbons" *AIChE J.* **21**, 1213 (1975).
- Chou, T.S. "Liquid Distribution in a Trickle-Bed with Redistribution Screen Placed in the Column" *Ind. Eng. Chem. Proc. Des. Dev.* **23**, 501 (1984).
- Chou, T.S., Worley, F.L., and Luss, D. "Transition to Pulsed Flow in Mixed-Phase Cocurrent Downflow through a Fixed Bed" *Ind. Eng. Chem. Proc. Des. Dev.* **16**, 424 (1977).
- Chou, T.S., Worley, F.L., and Luss, D. "Local Particle-Liquid Mass Transfer Fluctuations in Mixed-Phase Cocurrent Downflow through a Fixed Bed in the Pulsing Regime" *Ind. Eng. Chem. Fundam.* **18**, 279 (1979).

- Christensen, G., McGovern, S.J., and Sundaresan, S. "Cocurrent Downflow of Air and Water in a Two-Dimensional Packed Column" *AIChE J.* **32**, 1677 (1986).
- Chu, C.F., and Ng, K.M. "Model for Pressure Drop Hysteresis in Trickle-Beds" *AIChE J.* **35**, 1365 (1989).
- Clements, L.D., and Schmidt, P.C. "Pressure Drop in a Two-Phase Cocurrent Up-Flow" *1976 AIChE Annual Meeting*, Chicago (1976).
- Clements, L.D., and Schmidt, P.C. "Two-Phase Pressure Drop in Cocurrent Downflow in Packed Beds: Air-Silicone Oil System" *AIChE J.* **26**, 314 (1980a).
- Clements, L.D., and Schmidt, P.C. "Dynamic Liquid Holdup in Two-Phase Downflow in Packed Beds: Air-Silicone Oil System" *AIChE J.* **26**, 317 (1980b).
- Colombo, F., Corl, L., Dalloro, L., and Delogu, P. "Equilibrium Constant for the Methyl *tert*-Butyl Ether Liquid-Phase Synthesis by Use of UNIFAC" *Ind. Eng. Chem. Fundam.* **22**, 219 (1983).
- Crank, J. *The Mathematics of Diffusion*. 2nd edn. Oxford University Press, Oxford (1975).
- Crine, M., and L'Homme, G.A. "The Percolation Theory: A Powerful Tool for a Novel Approach to the Design of Trickle-Bed Reactors and Columns" *Am. Chem. Soc. Sym. Ser.* **196**, 407 (1982).
- Crine, M., and L'Homme, G.A. "Advances in Trickle-Bed Reactor Modeling" In *Recent Advances in the Engineering Analysis of Chemically Reacting Systems*. Doraiswamy, L.K. (ed.). Wiley, New York (1984).
- Crine, M., and Marchot, P. "Downward Cocurrent Gas-Liquid Flows in Fixed Particle Beds" *Entropie* **102**, 28 (1981).
- Crine, M., and Marchot, P. *Int. Chem. Eng.* **24**, 53 (1983).
- Crine, M., Marchot, P., and L'Homme, G.A. "A Phenomenological Description of the Trickle-Bed Reactor Applications to the Hydrotreating of Petroleum Fractions" *Chem. Eng. Sci.* **35**, 51 (1980).
- De Frutos Val, D. "Ahorro de Plomo en Gasolinas por la Utilizacion de Compuestos Oxigenados" *Ingeniería Química*, 73 (Diciembre, 1985).
- Delaunay, Ch.B., Storck, A., Laurent, A., and Charpentier, J.C. "Electrochemical Determination of Liquid-Solid Mass Transfer in a Fixed-Bed Irrigated Gas-Liquid Reactor with Downward Cocurrent Flow" *Int. Chem. Eng.* **22**, 244 (1982).
- Delion, A., Torck, B., and Hellin, M. "Equilibrium Constant for the Liquid-Phase Hydration of Isobutylene over Ion-Exchange Resin" *Ind. Eng. Chem. Proc. Des. Dev.* **25**, 889 (1986).
- Dharwadkar, A., and Silvester, N.D. "Liquid-solid Mass Transfer in Trickle Beds" *AIChE J.* **23**, 376 (1977).
- Dooley, K.M., Williams, J.A., Gates, B.C., and Albright, R.L. "Sulfonated Poly(styrene-divinylbenzene) Catalysts. II. Diffusion and the Influence of Macroporous Polymer Physical Properties on the Rate of Reesterification" *J. Catalysis* **74**, 361 (1982).
- Dwivedi, P.M., and Upadhyay, S.N. "Particle Fluid Mass Transfer in Fixed and Fluidized Beds" *Ind. Eng. Chem. Proc. Des. Dev.* **16**, 157 (1977).
- Eberz, W.F., and Lucas, H.J. "The Hydration of Unsaturated Compounds. II. The Equilibrium between *i*-Butene and *t*-Butanol and the Free Energy of Hydration of *i*-Butene" *J. Am. Chem. Soc.* **56**, 1230 (1934).
- El-Hisnawi, A.A., Duduković, M.P., and Mills, P.L. "Trickle-Bed Reactors: Dynamic Tracer Tests, Reaction Studies and Modeling of Reactor Performance" *7th Int. Symp. on Chem. Reaction Eng.*, Boston, (1982).
- Ellman, M.J., Midoux, N., Laurent, A. and Charpentier, J.C. "A new Improved Pressure Drop Correlation for Trickle-Bed Reactors" *Chem. Eng. Sci.* **43**, 2201 (1988).
- Ellman, M.J., Midoux, N., Wild, G., Laurent, A., and Charpentier, J.C. "A New, Improved Liquid Hold-up Correlation for Trickle-Bed Reactors." *Chem. Eng. Sci.* **45**, 1677 (1990).
- Ergun, S. "Fluid Flow through Packed Columns" *Chem. Eng. Prog.* **48**, 89 (1952).
- Eroğlu, I., and Doğu, T. "Dynamic Analysis of a Trickle Bed Reactor by Moment Technique" *Chem. Eng. Sci.* **38**, 801 (1983).
- Fox, R.O. "On the Liquid Flow Distribution in Trickle-Bed Reactors" *Ind. Eng. Chem. Res.* **26**, 2413 (1987).
- Fredenslung, A., Gmehling, J., and Ramunssen, P. *Vapor-Liquid Equilibria Using UNIFAC*. Elsevier, Amsterdam, (1977a).
- Fredenslund, A., Gmehling, J., Michelsen, M.L., Rasmussen, P., and Prausnitz, J.M. "Computerized Design of Multicomponent Distillation Columns Using the UNIFAC Group Contribution. Method for Calculation of Activity Coefficients" *Ind. Eng. Chem. Proc. Des. Dev.* **16**, 450 (1977b).
- Fredenslung, A., Rasmussen, P., and Michelsen, M.L. "Recent Progress in the Computation of Equilibrium Ratios" *Chem. Eng. Commun.* **4**, 485 (1980).

- Froment, G.F., and Bischoff, K.B. *Chemical Reactor Analysis and Design*. 2nd edn. Wiley, New York (1991).
- Fukushima, S., and Kusaka, K. "Interfacial Area and Boundary of Hydrodynamic Flow Region in Packed Column with Cocurrent Downward Flow" *J. Chem. Eng. Japan* **10**, 461 (1977a).
- Fukushima, S., and Kusaka, K. "Liquid-phase Volumetric Mass Transfer Coefficient and Boundary of Hydrodynamics Flow Region in Packed Column with Cocurrent Downward Flow" *J. Chem. Eng. Japan* **10**, 468 (1977b).
- Fukushima, S., and Kusaka, K. "Boundary of Hydrodynamic Flow Region and Gas-Phase Mass Transfer Coefficient in Packed Column with Cocurrent Downward Flow" *J. Chem. Eng. Japan* **11**, 241 (1978).
- Funk, G.A., Harold, M.P., and Ng, K.M. "Effectiveness of a Partially Wetted Catalyst for Biomolecular Reaction Kinetics" *AIChE J.* **34**, 1361 (1988).
- Funk, G.A., Harold, M.P., and Ng, K.M. "Reaction Adsorption Effects on Partially Wetted Catalyst Performance" *Chem. Eng. Sci.* **44**, 2509 (1989).
- Funk, G.A., Harold, M.P., and Ng, K.M. "A Novel Model for Reaction in Trickle-Beds with Flow Maldistribution" *Ind. Eng. Chem. Res.* **29**, 738 (1990).
- Funk, G.A., Harold, M.P., and Ng, K.M. "Experimental Study of Reaction in a Partially Wetted Catalytic Pellet" *AIChE J.* **37**, 202 (1991).
- Furzer, I.A., and Michell, R.W. "Liquid-Phase Dispersion in Packed Beds with Two-Phase Flow" *AIChE J.* **16**, 386 (1970).
- Gates, B.C., and Rodriguez, W. "General and Specific Acid Catalysis in Sulfonic Acid Resin" *J. Catal.* **31**, 27 (1973).
- Gates, B.C., Wisnouskas, J.S., and Heath, H.W.Jr. "The Dehydration of t-Butyl Alcohol Catalyzed by Sulfonic Acid Resin" *J. Catal.* **24**, 320 (1972).
- Gehlawat, J.K., and Sharma, M.M. "Absorption of Isobutylene in Aqueous Solutions of Sulfuric Acid" *Chem. Eng. Sci.* **23**, 1173 (1968).
- Gianetto, A., Baldi, G., and Specchia, F. "Absorption in Packed Towers with Cocurrent Downward, High-Velocity Flows. I. Interfacial Areas" *Ing. Chim.* **6**, 125 (1970).
- Gianetto, A., Baldi, G., Specchia, V., and Sicardi, S. "Hydrodynamics and Solid-Liquid Contacting Effectiveness in Trickle-Bed Reactors" *AIChE J.* **24**, 1087 (1978).
- Gianetto, A., Specchia, F., and Baldi, G. "Absorption in Packed Towers with Cocurrent Downward, High-Velocity Flows. II. Mass Transfer" *AIChE J.* **19**, 916 (1973).
- Goenaga, A., Smith, J.M., and McCoy, B.J. "Study of Gas-to-Liquid Mass Transfer by Dynamic Methods in Trickle Beds" *AIChE J.* **35**, 159 (1989).
- Goto, S., and Smith, J.M. "Trickle-Bed Reactor Performance. Part I. Holdup and Mass Transfer Effects" *AIChE J.* **21**, 706 (1975a).
- Goto, S., and Smith, J.M. "Trickle-Bed Reactor Performance. Part II. Reaction Studies" *AIChE J.* **21**, 714 (1975b).
- Goto, S., and Smith, J.M. "Analysis of Trickle-Bed Reactors" *AIChE J.* **24**, 294 (1978).
- Goto, S., Lakota, A., and Levec, J. "Effectiveness Factors of nth. Order Kinetics in Trickle-Bed Reactors" *Chem. Eng. Sci.* **36**, 157 (1981).
- Goto, S., Levec, J., and Smith, J.M. "Mass transfer in Packed Beds with Two Phase Flow" *Ind. Eng. Chem. Proc. Des. Dev.* **14**, 473 (1975).
- Goto, S., Levec, J., and Smith, J.M. "Trickle-Bed Oxidation Reactors" *Catal. Rev.-Sci. Eng.* **15**, 187 (1977).
- Gupta, V.P., and Douglas, W.J.M. "Diffusion and Chemical Reaction in Isobutylene Hydration within Cation Exchange Resin" *AIChE J.* **13**, 883 (1967a).
- Gupta, V.P., and Douglas, W.J.M. "Measurements of Isobutylene Absorption in Cation Exchange Resins" *Canadian J. Chem. Eng.* **45**, 57 (1967b).
- Hanika, J., Vychodil, P. and Ruzicka, V. "A Cell Model of the Isothermal Trickle-Bed Reactor" *Coll. Czech. Chem. Commun.* **43**, 2111 (1978).
- Hanratty, P.J., and Duduković, M.P. "Detection of Flow Maldistribution in Packed-Beds via Tracers" *AIChE J.* **36**, 127 (1990).
- Harold, M.P., and Ng, K.-M. "Effectiveness Enhancement and Reactant Depletion in a Partially Wetted Catalyst" *AIChE J.* **33**, 1448 (1987).

- Hashimoto, K., Muroyama, K., Fujiyoshi, K., and Nagata, S. "Effective Radial Thermal Conductivity in Cocurrent Flow of Gas and Liquid through a Packed Bed" *Int. Chem. Eng.* **16**, 720 (1976).
- Haure, P.M., Hudgins, R.R., and Silveston, P.L. "Steady-State Models for SO<sub>2</sub> Oxidation in a Trickle-Bed Reactor" *Chem. Eng. J.* **43**, 121 (1990).
- Hawley, G.G. *Diccionario de Química y Productos Químicos*. Omega, Barcelona (1975).
- Hayduk, W., and Cheng, S.C. "Review of Relation between Diffusivity and Solvent Viscosity in Dilute Liquid Solutions" *Chem. Eng. Sci.* **26**, 635 (1971).
- Heath, H.W., and Gates, B.C. "Mass Transport and Reaction in Sulfonic Acid Resin Catalyst: the Dehydration of t-Butyl Alcohol" *AIChE J.* **18**, 321 (1972).
- Helfferich, F. "Catalysis by Ion Exchangers". In *Ion Exchange*. Mc Graw Hill, New York (1962).
- Henry, H.C., and Gilbert, J.B. "Scale Up of Pilot Plant Data for Catalytic Hydroprocessing" *Ind. Eng. Chem. Proc. Des. Dev.* **12**, 328 (1973).
- Herskowitz, M., and Abuelhaija, M. "Liquid-Solid Mass Transfer in a Trickle-Bed Reactor Measured by Means of a Catalytic Reaction" *Chem. Eng. Sci.* **40**, 631 (1985).
- Herskowitz, M., and Mosseri, S. "Global Rates of Reaction in Trickle-Bed Reactors: Effects of Gas and Liquid Flow Rates" *Ind. Eng. Chem. Fundam.* **22**, 4 (1983).
- Herskowitz, M., and Smith, J.M. "Liquid Distribution in Trickle-bed Reactors." *AIChE J.* **24**, 439 (1978).
- Herskowitz, M., and Smith, J.M. "Trickle-Bed Reactors: a Review" *AIChE J.* **29**, 1 (1983).
- Herskowitz, M., Carbonell, R.G., and Smith, J.M. "Effectiveness Factors and Mass Transfer in Trickle-Bed Reactors" *AIChE J.* **25**, 272 (1979).
- Hirata, M., Ohe, S., and Nagahama, K. *Computer Aided Data Book of Vapor-Liquid Equilibria*. Kodansha-Elsevier, Tokyo (1975).
- Hirose, T., Toda, M., and Sato, Y. "Liquid-phase Mass Transfer in Packed-Bed Reactor with Cocurrent Gas-Liquid Downflow" *J. Chem. Eng. Japan* **7**, 187 (1974).
- Hirose, T., Toda, M., and Sato, Y. "Liquid-to-particle Mass Transfer in Fixed-Bed Reactor with Cocurrent Gas-Liquid Downflow" *J. Chem. Eng. Japan* **9**, 220 (1976).
- Hochman, J.M., and Effron, E. "Two-Phase Cocurrent Downflow in Packed Beds" *Ind. Eng. Chem. Fundam.* **8**, 63 (1969).
- Hofmann, H.P. "Multiphase Catalytic Packed-Bed Reactions" *Catal. Rev. Sci. Eng.* **17**, 21 (1978).
- Holub, R., Duduković, M.P., and Ramachandran, P.A. "The Hydrodynamics of Trickle-Bed Reactors: A Diagnostic Model of Phase Maldistribution" *1988 AIChE Annual Meeting*, Washington D.C. (1988).
- Hüls, C.W. "The Hüls TBA/Isobutene Process as a Supplement for MTB Process to Increase Flexibility" *Chemische Werke Hüls AG, Marl (Germany)* (1984).
- Hulton, B.E.G., and Leung, L.S. "Cocurrent Gas-Liquid Flow in Packed Columns" *Chem. Eng. Sci.* **29**, 1681 (1974).
- Hunter, D., *Chem. Eng.* **12 K** (November, 1986).
- Ihm, S.-K., and Oh, I.-H. "Correlation of a Two-Phase Model for Macroreticular Resin Catalyst in Sucrose Inversion" *J. Chem. Eng. Japan* **17**, 58 (1984).
- Ihm, S.-K., Chung, M.J., and Park, K.-Y. "Activity Difference between the Internal and External Sulfonic Groups of Macroreticular Ion-Exchange Resin Catalysts in Isobutylene Hydration" *Ind. Eng. Chem. Res.* **27**, 41 (1988).
- IMSL *Problem-Solving Software System*. IMSL Inc., Houston, Texas, (1987).
- Kaiser, J.R., Beuther, H., Moore, L.D., and Odioso, A.C. "Direct Hydration of Propylene Over Ion-Exchange Resins" *Ind. Eng. Chem. Prod. Res. Dev.* **1**, 266 (1962).
- Kan, K.M., and Greenfield, P.F. "Multiple Hydrodynamic States in Cocurrent Two-Phase Flow through Packed Beds" *Ind. Eng. Chem. Proc. Des. Dev.* **17**, 482 (1978).
- Kazanskii, V.S., Entelis, S.G., and Chirkov, N.M. "Solubility of Gaseous Isobutylene in Water" *Z. Fiz. Khim.* **23**, 1409 (1959).
- Kennedy, C.R., and Jaffe, S.B. "Analysis of Tracer Experiments from Commercial-Scale Trickle-Bed Reactors" *Chem. Eng. Sci.* **41**, 845 (1986).
- Kenttämää, J., Tommila, E., and Martti, M. "Some Thermodynamic Properties of the System t-Butanol-Water" *Ann. Acad. Sci. Fennicae Series A II*, **93**, 2 (1959).

- Klingbiel, W.J., and Coughenour, G.E. "Which Oxygenates Will Fill The Octane Gap?" *Energy Progress* **6**, 106 (1986).
- Kobayashi, S., Kushiyama, S., Ida, Y., and Wakao, W. "Flow Characteristics and Axial Dispersion in Two-Phase Downflow in Packed Columns" *Kagaku Kogaku Ronbunshu* **5**, 256 (1979).
- Kohler, M., and Richarz, W. "Investigation of Liquid Holdup in Trickle Bed Reactors" *Ger. Chem. Eng.* **8**, 295 (1985).
- Komiyama, H., and Smith, J.M. "Intraparticle Mass Transport in Liquid-Filled Pores" *AIChE J.* **20**, 728 (1974a)
- Komiyama, H., and Smith, J.M. "Surface Diffusion in Liquid-filled Pores" *AIChE J.* **20**, 1110 (1974b)
- Koros, R.M. "Engineering Aspects of Trickle Bed Reactors". In *Chemical Reactor Design and Technology*. de Lasa, H.I. (ed.). NATO AISI Ser. E, no. 110. Martinus Nijhoff, Dordrecht (1986).
- Kun, K.A., and Kunin, R. "The Pore Structure of Macroporous Ion Exchange Resins" *J. Polymer Sci. Part C*, **16**, 1457 (1967).
- Lai, C.-C., and Tan, C.-S. "Approximate Expressions for Second-Order Reaction Effectiveness Factors in Trickle-Bed Reactors" *Chem. Eng. Sci.* **46**, 575 (1991).
- Lakota, A., and Levec, J. "Solid-Liquid Mass Transfer in Packed Beds with Cocurrent Downward Two-Phase Flow" *AIChE J.* **36**, 1444 (1990).
- Larachi, F. "Etude hydrodynamique d'un reacteur catalytique à lit fixe arrosé fonctionnant sous pression à co-courant de gaz et liquide vers le bas: pertes de charge, taux de rétention du liquide et régimes d'écoulement" Dissertation for the Diplôme d'Etudes Approfondies (DEA). Institut National Polytechnique de Lorraine, Nancy, France (1988).
- Larkins, R.P., White, R.R., and Jeffrey, D.W. "Two Phase Cocurrent Flow in Packed Beds" *AIChE J.* **7**, 231 (1961).
- Latifi, M.A., Laurent, A., and Storck, A. "Liquid-Solid Mass Transfer in a Packed Bed with Downward Cocurrent Gas-Liquid Flow: an Organic Liquid Phase with High Schmidt Number" *Chem. Eng. J.* **38**, 47 (1988).
- Lee, H.M., and Smith J.M. "Trickle-Bed Reactors: Criteria of Negligible Transport Effects and of Partial Wetting" *Chem. Eng. Sci.* **37**, 223 (1982).
- Leffler, J., and Cullinan, H.T.Jr. "Variation of Liquid Diffusion Coefficients with Composition. Binary Systems" *Ind. Eng. Chem. Fundam.* **9**, 84 (1970).
- Lekshmi-Narayanan, H., Pan., C.-M., Haure, P.M., and Hudgins, R.R. "A Model for Trickle-Bed Reactors in View of Changing Gas Velocity" *Can. J. Chem. Eng.*, **68**, 327 (1990).
- Lemay, Y., Pineault, G., and Ruether, J.A. "Particle-Liquid Mass Transfer in a Three-Phase Fixed-Bed Reactor with Cocurrent Flow in the Pulsing Regime" *Ind. Eng. Chem. Proc. Des. Dev.* **14**, 280 (1975).
- Lerou, J., Glasser, D., and Luss, D. "Packed Bed Liquid Phase Dispersion in Pulsed Gas-Liquid Downflow" *Ind. Eng. Chem. Fundam.* **19**, 66 (1980).
- Leung, P.C. *Hydration of Isobutene in Trickle-Bed Reactors*. Ph.D. Thesis, Univ. California, Davis (1986).
- Leung, P., Zorrilla, C., Recasens, F., and Smith J.M. "Hydration of Isobutene in Liquid-full and Trickle-Bed Reactors" *AIChE J.* **32**, 1839 (1986).
- Leung, P.C., Zorrilla, C., Puigjaner, L., and Recasens, F. "Solubilities and Enthalpies of Absorption of Isobutene into tert-Butyl Alcohol-Water Mixtures," *J. Chem. Eng. Data*, **32**, 169 (1987a).
- Leung, P.C., Recasens, F., and Smith, J.M. "Hydration of Isobutene in a Trickle-bed Reactor: Wetting Efficiency and Mass Transfer" *AIChE J.* **33**, 996 (1987b).
- Levec, J., Grosser, K., and Carbonell, R.G. "The Hysteretic Behavior of Pressure Drop and Liquid Hold-Up in Trickle-Beds" *AIChE J.* **34**, 1027 (1988).
- Levec, J., Sáez, A.E., and Carbonell, R.G. "The Hydrodynamics of Trickling Flow in Packed Beds. II. Experimental Observations" *AIChE J.* **32**, 369 (1986).
- Levenspiel, O. *Chemical Reaction Engineering*. John Wiley, New York (1972).
- Levenspiel, O. *The Chemical Reactor Omnibook*. Oregon State University Press, Corvallis (1979).
- Lorenzetti, M.S. "Alcohols Continue Important Role in Motor Fuel Mix." *Fuel Reformulation* **1**, 62 (1991).
- Lucas, H.J., and Eberz, W.F. "The Hydration of Unsaturated Compounds. I. The Hydration Rate of Isobutene in Dilute Nitric Acid" *J. Am. Chem. Soc.* **56**, 460 (1934).

- Mahajani, V.V., and Sharma, M.M. "Effective Interfacial Area and Liquid-Side Mass Transfer Coefficient in Trickle-Bed Reactors" *Chem. Eng. Sci.* **34**, 1425 (1979).
- Mahajani, V.V., and Sharma, M.M. "Mass Transfer in Packed Columns: Cocurrent (Downflow) Operation: 1 in. and 1.5 in. Metal Pall Rings and Ceramic Intalox Saddles: Multifilament Gauze Packings in 20 cm and 38 cm I.D. Columns" *Chem. Eng. Sci.* **35**, 941 (1980).
- Martin, J.M., Combarrous, M., and Charpentier, J.C. "Physical Gas-Liquid Mass Transfer for Cocurrent Flow through Porous Medium with Low Liquid and Gas Flowrates Corresponding to the Conditions of Enhanced Oil Recovery" *Chem. Eng. Sci.* **35**, 2362 (1980).
- Massaldi, H.A., and Maymó, J.A. "Error in Handling Finite Conversion Reactor Data by the Differential Method" *J. Catal.* **14**, 61 (1969).
- Mata, A.R., and Smith, J.M. "Oxidation of Sulfur Dioxide in a Trickle-Bed Reactor" *Chem. Eng. J.* **22**, 229 (1981).
- Matsuura, A., Akehata, T., and Shirai, T. "Correlation of Dynamic Holdup in Packed Beds with Cocurrent Gas-Liquid Downflow" *J. Chem. Eng. Japan*, **12**, 263 (1979a).
- Matsuura, A., Akehata, T., and Shirai, T. "Effective Radial Thermal Conductivity in Packed Beds with Gas-Liquid Downflow" *Heat Trans. Jap. Res.* **8**, 44 (1979b).
- Matsuura, A., Akehata, T., and Shirai, T. "Apparent Wall Heat Transfer Coefficient in Packed Beds with Downward Cocurrent Gas-Liquid Flow" *Heat. Trans. Jap. Res.* **8**, 53 (1979c).
- Mears, D.E. "The Role of Axial Dispersion in Trickle-Flow Laboratory Reactors" *Chem. Eng. Sci.* **26**, 1361 (1971).
- Mears, D.E. "The Role of Liquid Holdup and Effective Wetting in the Performance of Trickle-Bed Reactors" *Adv. Chem. Series* no. 133, North Holland Publishing Co., Amsterdam (1974).
- Melli, T.R., and Scriven, L.E. "Theory of Two-Phase Cocurrent Downflow in Networks of Passages" *Ind. Eng. Chem. Res.* **30**, 951 (1991).
- Michell, R., and Furzer, I.A. "Mixing in Trickle Flow through Packed Beds" *Chem. Eng. J.* **4**, 53 (1972).
- Midoux, N., Favier, M., and Charpentier J.C. "Flow Pattern, Pressure Loss and Liquid Holdup Data in Gas-Liquid Downflow Packed Beds with Foaming and Nonfoaming Hydrocarbons" *J. Chem. Eng. Japan* **9**, 350 (1976).
- Midoux, N., Morsi, B.I., Purwasasmita, M., Laurent, A., and Charpentier, J.C. "Interfacial Area and Liquid Side Mass Transfer Coefficient in Trickle Bed Reactors Operating with Organic Liquids" *Chem. Eng. Sci.* **39**, 781 (1984).
- Mills, P.L., and Duduković, M.P. "Analysis of Catalyst Effectiveness in Trickle-Bed Reactors Processing Volatile and Nonvolatile Reactants" *Chem. Eng. Sci.* **35**, 2267 (1980).
- Mills, P.L., and Duduković, M.P. "Evaluation of Liquid-Solid Contacting in Trickle-Bed Reactors by Tracer Methods" *AIChE J.* **27**, 893 (1981).
- Mitsubishi Rayon Co.: Mastsuzawa, H., Ikeda, H., Sugimoto, Y., and Shy, U. *Tertiary butyl Alcohol* US Patent 4,011,272 (1973).
- Montagna, A.A., Shah, Y.T., and Paraskos, J.A. "Effect of Catalyst Particle Size Performance of a Trickle-Bed Reactor" *Ind. Eng. Chem. Proc. Des. Dev.* **16**, 152 (1977).
- Morita, S., and Smith, J.M. "Mass Transfer and Contacting Efficiency in a Trickle-Bed Reactor" *Ind. Eng. Chem. Fundam.* **17**, 113 (1978).
- Morsi, B.I. "Contribution à l'étude de l'hydrodynamique et du transfert de matière dans un réacteur gaz-liquide catalytique à lit fixe fonctionnant à co-courant vers le bas. Comparaison des résultats en milieux liquides aqueux et organiques" Thèse de Docteur Ingénieur, Institut National Polytechnique de Lorraine. Nancy, France (1979).
- Morsi, B.I. "Mass Transfer Coefficients in a Trickle-Bed Reactor with High and Low Viscosity Organic Solutions" *Chem. Eng. J.* **41**, 41 (1989).
- Morsi, B.I., Laurent, A., Midoux, N., and Charpentier, J.C. "Interfacial Area in Trickle-Bed Reactors. Comparison Between Ionic and Organic Liquids and Between Raschig Rings and Small Diameter Particles" *Chem. Eng. Sci.* **35**, 1467 (1980).
- Morsi, B.I., Laurent, A., Midoux, N., Delaunay, G.B., Storck, A., and Charpentier, J.C. "Hydrodynamics and Gas-Liquid-Solid Interfacial Parameters of Cocurrent Downward Two-Phase Flow in Trickle-Bed Reactors" *Chem. Eng. Commun.* **25**, 267 (1984).

- Munro, W.D., and Amundson, N.R. "Solid-Fluid Heat Exchange in Moving Beds" *Ind. Eng. Chem.* **42**, 1481 (1950).
- Muroyama, K., Hashimoto, K., and Tomita, T. "Heat Transfer from Wall in Gas-Liquid Cocurrent Packed Bed" *Kagaku Kogaku Rombunshu* **3**, 612 (1977).
- NAG FORTRAN Library. National Algorithm Group, Oxford University, Oxford (1983).
- Naor, P., and Shinnar, R. "Representation and Evaluation of Residence Time Distribution" *Ind. Eng. Chem. Fundam.* **2**, 278 (1963).
- Neier, W., and Woellner, J. "Isopropyl Alcohol by Direct Hydration" *Chem. Tech.* **95** (February, 1973).
- Ng, K.M. "A Model for Flow Regime Transitions in Cocurrent Down-Flow Trickle-Bed Reactors" *AIChE J.* **32**, 115 (1986).
- Ng, K.M., and Chu, C.F. "Trickle-Bed Reactors" *Chem. Eng. Prog.* **55** (November, 1987).
- Novak, L.T., and Mateer, D.D. "Trickling Flow Pressure Drop in Packed Beds of Formed Catalysts" *Ind. Eng. Chem. Proc. Des. Dev.* **25**, 1034 (1986).
- Nowlan, V.J., and Tidwell, T.T. "Structural Effects on the Acid-Catalyzed Hydration of Alkenes" *Accounts Chem. Res.* **10**, 252 (1977).
- O'Sullivan, D.A. "Arco Increasing Chemicals Stake In Western Europe" *Chem. Eng. News*, March 18, 10 (1985).
- Odioso, R.C., Henke, A.M., Stauffer, H.C., and Frech, K.J. "Direct Hydration of Olefins" *Ind. Eng. Chem.* **53**, 209 (1961).
- Otake, T., and Okada, K. "Liquid Holdup in Packed Towers-Operating Holdup without Gas Flow" *Kagaku Kogaku* **17**, 176 (1953).
- Paraskos, J.A., Frayer, J.A., and Shah, Y.T. "Effect of Holdup, Incomplete Catalyst Wetting and Backmixing during Hydroprocessing in Trickle-Bed Reactors" *Ind. Eng. Chem. Proc. Des. Dev.* **14**, 315 (1975).
- Pass, G., Holzhauser, C., Akgerman, A., and Anthony, R.G. "Methanol Synthesis in a Trickle-Bed Reactor" *AIChE J.* **36**, 1054 (1990).
- Petrus, L., De Roo, R.W., Stamhuis, E.J., and Joosten, G.E.H. "Kinetics and Equilibria of the Hydration of Propene Over a Strong Acid Ion Exchange Resin as Catalyst" *Chem. Eng. Sci.* **39**, 433, (1984).
- Petrus, L., De Roo, R.W., Stamhuis, E.J., and Joosten, G.E.H. "Kinetics and Equilibria of the Hydration of Linear Butenes Over a Strong Acid Ion-Exchange Resin as Catalyst" *Chem. Eng. Sci.* **41**, 217 (1986).
- Pitochelli, A.R. *Ion-Exchange Catalysis and Matrix Effects*. Rohm & Haas. Philadelphia (1975).
- Prasher, B.D., Gabrill, G.A., and Ma, Y. "Restricted Diffusion of Liquids in Microporous Catalysts" *AIChE J.* **24**, 1118 (1978).
- Prausnitz, J.M. *Molecular Thermodynamics of Fluid-Phase Equilibria*. Prentice-Hall, Englewood-Cliffs, New Jersey, (1969).
- Prchlik, J., Soukup, J., Zapletal, V., and Ruzicka, V. "Liquid Distribution in Reactors with Randomly Porous Beds" *Coll. Czech. Chem. Commun.* **40**, 845 (1975).
- Purlee, E.L., Taft, R.W., and DeFazio, C.A. "Enthalpies and Entropies of Activation for the Hydration of Dissolved Isobutene and Trimethylethylene from the Thermodynamic Properties for Solution of Gaseous Olefins in Aqueous Nitric Acid" *J. Am. Chem. Soc.* **77**, 837 (1955).
- Ramachandran, P.A., and Chaudhari, R.V. *Three-Phase Catalytic Reactors*. Gordon and Breach Science Pub., New York (1983).
- Ramachandran, P.A., and Smith, J.M. "Effectiveness Factors in Trickle-Bed Reactors" *AIChE J.* **25** 538 (1979a).
- Ramachandran, P.A., and Smith, J.M. "Mixing-Cell Method for Design of Trickle-Bed Reactors" *Chem. Eng. J.* **17**, 91 (1979b).
- Ramachandran, P.A., Duduković, M.P., and Mills, P.L. "A new Model For Assessment of External Liquid-Solid Contacting in Trickle-Bed Reactors From Tracer Response Measurements" *Chem. Eng. Sci.* **41**, 855 (1986).
- Ramírez, R. "No-Lead Gas Turn Into a World Boon for MTBE" *Chem. Eng.* May 25, 19 (1987).
- Rao, V.G., and Drinkenburg, A.A.H. "Solid-Liquid Mass Transfer in Packed Beds with Cocurrent Gas-Liquid Downflow" *AIChE J.* **31**, 1059 (1985).
- Recasens, F., Velo, E., and Puigjaner, L. "MTBE vs. Oxinol: Octane Value and Cost-Effectiveness to the Refiner" *4th Mediterranean Congress Chem. Eng.* Barcelona (1987).



- Reid, R.C., Prausnitz, J.M., and Poling, B.E. *The Properties of Gases and Liquids*. 4th edn. McGraw-Hill, New York (1987).
- Reiss, L.P. "Cocurrent Gas-Liquid Contacting in Packed Columns." *Ind. Eng. Chem. Proc. Des. Dev.* **6**, 486 (1967).
- Ring, Z.E., and Missen, R.W. "Trickle-Bed Reactors: Effect of Wetting Geometry on Overall Effectiveness Factors" *Can. J. Chem. Eng.* **64**, 117 (1986).
- Ring, Z.E., and Missen, R.W. "Trickle-Bed Reactors: And Experimental Study of Partial Wetting Effect" *AIChE J.* **35**, 1821 (1989).
- Robinson, B.A., and Tester, J.W. "Characterization of Flow Maldistribution Using Inlet-Outlet Tracer Techniques: an Application of Internal Residence Time Distributions" *Chem. Eng. Sci.* **41**, 469 (1986).
- Rohm & Haas *Amberlyst 15 Technical Bulletin*. Rohm & Haas Co., Philadelphia (1972).
- Ruecker, C.M., and Akgerman, A. "Determination of Wetting Efficiencies for a Trickle-Bed Reactor at High Temperatures and Pressures" *Ind. Eng. Chem. Res.* **26**, 164 (1987).
- Ruether, J.A., Yang, C.S., and Hayduk, W. "Particle Mass Transfer During Cocurrent Downward Gas-Liquid Flow in Packed Beds" *Ind. Eng. Chem. Proc. Des. Dev.* **19**, 103 (1980).
- Ruiz, P., Crine M., Germain, A., and L'Homme, G. "Influence of the Reactional System on the Irrigation Rate in Trickle-Bed Reactors" *ACS Symp. Ser.* **237**, 15 (1984).
- Sáez, A.E., and Carbonell, R.G. "Hydrodynamic Parameters for Gas-Liquid Cocurrent Flow in Packed-Beds" *AIChE J.* **31**, 52 (1985).
- Sahay, B.N., and Sharma, M.M. "Effective Interfacial Area and Liquid and Gas side Mass Transfer Coefficients in a Packed Column" *Chem. Eng. Sci.* **28**, 41 (1973).
- Sater, V.E., and Levenspiel, O. "Two-Phase Flow in Packed Beds" *Ind. Eng. Chem. Fundam.* **5**, 86 (1966).
- Sato, Y., Hirose, H., Takahashi, F., and Toda, M. "Performance of Fixed-Bed Catalytic Reactor with Cocurrent Gas-Liquid Flow" *1st Pacific Chem. Eng. Congress*, p.187 (1972).
- Sato, Y., Hirose, H., Takahashi, F., and Toda, M. "Pressure Loss and Liquid Holdup in Packed-Bed Reactor with Cocurrent Gas-Liquid Downflow" *J. Chem. Eng. Japan.* **6**, 147 (1973a)
- Sato, Y., Hirose, H., Takahashi, F., Toda, M., and Hashiguchi, Y. "Flow Pattern and Pulsation Properties of Cocurrent Gas-Liquid Downflow in Packed Beds" *J. Chem. Eng. Japan* **6**, 315 (1973b).
- Satterfield, C.N. *Mass Transfer in Heterogeneous Catalysis*. M.I.T. Press, Cambridge, MA (1970).
- Satterfield, C.N. "Trickle-Bed Reactors" *AIChE J.* **21**, 209 (1975).
- Satterfield, C.N., and Katzer, J.R. "The Counter-Diffusion of Liquid Hydrocarbons in Type Y Zeolites" *Adv. Chem. Ser.* **102**, 193 (1971).
- Satterfield, C.N., Colton, C.K., and Pitcher, W.H. "Restricted Diffusion in Liquids within Fine Pores" *AIChE J.* **19**, 628 (1973).
- Satterfield, C.N., van Eek, M.W., and Bliss, G.S. "Liquid-solid Mass Transfer in Packed Beds with Downflow Cocurrent Gas-Liquid Flow" *AIChE J.* **24**, 709 (1978).
- Savage, P.E., and Javanmardian, M. "Effect of Reactant Size Reductions on Catalytic Reaction Rates" *Ind. Eng. Chem. Res.* **28**, 381 (1989).
- Schneider, P., and Smith, J.M. "Adsorption Rate Constants from Chromatography" *AIChE J.* **14**, 762 (1968).
- Schnitzlein, K., and Hofmann, H. "An Alternative Model for Catalytic Fixed Bed Reactors" *Chem. Eng. Sci.* **42**, 2569 (1987).
- Schubert, C.N., Linder, J.R., and Kelly, R.M. "Experimental Methods for Measuring Static Liquid Hold-up in Packed Columns" *AIChE J.* **32**, 1920 (1986).
- Schwartz, J.G., and Roberts, G.W. "An Evaluation of Models for Liquid Backmixing in Trickle-Bed Reactors" *Ind. Eng. Chem. Proc. Des. Dev.* **12**, 262 (1973).
- Sedriks, W., and Kennedy, C.N. "Partial Wetting in Trickle-Bed Reactors: the Reduction of Crotonaldehyde over a Palladium Catalyst" *Chem. Eng. Sci.* **28**, 559 (1973).
- Serafi, H.A., and Smith, J.M. "Mass Transfer and Adsorption in Liquid Full and Trickle Beds" *AIChE J.* **26**, 711 (1980).
- Shende, B.W., and Sharma, M.M. "Mass Transfer in Packed Columns: Cocurrent Operation" *Chem. Eng. Sci.* **29**, 1763 (1974).
- Sicardi, S., Baldi, G., Gianetto, A., and Specchia, V. "Catalyst Area Wetted by Flowing and Semistagnant Liquid in Trickle-Bed Reactors" *Chem. Eng. Sci.* **35**, 67 (1980).

- Skjold-Jorgensen, S., Kolbe, B., Gmehling, J., and Rasmussen, P. "Vapor-Liquid Equilibria by UNIFAC Group Contribution. Revision and Extension" *Ind. Eng. Chem. Proc. Des. Dev.* **18**, 714 (1979).
- Smith, J.M. *Chemical Engineering Kinetics*. 3rd edn. McGraw-Hill, New York (1981).
- Specchia, V., and Baldi, G. "Pressure Drop and Liquid Holdup for Two-Phase Cocurrent Flow in Packed Beds" *Chem. Eng. Sci.* **32**, 515 (1977).
- Specchia, V., and Baldi, G. "Solid-Liquid Mass Transfer in Cocurrent Two-Phase Flow through Packed Beds" *Ind. Eng. Chem. Proc. Des. Dev.* **17**, 362 (1978).
- Specchia, V., and Baldi, G. "Heat Transfer in Trickle-Bed Reactors" *Chem. Eng. Commun.* **3**, 483 (1979).
- Specchia, V., Baldi, G., and Gianetto, A. "Solid-Liquid Mass Transfer in Cocurrent Two Phase Flow through Packed Beds" *Ind. Eng. Chem. Proc. Des. Dev.* **17**, 362 (1978).
- Specchia, V., Rossini, A., and Baldi, G. "Distribution and Radial Spread of Liquid in Two-Phase Cocurrent Flows in a Packed Bed" *Ing. Chim. Ital.* **10**, 171 (1974).
- Sylvester, N.D., and Pitayagulsarn, P. "Mass Transfer for Two-Phase Cocurrent Downflow in a Packed-Bed" *Ind. Eng. Chem. Proc. Des. Dev.* **14**, 421 (1975).
- Taft, R.W., Purlee, E.L., and Riesz, P. "Thermodynamic Properties for the System Isobutene-t-Butyl Alcohol" *J. Am. Chem. Soc.* **77**, 899 (1955).
- Talmor, E. "Two-Phase Downflow through Catalyst Beds. Part I. Flow Maps" *AIChE J.* **23**, 868 (1977).
- Tan, C.-S., and Smith, J.M. "Catalyst Particle Effectiveness with Unsymmetrical Boundary Conditions" *Chem. Eng. Sci.* **35**, 1601 (1980).
- Tan, C.-S., and Smith, J.M. "A Dynamic Method for Liquid- Particle Mass Transfer in Trickle Beds" *AIChE J.* **28**, 190 (1982).
- Ternan, M., and Packwood, R.H. "Catalyst Technology for Reactors Used to Hydrocrack Petroleum Residua" In *Chemical Reactor Design and Technology*. de Lasa, H.I. (ed.), Martinus Nijhoff Publishers, Dordrecht, The Netherlands (1986).
- Tosun, G. "A Study of Cocurrent Downflow of Nonfoaming Gas-Liquid Systems in a Packed-Bed. 1. Flow Regimes: Search for a Generalized Flow Map" *Ind. Eng. Chem. Proc. Des. Dev.* **23**, 29 (1984a).
- Tosun, G. "A Study of Cocurrent Downflow of Nonfoaming Gas-Liquid Systems in a Packed-Bed. 2. Pressure Drop: Search for a Correlation" *Ind. Eng. Chem. Proc. Des. Dev.* **23**, 35 (1984b).
- Tukač, V., and Hanika, J. "The Effect of Mass Transfer on the Oxidation of Ethanol in a Trickle-Bed Reactor" *Int. Chem. Eng.* **29**, 177 (1989).
- Turek, F., and Lange, R. "Mass Transfer in Trickle-Bed Reactors at Low Reynolds Number" *Chem. Eng. Sci.* **36**, 569 (1981).
- Turpin, J.L., and Huntington, R.L. "Prediction of Pressure Drop for Two-Component Cocurrent Flow in Packed-Beds" *AIChE* **13**, 1196 (1967).
- Ufford, R.C., and Perona, J.J. "Liquid-Phase Mass Transfer with Cocurrent Flow through Packed Towers" *AIChE. J.* **19**, 1223 (1973).
- van Klinken, J., and van Dongen, R.H. "Catalyst Dilution for Improved Performance of Laboratory Trickle-Bed Reactors" *Chem. Eng. Sci.* **35**, 59 (1980).
- van Krevelen, D.W., and Krekels, J.T.C. "Rate of Dissolution of Solid Substances" *Rec. Trav. Chim.* **67**, 512 (1948).
- Vatcha, S. R., and Dadyburjor, D. B. "Weighting Factors To Obtain Kinetic Parameters from Integral Reactors with Differential Reactor Methods" *Ind. Eng. Proc. Des. Dev.* **25**, 229 (1986).
- Velo, E., Recasens, F., and Puigjaner, L. "Revaloració Energètica de Fraccions C4 Mitjançant Hidratació Selectiva de l'Isobutè" *But. Soc. Cat. Cièn.* Vol. XI, 99 (1991a).
- Velo, E., Smith, J.M., and McCoy, B.J. "Effect of Solid Particles on Liquid-to-Gas-Bubble Mass Transfer in a Sparged, Stirred Slurry" *1991 Spring AIChE Meeting*, p. 35d, Houston (1991b).
- Wammes, W.J.A., Mechielsen, S.J. and Westerterp, K.R. "The Transition between Trickle Flow and Pulse Flow in a Cocurrent Gas-Liquid Trickle-Bed Reactor at Elevated Pressures" *Chem. Eng. Sci.* **45**, 3149 (1990).
- Wammes, W.J.A., Mechielsen, S.J. and Westerterp, K.R. "The Influence of Pressure on the Liquid Hold-Up in a Cocurrent Gas-Liquid Trickle-Bed Reactor Operating at Low Gas Velocities" *Chem. Eng. Sci.* **46**, 409 (1991).
- Wakao, N., and Smith, J.M. "Diffusion in Catalyst Pellets" *Chem. Eng. Sci.* **17**, 825 (1962).

- Weast, R.C. (ed.) *Handbook of Chemistry and Physics*. 61st edn. CRC Press, Boca Raton (1980).
- Weekman, V.W, and Myers, J.E. "Fluid Flow Characteristics of Cocurrent Gas-Liquid Flow in Packed Beds" *AIChE J.* **10**, 951 (1964).
- Weekman, V.W, and Myers, J.E. "Heat Transfer Characteristics of Cocurrent Gas-Liquid Flow in Packed Beds" *AIChE J.* **11**, 13 (1965).
- Wheeler, A. In *Advances in Catalysis*. Vol. III. Academic Press, New York (1951).
- Yaici, W., Laurent, A., Midoux, N., and Charpentier, J.C. "Determination des Coefficients de Transfert de Matiere en Phase Gazeuse dans un Reacteur Catalytique Lit Fixe Arrosé en Présence de Phases Liquides Aqueuse et Organique" *Bull. Soc. Chim. Fr.* **6**, 1032 (1985).
- Yaici, W., Laurent, A., Midoux, N., and Charpentier, J.C. "Determination of Gas-Side Mass Transfer Coefficients in Trickle-Bed Reactors in the Presence of an Aqueous or an Organic Liquid Phase." *Int. Chem. Eng.* **28**, 299 (1988).
- Yentekakis, I.V., and Vayenas, G.G. "Effectiveness Factors for Reactions between Volatile and Nonvolatile Components in Partially Wetted Catalysts" *Chem. Eng. Sci.* **42**, 1323 (1987).
- Zimmerman, S.P., and Ng, K.M. "Liquid Distribution in Trickle-Flow Trickle-Bed Reactors" *Chem. Eng. Sci.* **41**, 861 (1986).
- Zimmerman, S.P., Chu, C.F., and Ng, K.M. "Axial and Radial Dispersion in Trickle-Bed Reactors with Trickle-Flow Gas-Liquid Down Flow" *Chem. Eng. Commun.* **50**, 213 (1987).