

9. REFERENCES

1. F. Derbyshire and D. Gray, Coal Liquification, Ullman's Encyclopedia of Industrial Chemistry, Vol A7, 197-243, Fifth Edition, 1985.
2. M.B. Sherwin and M.E. Frank, Make Mathanol by Three Phase Reaction, Hydrocarbon Processing, 122-124, November, 1976.
3. J.C.W. Kuo, Two-Stage Slurry Fischer-Tropsch/ZSM-5 Process of Converting Syngas to High Octane Gasoline, Proc. DOE Contractors' Conference on Indirect Liquification, pp.13-1 to 13-28, May 20-21, 1981.
4. J.C.W. Kuo, Two-Stage Slurry Fischer-Tropsch/ZSM-5 Process of Converting Syngas to High Octane Gasoline, Proc. DOE Contractors' Conference on Indirect Liquification, pp. 10-1 to 10-36, September 8-9, 1982.
5. J.C.W. Kuo, Two-Stage Process for Conversion of Synthesis Gas to High Quality Transportation Fuels, Final Report on the DOE Contract No. DE-AC22-83PC60019, October 1985.
6. J. Klosek and R.L. Mednick, Liquid Phase Methanol PDU: Project Status and Plans, A paper presented at the U.S. DOE Contractors' Conference Indirect Liquefaction, Pittsburgh, PA, September 8-9, 1982.
7. D.M. Brown and J. Klosek, Liquid Phase Methanol Update, A paper presented at the U.S. DOE Contractors' Conference Indirect Liquefaction, Pittsburgh, PA, October 12-13, 1983.
8. T.R. Tsao, Results of Laporte Liquid Phase Methanol PDU Operation, A paper presented at the U.S. DOE Contractors' Conference Indirect, Liquefaction, Pittsburgh, PA, October 30-31, 1984.
9. T.R. Tsao and E.C. Heydorn, Liquid Phase Methanol PDU Results, A paper presented at the U.S. DOE Indirect Liquefaction Contractors' Review Meeting, Houston, TX, December 2-5, 1985.
10. J.J. Lewnard, P.R. Stepanoff and P. Rao, Recent Laboratory Activities Towards Developing the Liquid Phase Methanol Process, A paper presented at the U.S. DOE Indirect Liquefaction Contractors' Review Meeting, Pittsburgh, PA, December 2-4, 1986.
11. Liquid Phase Methanol Process Development Unit: Installation, Operation, and Support Studies, Final Report, Prepared for the United States Department of Energy Under Contract No. DE-AC 22-81PC30019 by Air Products and Chemicals, Inc., and Chem Systems Inc., p. 398, August 21, 1987.

12. J.H. Frey, D.W. Studer, J.L. Henderson and R.F. Weimer, Further Process Improvements at the Laporte Liquid Phase Methanol Facility, A paper presented at the U.S. DOE Indirect Liquefaction Contractors' Review Meeting, Pittsburgh, PA, November 15-17, 1988.
13. D.W. Studer, J.L. Henderson, T.H. Hsiung and D.M. Brown, Status Report on the Liquid Phase Methanol Project, A paper presented at the EPRI 14th Annual Conference on Fuel Science and Conversion, Palo Alto, CA, May 18-19, 1989.
14. D.W. Studer, D.M. Brown, J.L. Henderson and T.S. Hsiung, Status of the Development of Methanol Synthesis by the LPMEOH Process, A paper presented at the DOE Indirect Liquefaction Contractors' Review Meeting, Pittsburgh, PA, November 13-15, 1989.
15. H. Schultz, Chemicals, Feedstocks and Fuels from Fischer-Tropsch and Related Synthesis, in L.E. St-Pierre and G.R. Brown (Editors), Future Sources of Organic Raw Materials, CHEMRAWNI, 167-183, Pergamon Press, New York, 1978.
16. J.B. O'Hara, A. Bela, N.E. Jentz and S.K. Khaderi, Fischer-Tropsch Plant Design Criteria, Chem. Eng. Prog. 72(8), 65-67, 1976.
17. F.C. Thyron, Indirect Liquefaction, in Synthetic Fuels from Coal, Edited by I. Romey, P.F.M. Paul and G. Imarisio, 5-118, Graham and Trotman LTD., London, 1987.
18. R.B. Anderson, The Fischer-Tropsch Synthesis, Academic Press, New York, 1984.
19. M.E. Dry, The Sasol Fischer-Tropsch Processes, B.E. Leach (Editor), Applied Industrial Catalysis, Volume 2, Chapter 5, 167-213, Academic Press, New York, 1983.
20. D. Frohning, Fischer-Tropsch Synthesis for Fuel Production from Coal, in G.E. Beghi (Editor), Synthetic Fuels, 113-134, D. Reidel Publishing Company, Boston, 1985.
21. J.H. Field, H.E. Benson and R.B. Anderson, Synthetic Liquid Fuels by Fischer-Tropsch Process, Chem. Eng. Prog., 56(4), 44-48, 1960.
22. H. Kolbel and M. Ralek, The Fischer-Tropsch Synthesis in the Liquid Phase, Catal. Rev. Sci. Eng. 21(2), 225-274, 1980.
23. M.J. Baird, R.R. Schehl and W.P. Haynes, Fischer-Tropsch Processes Investigated at the Pittsburgh Energy Technology Center Since 1944, Ind.

- Eng. Chem. Prod. Res. Dev. 19, 175-191, 1980.
24. P.C. Keith, Gasoline from Natural Gas, The Oil and Gas Journal, 45, 102-112, 1946.
 25. M.L. Kastens, L.L. Hirst and R.G. Dressler, An American Fischer-Tropsch Plan, Ind. Eng. Chem. 44 (3), 450-466, 1952.
 26. UOP Inc., Comparison of FT Reactor Systems - Phase I, Final Report, DOE Contract DEA CO10-78ET 10159, 1981.
 27. W.D. Deckwer, FT Process Alternatives Hold Promise, The Oil and Gas Journal, 78, No. 45 198-213, Nov. 10, 1990.
 28. M.L. Reikena, A.G. Vickers, E.C. Haun and R.C. Koltz, A Comparison of Fischer-Tropsch Reactors, Chem. Eng. Prog. 78(4), 86-90, 1982.
 29. C.N. Satterfield, G.A. Huff, H.G. Stenger, J.L. Carter and R.J. Madon, Ind. Eng. Chem. Fundam. 24, 450-454, 1985.
 30. J.B. O'Hara, A. Bela, N.E. Jentz, S.K. Khaderi, H.W. Klumpe, B.I. Loran, D.G. Reynolds and R.V. Teeple, Fischer-Tropsch Complex Conceptual Design/Economic Analysis, ERDA R and D Report No. 114 - Interim Report No. 3, ERDA Contract No. E (49-18) - 1775, January 1977; as quoted in references 28 and 22.
 31. A.J. Forney, D. Bienstock and R.J. Demski, Use of a Large Diameter Reactor in Synthesizing Pipeline Gas and Gasoline by the Hot-Gas Recycle Process, U.S. Bureau of Mines, ROI 6126, 1962, as quoted in reference 28.
 32. G.J. Thompson, A.G. Vickers and P.R. Pujado, Mathematically Modeled Comparison of Fischer-Tropsch Reaction System, 90th National AIChE Meeting, Houston, Texas, April 1981, as quoted in reference 28.
 33. W. Faragher and J. Foucher, FIAT Final Report, 1267, PB 97, 368, Vol. I, Part C, p. 123, 1947, as quoted in reference 22.
 34. H.H. Storch, N. Golumbric and R.B. Anderson, The Fischer-Tropsch and Related Synthesis, Wiley, New York, 1951.
 35. J.H. Crowell, H.E. Benson, J.H. Field and H.H. Storch, Fischer-Tropsch Oil Circulation Processes, Ind. Eng. Chem. 42, 2376-2384, 1950.
 36. H.E. Benson, J.H. Field, D. Beinstock and H.H. Storch, Oil Circulation Process for Fischer-Tropsch Synthesis, Ind. Eng. Chem. 46, 2278-2285, 1954.

37. M.E. Dry, In *Catalysis Science and Technology*, J.R. Anderson and M. Boudart (Editors), Vol. I, 159-255, Springer-Verlag, Berlin, 1981.
38. A. Zaidi, Y. Louisi, M. Ralek and W.D. Deckwer, Mass Transfer in the Liquid Phase Fischer-Tropsch Synthesis, *Ger. Chem. Eng.* 2, 94-120, 1979.
39. W.D. Deckwer, Y. Serpmen, M. Ralek and B. Schmidt, Fischer-Tropsch Synthesis in the Slurry Phase on Mn/Fe Catalysts, *Ind. Eng. Chem. Process Des. Dev.* 21, 222-231, 1982.
40. M.D. Schlesinger, J.H. Crowell, M. Leva and H.H. Storch, Fischer-Tropsch Synthesis in Slurry Phase, *Ind. Eng. Chem.* 43 (6), 1474-1479, 1951.
41. M.D. Schlesinger, H.E. Benson, E.M. Murphy and H.H. Storch, Chemicals from the Fischer-Tropsch Synthesis, *Ind. Eng. Chem.* 46 (6), 1322-1326, 1954.
42. C.C. Hall and A.H. Taylor, Design and Operation of a Fluid Catalyst Pilot Plant for Fischer-Tropsch Synthesis, *J. Inst. Petrol.* 41, 101-124, 1955.
43. R. Farley and D.J. Ray, The Design and Operation of a Pilot-Scale Plant for Hydrocarbon Synthesis in the Slurry Phase, *J. Inst. Petrol.* 50, No. 482, 27-48, 1964.
44. P.H. Calderbank, F. Evans, R. Farley, G. Jepson and A. Poll, Rate Processes in the Catalyst-Slurry Fischer-Tropsch Reaction, *Catalysis in Practice* (Instn, Chem. Engrs.) 66-74, 1964.
45. A.K. Mitra and A.N. Roy, Performance of Slurry Reactor for Fischer-Tropsch and Related Synthesis, *Indian Chemical Engineer*, 127-132, 1963.
46. T. Sakai and T. Kunugi, Liquid Phase (Slurry) Method-Fischer-Tropsch Synthesis, *Sekiyu Gakkai Shi.* 17, 863-868, 1974.
47. S.C. Saxena, Indirect Liquefaction of Coal: Fischer-Tropsch Synthesis and Transport Processes in Slurry Bubble Column Reactors, *Advances in Transport Processes*, to be published.
48. J. Zahradnik and F. Kastanek, Gas Holdup in Uniformly Aerated Bubble Column Reactors, *Chem. Eng. Commun.* 3, 413-429, 1979.
49. Y.S. Touloukian, R.W. Powell, C.Y. Ho and P.G. Klemens, Thermophysical Properties of Matter, Volume 2, Thermal Conductivity-Nonmetallic Solids, 1970, IFI/Plenum, New York.
50. Y.S. Touloukian and E.H. Buyco, Thermophysical Properties of Matter, Volume 5, Specific Heat-Nonmetallic Solids, 1970, IFI/Plenum, New York.

51. As given in W.D. Deckwer, Y. Louisi, A. Zaidi and M. Ralek, Hydrodynamic Properties of the Fischer-Tropsch Slurry Process, Ind. Eng. Chem. Process Des. Dev. 19, 699-708, 1980.
52. V. Vand, Viscosity of Solutions and Suspensions, J. Phys. Chem. 52, 277-321, 1948.
53. K. Akita and F. Yoshida, Gas Holdup and Volumetric Mass Transfer Coefficient in Bubble Columns, Ind. Eng. Chem. Process Des. Dev., 12, 76-80, 1973.
54. G.A. Hughmark, Holdup and Mass Transfer in Bubble Columns, Ind. Eng. Chem. Process Des. Dev., 6, 218-220, 1967.
55. H. Hikita, S. Asai, K. Tanigawa, K. Segawa and M. Kitao, Gas Holdup in Bubble Columns, Chem. Eng. J., 20, 59-67, 1980.
56. I.G. Reilly, D.S. Scott, T. DeBruijn, A. Jain and J. Piskorz, A Correlation for Gas Holdup in Turbulent Coalescing Bubble Columns, Canadian J. Chem. Eng., 64, 705-717, 1986.
57. D.N. Smith, W. Fuchs, R.J. Lynn, D.M. Smith and M. Hess, Bubble Behavior in a Slurry Bubble Column Reactor Model, ACS Symp. Series 237, Chemical and Catalytic Reactor Modeling, Editors: M.P. Dudukovic and P.L. Pills, pp. 125-147, 1984.
58. E. Barnea and J. Mizrahi, A General Approach to the Fluid Dynamics of Particulate Systems. Part I. General Correlation for Fluidization and Sedimentation, Chem. Eng. J., 5, 171-189, 1973.
59. A Kumar, T.E. Dugaleesan, G.S. Ladda and H.E. Hoelscher, Bubble Swarm Characteristics in Bubble Columns, Canadian J. Chem. Eng., 54, 503-508, 1976.
60. E. Sada, S. Katoh, H. Yoshil, T. Yamanishi and A. Nakanishi, Performance of the Gas Bubble Column in Molten Salt Systems, Ind. Eng. Chem. Process Des. Dev. 23, 151-154, 1984.
61. J.H. Hills, The Operation of a Bubble Column at High Throughputs I. Gas Holdup Measurements, Chem. Eng. J., 12, 89-99, 1976.
62. G.S. Grover, C.V. Rode and R.V. Chaudhari, Effect of Temperature on Flow Regimes and Gas Holdup in a Bubble Column, Can. J. Chem. Eng. 64, 501-504, 1986.
63. R. Zou, X. Jiang, B. Li, Y. Zu and L. Zhang, Studies on Gas Holdup in a Bubble Column Operated at Elevated Temperatures, Ind. Eng. Chem. Res. 27, 1910-1916, 1988.

64. N.K. Roy, D.K. Guha and M.N. Rao, Fractional Gas Holdup in Two-Phase and Three-Phase Batch-Fluidized Bubble-Bed and Foam-Systems, *Indian Chem. Eng., Trans.* **27-Trans. 31**, April 1963.
65. D.H. Ying, E.N. Givens and R.F. Weimer, Gas Holdup in Gas-Liquid and Gas-Liquid-Solid Flow Reactors, *Ind. Eng. Chem. Process Des. Dev.*, **19**, 635-638, 1980.
66. D.N. Smith and J.A. Ruether, Dispersed Solid Dynamics in a Slurry Bubble Column, *Chem. Eng. Sci.* **40**, 741-754, 1985.
67. S.C. Saxena, Heat Transfer From a Cylindrical Probe Immersed in a Bubble Column, *Chem. Eng. J.*, **41**, 25-39, 1989.
68. S.C. Saxena, R. Vadivel and A.K. Verma, Heat Transfer and Hydrodynamics of Bubble Columns with Internals, *Proc. Third Congreso Latinoamericano De Transferencia De Calor Y Materia*, Guanajuato, GTO, Mexico, pp. 131-140, July 4-7, 1988.
69. S.C. Saxena and A.K. Verma, Transport Phenomena in Multiphase Reactors, *Proc. Int. Conf. on Advances in Chem. Eng.*, 371-380, D.N. Saraf and D. Kunzru (Editors), Tata McGraw-Hill Publishing Company Limited, New Delhi, India, 1989.
70. T. Maruyama, S. Yoshida and T. Mizushima, The Flow Transition in a Bubble Column, *J. Chem. Eng. Japan*, **14**, 352-357, 1981.
71. D.B. Bukur and J.G. Daly, Gas Holdup in Bubble Columns for Fischer-Tropsch Synthesis, *Chem. Eng. Sci.*, **42**, 2967-2969, 1987.
72. D.B. Bukur, D. Petrovic and J.G. Daly, Flow Regime Transitions in a Bubble Column with a Paraffin Wax as the Liquid Medium, *Ind. Eng. Chem. Res.*, **26**, 1087-1092, 1987.
73. S.C. Saxena and R. Vadivel, Heat Transfer From a Tube Bundle in a Bubble Column, *Int. Commun. Heat Mass Transfer*, **15**, 657-667, 1988.
74. D.J. Nicklin, Two-Phase Bubble Flow, *Chem. Eng. Sci.* **17**, 693-702, 1962.
75. G.B. Wallis, *One-Dimensional Two-Phase Flow*, McGraw-Hill Book Company, 1969.
76. W. O'Dowd, D.N. Smith, J.A. Ruether and S.C. Saxena, Gas and Solids Behavior in a Baffled and Unbaffled Slurry Bubble Column, *A.I.Ch.E. J.* **33**, 1959-1970, 1987.

77. A.C. Saxena, N.S. Rao and S.C. Saxena, Bubble Size Distribution in Bubble Columns, *Can. J. Chem. Eng.* 68, 159-161, 1990.
78. S.C. Saxena, D. Patel, D.N. Smith and J.A. Ruether, An Assessment of Experimental Techniques for the Measurement of Bubble Size in a Bubble Slurry Reactor as Applied to Indirect Coal Liquefaction, *Chem. Eng. Comm.* 63, 87-127, 1988.
79. S.A. Patel, J.G. Daly and D.B. Bukur, Holdup and Interfacial Area Measurements Using Dynamic Gas Disengagement, *A.I.Ch.E. J.* 35, 931-942, 1989.
80. S.C. Saxena and B.B. Patel, Heat Transfer and Hydrodynamic Investigations in a Baffled Bubble Column: Air-Water-Glass Bead System, *Chem. Eng. Comm.*, to be published.
81. N. Zuber and J.A. Findlay, Average Volumetric Concentration in Two-Phase Flow Systems, *Trans. ASME: J. Heat Transfer* 87, Series C, 453-468, 1965.
82. S.C. Saxena, N.S. Rao and M.Y. Kagzi, Hydrodynamic and Heat Transfer Investigations Conducted in a Bubble Column With Fine Powders and a Viscous Liquid, *Powder Technology*, to be published.
83. S.C. Saxena and N.S. Rao, Heat Transfer and Gas Holdup in a Two-Phase Bubble Column: Air-Water System-Review and New Data, *Exptl. Thermal and Fluid Science*, in press.
84. H. Kolbel, W. Seimes and R. Muller, Wärmeübergang in Blasensäulen, *Chem. Ing. Tech.* 30, 400-404, 1958.
85. J.R. Fair, A.J. Lambright and J.W. Anderson, Heat Transfer and Gas Holdup in a Sparged Contactor, *Ind. Eng. Chem. Process Des. Dev.* 1, 33-36, 1962.
86. W. Burkel, Der Wärmeübergang an Heiz- und Kühlflächen in bewegten Flüssigkeiten, *Chem. Ing. Tech.* 44, 265-268, 1972.
87. H. Hakita, S. Asai, H. Kikukawa, T. Zalke and M. Ohue, Heat Transfer Coefficient in Bubble Columns, *Ind. Eng. Process Des. Dev.* 20, 540-545, 1981.
88. W.F. Hart, Heat Transfer in Bubble-Agitated Systems. A General Correlation, *Ind. Eng. Chem. Process Des. Dev.* 15, 109-114, 1976.
89. A. Steiff and P.M. Weinspach, Heat Transfer in Stirred and Non-Stirred Gas-Liquid Reactors, *Ger. Chem. Eng.* 1, 150-161, 1978.

90. W. Kast, Analyse Des Wärmeübergangs in Blasensäulen, Int. J. Heat Mass Transfer, 5, 329-336, 1962.
91. A. Mersmann, Heat Transfer in Bubble Columns, Int. Chem. Engng. 17, 385-388, 1977.
92. P. Zehner, Momentum, Mass and Heat Transfer in Bubble Columns Part 2. Axial Blending and Heat Transfer, Int. Chem. Engng. 26, 29-35, 1986.
93. W.D. Deckwer, On the Mechanism of Heat Transfer in Bubble Column Reactors, Chem. Eng. Sci. 35, 1341-1346, 1980.
94. H. Kolbel and H. Langemann, Erdoel-Zeitschv. 80, 405, 1964, as quoted in reference 38.
95. A.G. Shaykhutdinov, N.U. Bakirov and A.G. Usmanov, Determination and Mathematical Correlation of Heat Transfer Coefficient Under Conditions of Bubble Flow, Cellular and Turbulent Foam, Int. Chem. Engng. 11, 641-645, 1975.
96. M. Nishikawa, H. Kato and K. Hashimoto, Heat Transfer in Aerated Tower Filled with Non-Newtonian Liquid, Ind. Eng. Chem. Process Des. Dev. 16, 133-144, 1977.
97. J.B. Joshi and M.M. Sharma, Liquid Phase Backmixing in Sparged Contactors, Can. J. Eng. 56, 116-119, 1978.
98. J.B. Joshi, M.M. Sharma, Y.T. Shah, C.P.P. Singh, M. Ally and G.E. Klinzing, Heat Transfer in Multiphase Contactors, Chem. Eng. Commun. 6, 257-271, 1980.
99. D.N. Smith, G.J. Stiegel and J.A. Ruether, Modeling Three-Phase Reactor Systems, in Encyclopedia of Fluid Mechanics, Vol. 6, Chapter 15, pp: 535-682, Gulf Publishing Co., Houston, 1986.
100. H. Kolbel, E. Borchers and J. Martins, Wärmeübergang in Blasensäulen III, Messungen an Gasdurchströmten Suspensionen, Chemie-Ing.-Techn. 32, 84-88, 1960.
101. H. Kolbel, W. Siemes and K. Müller, Wärmeübergang an Blasensäulen, Chemie-Ing.-Techn. 30, 400-404, 1958.
102. H. Kolbel, E. Borchers and K. Müller, Wärmeübergang in Blasensäulen II. Messungen an Viscosen Suspensionen, Chemie-Ing.-Techn. 30, 729-734, 1958.

103. A. Mersmann, H. Noth, D. Ringer and R. Wunder, Maximum Heat Transfer in Equipment with Dispersed Two-Phase Systems, *Int. Chem. Eng.* 22, 16-29, 1982.
104. S.C. Saxena, M. Rosen, D.N. Smith and J.A. Ruether, Mathematical Modeling of Fischer-Tropsch Slurry Bubble Column Reactors, *Chem. Eng. Comm.* 40, 97-151, 1986.
105. S.C. Saxena, N.S. Rao and A.C. Saxena, Heat Transfer from a Cylindrical Probe Immersed in a Three-Phase Slurry Bubble Column, *Chem. Eng. J.* 44, 141-156, 1990.
106. A.B. Pandit and J.B. Joshi, Three-Phase Sparged Reactors-Some Design Aspects, *Revs. Chem. Eng.* 2, 1-84, 1984.
107. S.D. Kim, Y. Kang and H.K. Kwon, Heat Transfer Characteristics in Two- and Three-Phase Slurry-Fluidized Beds, *A.I.Ch.E. J.* 32, 1397-1400, 1986.
108. I.S. Suh, G.T. Jin and S.D. Kim, Heat Transfer Coefficients in Three-Phase Fluidized Beds, *Int. J. Multiphase Flow* 11, 255-259, 1985.
109. I.S. Suh and W.D. Deckwer, Unified Correlation of Heat Transfer Coefficients in Three-Phase Fluidized Beds, *Chem. Eng. Sci.* 44, 1455-1458, 1989.
110. Y. Kato, K. Uchida, T. Kago and S. Morooka, Liquid Holdup and Heat Transfer Coefficient Between Bed and Wall in Liquid-Solid and Gas-Liquid-Solid Fluidized Beds, *Powder Tech.* 28, 173-179, 1981.
111. S.C. Saxena, N.S. Rao and A.C. Saxena, Heat Transfer and Gas Holdup Studies in a Bubble Column: Air-Water-Glass Bead System, *Chem. Eng. Comm.*, in press.
112. S.C. Saxena, P.R. Thimmapuram and N.S. Rao, Gas Holdup and Heat Transfer in a Baffled Slurry Bubble Column, *A.I.Ch.E. Annual Meeting*, Los Angeles, CA, 1991.
113. S.C. Saxena, N.S. Rao and A.C. Saxena, Heat Transfer and Holdup Studies in a Three-Phase Slurry Bubble Column with Internals, *A.I.Ch.E. Sym. Series* (Editor: A.W. Weimer), in press.
114. S.C. Saxena, N.S. Rao and M. Yousuf, Heat Transfer and Hydrodynamic Investigations Conducted in a Bubble Column with Powders of Small Particles and a Viscous Liquid, *Chem. Eng. J.*, to be published.
115. S.C. Saxena, N.S. Rao and P.R. Thimmapuram, Transport Studies in a Baffled Bubble Column with Slurries Involving Viscous Fluids, *Indian*

Chem. Eng. Congress-1990, held at Varanasi, India, 1991.

116. S.C. Saxena, R. Vadivel and A.C. Saxena, Gas Holdup and Heat Transfer from Immersed Surfaces in Two- and Three-Phase Systems in Bubble Columns, Chem. Eng. Comm. 85, 63-83, 1989.
117. J.B. Joshi and M.M. Sharma, A Circulation Cell Model for Bubble Columns, Trans. Instn. Chem. Engrs. 57, 244-251, 1979.
118. R.A. Mashelkar, Bubble Columns, Br. Chem. Eng. 15, 1297-1304, 1976.
119. P. Zehner, Momentum, Mass and Heat Transfer in Bubble Columns, Part I. Flow Model of the Bubble Column and Liquid Velocities, Int. Chem. Eng. 26, 22-28, 1986.
120. S.C. Saxena, N.S. Rao and A.C. Saxena, Estimation of Heat Transfer Coefficient for Immersed Surfaces in Bubble Columns Involving Fine Powders, Powder Technology 63(2), 197-202, 1991.
121. S.C. Saxena N.S. Rao and I.A. Khan, Heat Transfer from an Immersed Tube Bundle in a Three-Phase Slurry Bubble Column, 4th Int. Symp. on Transport Phenomena in Heat and Mass Transfer, July 14-18, 1991, Kensington, Australia.
122. S.C. Saxena, R. Vadivel and A.C. Saxena, Hydrodynamics and Heat Transfer Characteristics of Bubble Columns Involving Fine Powders, Powder Technology 59, 25-35, 1989.
123. R.F. Probstein and M.Z. Sengun, Dense Slurry Rheology with Application to Coal Slurries, Physico-Chemical Hydrodynamics 9, 299-313, 1987.
124. R. Botton, D. Cosserat and J.C. Charpentier, Influence of Column Diameter and High Gas Throughputs on the Operation of a Bubble Column, Chem. Eng. J. 16, 107-115, 1978.
125. S.C. Saxena, A.C. Saxena and N.S. Rao, Prediction of Heat Transfer Coefficient from an Immersed Surface in a Slurry Bubble Column, Int. Comm. Heat Mass Transfer 17, 247-258, 1990.
126. S.C. Saxena and B.B. Patel, Heat Transfer Investigations in a Bubble Column with Immersed Probes of Different Diameters, Chem. Eng. Comm., to be published.
127. S.C. Saxena, A.K. Verma, R. Vadivel and A.C. Saxena, Heat Transfer from a Cylindrical Probe in a Slurry Bubble Column, Int. Comm. Heat Mass Transfer 16, 267-281, 1989.

128. S.C. Saxena, N.S. Rao and A.C. Saxena, Investigation of Heat Transfer Phenomenon in Three-Phase Slurry Bubble Columns: Simulation of Indirect Coal Liquefaction Process, Proc. 1989 Int. Conf. on Coal Science, Volume II, 679-682, 1989, Tokyo, Japan.
129. S.C. Saxena, N.S. Rao and B.B. Patel, Heat Transfer and Hydrodynamic Investigations in Two- and Three-Phase Systems in a Baffled Bubble Column, Proc. Ninth Int. Heat Transfer Conf., Jerusalem, Israel, Ed. G. Hetsroni, 3, 407-412, 1990.
130. S.C. Saxena and B.B. Patel, Heat Transfer from a Tube Bundle in a Slurry Bubble Column Involving Fine Powders, Powder Technology 61, 207-610, 1990.

10. LIST OF FIGURES

Fig. 3.1. Schematic of the 0.108 m diameter bubble column along with air supply loop, temperature and pressure measuring circuits and liquid circulation loop: (1) air compressor, (2) surge tank, (3) refrigerator drier, (4) oilscr filter, (5) pressure regulator valves, (6) gate valves, (7) rotameter, (8) pressure gauge, (9) one-way valve, (10) bubble cap distributor, (11) perforated-plate distributor, (12) stainless steel wire cloth, (13) water inlet, (14) thermocouples, (15) Plexiglas column, (16) water outlet, (17) disengaging section, (18) liquid drain, (19) purgemeters, (20) trap bottles, (21) manometers, (22) data acquisition system, (23) computer, (24) keyboard, (25) disc drive, (26) monitor, (27) printer, (28) plotter, (29) liquid storage tank, (30) liquid circulation pump, (31) stirrer and (32) venturimeter.

Fig. 3.2. Design details of the bubble column cap air distributor plate for the calming section (A), and of the air distributor plate for the slurry bubble column (B). All dimensions are in cm.

Fig. 3.3. Schematic of the pressure measurement and control systems.

Fig. 3.4. Design details of the heat transfer probe (A), mounting clamp (B), orientation of the five-tube bundle (C), and bubble column with the tube-bundle.

Fig. 3.5. Design details of the 31.8 mm heat transfer probe (A), and of the heated section (B). All dimensions are in mm.

Fig. 3.6. Design details of the 50.8 mm heat transfer probe (A), and of the heated section (B). All dimensions are in mm.

Fig. 3.7. A sectional top view through the center of the probe bundle comprising of seven simulated heat transfer probes arranged in an equilateral triangular configuration. (1) heat transfer probe, (2) ring clamp, (3) spacer plates, (4) locating stud, (5) telescopic locating stud, (6) column surface, (7) Teflon rounded cap, (8) stainless steel spring, (9) locking pin, (10) calrod heater, and (11) brass tube.

Fig. 3.8. Design details of the radial thermocouple probe. (1) copper-constantan thermocouples, (2) thermocouple well, (3) Silicone rubber, (4) Acrylic tube, (5) column wall, and (6) Swagelock connector. All dimensions are in mm.

Fig. 3.9 Design details of the thermocouple probe: (1) copper constantan thermocouple, (2) thermocouple well, (3) copper cement, (4) Teflon plug, (5) stainless steel tube, (6) column well, (7) Swagelock connector, (8) front ferrule, (9) back ferrule, (10) shrink tube, (11) thermocouple leads. All dimensions are in mm.

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Table 4.9. Smoothed heat transfer coefficient and air holdup values for air-water-magnetite system at 308K. Column diameter: 0, 108 m, Internal: 19 mm Single tube, Particle diameters: 35.7, 49, 58, 69, 90.5, 115.5 and 137.5, Solids concentration: 0, 10, 15, 20 and 30 wt%.

Table 4.10. Experimental air holdup values for air-water-magnetite system at 309K. Column diameter: 0.105 m, Internal: Seven-tube bundle, Particle diameters: 35.7, 90.5 and 137.5 μm , Solids concentrations: 10 and 30 wt%.

Table 4.11. Smoothed nitrogen holdup values for nitrogen-Therminol-red iron oxide system at 301-309K. Column diameter: 0.108 m, Internal: 19, 31.8, 50.8 mm single tubes and seven-tube bundle. Particle diameter: 1.7 μm , Solids concentrations: 0, 15, 30 and 50 wt%.

Table 4.12. Experimental values of h_w ($\text{kW}/\text{m}^2\text{K}$) for different electrical power inputs to the heater at a fixed column temperature T_c . Column diameter: 0.108m, Internal: 19 mm single tube. System: Air-water.

Table 4.13. Experimental h_w ($\text{kW}/\text{m}^2\text{K}$) and air holdup values for air-water system in the continuous mode operation at $307 \pm 1\text{K}$. Column diameter: 0.108 m, Internal: 19 mm single tube.

Table 4.14. Experimental h_w ($\text{kW}/\text{m}^2\text{K}$) and air holdup values at different heater locations for air-water system at $315 \pm 1\text{K}$. Column diameter: 0.108 m, Internal: Seven-tube bundle.

Table 4.15. Experimental (A) and smoothed (B) h_w ($\text{kW}/\text{m}^2\text{K}$) values for air-water system at 309K. Column diameter: 0.108 m, Internal: 19 mm single tube.

Table 4.16. Experimental h_w ($\text{kW}/\text{m}^2\text{K}$) values for air-water system at 309K. Column diameter: 0.108 m, Internal: Seven-tube bundle.

Table 4.17. Experimental h_w ($\text{kW}/\text{m}^2\text{K}$) values for air-water-red iron oxide and air-water-magnetite systems at 313K. Column diameter: 0.108 m, Internal: 19 mm single tube.

Table 4.18. Experimental h_w ($\text{kW}/\text{m}^2\text{K}$) values for air-water-glass bead values at 315K. Column diameter: 0.109 m, Internal: 19 mm single tube.

Table 4.19. Smoothed h_w ($\text{kW}/\text{m}^2\text{K}$) values for air-water-glass bead system at 309K. Column diameter: 0.108 m, Internals: 19 mm single tube and seven-tube bundle.

Table 4.20. Smoothed h_w (kW/m²K) values for air-water-magnetite system at 309K. Column diameter: 0.108 m, Internal: Seven-tube bundle, Particle diameters: 37.5, 90.5 and 137.5 μ m, solids concentrations: 10 and 30 wt%.

Table 4.21. Smoothed h_w (kW/m²K) values for nitrogen-Therminol-red iron oxide system at 301-309K. Column diameter: 0.108 m, Internals: 19.0, 31.8, 50.8 mm single tubes and seven-tube bundle.

Table 4.22. Smoothed h_w (kW/m²K) values for nitrogen-Therminol-magnetite system at 306K. Column diameter: 0.108 m, Internal: 19.0, 31.8 and 51.8 mm single tubes, Particle diameters: 26.6, 37.7 and 45.5 μ m.

Table 4.23. Air holdup values smoothed over-concentration range for air-water and air-water-glass bead systems for different particle diameters and at different temperature levels. Column diameter: 0.305 m, Internal: Seven-tube bundle.

Table 4.24. Smoothed air holdup values for air-water system at different temperature levels. Column diameter: 0.305 m, Internal: Thirty-seven bundle.

Table 4.25. Nitrogen gas holdup values smoothed over the solids concentration range for nitrogen-Therminol-magnetite system at different temperature levels. Column diameter: 0.305 m, Internal: Thirty-seven tube bundle, Particle diameter: 36.0 μ m, solids conc. : 0, 15, 30 and 40 wt%.

Table 4.26. Smoothed air holdup and h_w (kW/m²K) values for air-water-silica sand system at different temperature levels. Column diameter: 0.305m, Internal: Seven-tube bundle.

Table 4.27. Smoothed air holdup values for air-water-glass bead system at different temperature levels. Column diameter: 0.305 m, Internal: Thirty-seven tube bundle.

Table 4.28. Air holdup values smoothed over particle size and the solids concentration range for air-water-magnetite system at different temperature levels. Column diameter: 0.305 m, Internal: Seven-tube bundle. Particle diameters: 50 and 90 μ m, Solids concentrations: 3, 5 and 10 wt%.

Table 4.29. Experimental h_W (kW/m²K) values as a function of power input to the probe at $U_g = 0.376$ m/s. Column diameter: 0.305 m, Internal: 19 mm single tube, System: Air-water.

Table 4.30. Experimental h_W (kW/m²K) values in different regions of the 0.305 m bubble column for air-water system at 297 ± 3 K. Internal: 19 mm single tube.

Table 4.31. Smoothed h_W (kW/m²K) values for air-water system at different temperature levels. Column diameter: 0.305 m, Internal: Seven-tube bundle.

Table 4.32. Smoothed h_W (kW/m²K) values for air-water system at different temperature levels in different regions of the tube bundle. Column diameter: 0.305m, Internal: Thirty-seven tube bundle.

Table 4.33. Smoothed h_W (kW/m²K) values for nitrogen-Therminol-magnetite system at different temperature levels. Column diameter: 0.305 m, Internal: Thirty-seven tube bundle. Particle diameter: 36.6 μ m, Solids concentrations: 0, 15, 30 and 40 wt%.

Table 4.34. Smoothed h_W (kW/m²K) values for air-water and air-water-silica sand systems at different temperature levels. Column diameter: 0.305 m, Internal: Seven-tube bundle, Particle diameter: 65.0 μ m.

Table 4.35. Smoothed h_W (kW/m²K) values for air-water and air-water-glass bead systems at different temperature levels. Column diameter: 0.305 m, Internal: Seven-tube bundle, Particle diameters: 50, 90 and 143.3 μ m.

Table 4.36. Smoothed h_W (kW/m²K) values for air-water-glass bead system at different temperature levels. Column diameter: 0.305 m, Internal: Thirty-seven tube bundle, Particle diameters: 125, 168 and 212 μ m.

Table 4.37. Smoothed h_W (kW/m²K) values for air-water and air-water-magnetite systems at different temperature levels. Column diameter: 0.305 m, Internal: Seven-tube bundle. Particle diameters: 50 and 90 μ m. Solids concentrations: 3, 5 and 10 wt%.

Table 5.1. Values of $U_{b\infty}$ based on Eq. (5.21) and determined from experimental gas holdup data for air-water and air-water-glass bead systems at 309K in 0.108m bubble column.

Table 5.2. Values of $U_{b\infty}$ based on Eq. (5.21) and determined from experimental gas holdup data for nitrogen-Therminol and nitrogen-Therminol-red iron oxide systems in 0.108 m bubble column at ambient temperature.

Table 5.3. Values of $U_{b\infty}$ based on Eq. (5.21) and determined from experimental gas holdup data for air-water magnetite system in 0.108 m in bubble column equipped with a 19 m tube. The data was measured at 308K for particles in the size range 35.7 - 137.5 μm and slurry concentrations in the range 10 - 30 wt%.

Table 5.4. Values of $U_{b\infty}$ based on Eq.(5.21) and determined from experimental gas holdup data for nitrogen-Therminol-magnetite system for different internals in 0.108 m bubble column at ambient temperature.

Table 6.1. Constants of Eqs. (6.51) and (6.54) as determined from the experimental h_{Wj} values for air-water-red iron oxide system at 313K and measured in 0.108 m bubble column equipped with 19 mm heat transfer probe.

Table 6.2. Values of the constants of Eqs. (6.51) and (6.54) as determined from the experimental h_{Wj} values for three different systems in the temperature range 308 - 316K and measured in 0.108 m bubble column equipped with 19 mm heat transfer probe.

Table 6.3. Global constants of Eqs. (6.51) and (6.52) as determined from the experimental h_{Wj} values for air-water-magnetite and air-water-glass bead systems in the temperature range 308 - 316K and measured in 0.108 m bubble column equipped with 19 mm heat transfer probe.

Table 6.4. Values of the constants of Eqs. (6.51) and (6.54) as determined from the experimental h_{Wj} values for air-water and air-water-glass bead systems at 393K and measured in 0.108 m bubble column equipped with a 19 mm single tube and a seven-tube bundle.

Table 6.5. Values of the constants of Eqs. (6.51) and (6.54) as determined from the experimental h_{Wj} values for air-water-magnetite system at 308K and measured in 0.108m bubble column equipped with a 19 mm single heat transfer probe.

Table 6.6. Values of the constants of Eq. (6.51) as determined from the experimental h_{Wj} values for air water and air-water-magnetite systems and measured in 0.305m bubble column equipped with a seven-tube bundle.

Table 6.7. Values of the constants of Eq. (6.51) as determined from the experimental h_w values for nitrogen-therminol-magnetite system at 306-312K and measured in 0.108m bubble column equipped with three single heat transfer probes.

Table 6.8. Values of the constants of Eqs. (6.51) and (6.64) as determined from the experimental h_w values for air-water and air-water-sand systems at several temperatures and measured in 0.305m bubble column equipped with a seven-tube bundle.

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