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REVIEW OF EXPERIMENTAL CAPABILITIES AND HYDRODYNAMIC DATA FOR VALIDATION OF CFD BASED PREDICTIONS FOR SLURRY BUBBLE COLUMN REACTORS

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Abstract

The purpose of this paper is to document the review of several open-literature sources of both experimental capabilities and published hydrodynamic data to aid in the validation of a Computational Fluid Dynamics (CFD) based model of a slurry bubble column (SBC). The review included searching the Web of Science, ISI Proceedings, and Inspec databases, internet searches as well as other open literature sources. The goal of this study was to identify available experimental facilities and relevant data. Integral (i.e., pertaining to the SBC system), as well as fundamental (i.e., separate effects are considered), data are included in the scope of this effort. The fundamental data is needed to validate the individual mechanistic models or closure laws used in a Computational Multiphase Fluid Dynamics (CMFD) simulation of a SBC. The fundamental data is generally focused on simple geometries (i.e., flow between parallel plates or cylindrical pipes) or custom-designed tests to focus on selected interfacial phenomena. Integral data covers the operation of a SBC as a system with coupled effects. This work highlights selected experimental capabilities and data for the purpose of SBC model validation, and is not meant to be an exhaustive summary.

Introduction

Slurry Bubble Column Reactors (SBCRs) are used by industry to manufacture liquid hydrocarbon fuels (i.e., diesel or gasoline) via the Fischer Tropsch (FT) process (Figure 1). In the FT process, a synthesis gas comprised of hydrogen and carbon monoxide is sparged through a distributor into a suspension of liquid and solid catalyst particles. Generally, in order to be economically viable, a bubble/slurry bubble column reactor must be operated at high volumetric flow rates. This requires a very active catalyst, high catalyst loading of the slurry, and high gas conversion rates. To achieve a complete catalyst suspension and the desired product reaction, these reactors need to be

Figure 1. Churn-turbulent three-phase flow in a SBCR.

operated at a high superficial gas velocity in the churn-turbulent flow regime. At these conditions, the two-phase interfacial dynamics dominates the reactor hydrodynamics. Due to the radial gradient of the buoyancy force resulting from non-uniform lateral gas holdup, liquid or slurry recirculation is induced where liquid moves upward in the central region of the bubble column and downward near the wall region of the column. In the case of a SBC, the catalyst particles are very small, hence they closely follow the motion of the liquid flow. The key to successfully modeling this process lies in accurate predictions of the heat and mass transfer along with turbulent mixing, which affects kinetics and thus product yield and selectivity.

Although the FT reaction process was developed in the early 1900's [1], details concerning the hydrodynamic processes, which control the reactor flow, are still poorly understood. For example, significant progress is clearly needed to better understand the unsteady, multiphase fluid dynamics that controls the fluid mixing and interphase transport processes, which in turn determine the overall reactor performance. Due to the complexity of the reaction and hydrodynamic processes occurring in the SBCR, the system performance has traditionally been characterized empirically, rather than from a fundamental physical basis. Since empirical correlations are generally valid only for the (typically narrow) parameter ranges over which they are generated, mechanistic models of the sub-processes occurring in a SBCR as necessary to optimize the overall process and scale laboratory data to industrial applications.

This paper provides a limited summary of institutions with existing experimental facilities capable of providing validation data and sources of validation data published in the open literature. An emphasis is placed on data for churn-turbulent flows, since the hydrodynamics of the flow, as well as the flow mechanisms, change significantly from one flow regime to another [2]. The scope of this effort is limited to hydrodynamics only, without reactions occurring. Once the computational model is validated using suitable hydrodynamic data, reaction kinetics will be incorporated.

Hydrodynamic Data in the Open Literature

The Idaho National Laboratory and Rensselaer Polytechnic Institute (RPI) have embarked on a joint effort to develop scientific and technological advances for the design and development of next generation FT reactors. This goal will be achieved by employing state-of-the-art modeling and computational concepts of multidimensional, multiphase reacting flows in complex geometries and linking together multiple scales to upgrade multi-scale simulation capabilities of the computational multiphase fluid dynamic (CMFD) code, NPHASE [3] under development at RPI. An ensemble-averaged, multifield, mechanistic model formulation will be used to develop closure relations for use with the NPHASE software. Once validated and fully functional, the FT SBCR model will be used as a numerical test bed to virtually simulate new concepts and ideas to improve the process.

The complexity in the design of gas-liquid-solid systems lies in the existence of the three phases with mass, momentum and energy transfer occurring between them. The interfacial structure between the liquid and the gas phase can be considerably different depending upon system configuration and operating conditions. Due to complicated interaction of phases (particularly in churn-turbulent flow regime), the hydrodynamics is not yet fully understood and hence, the reactor design and scale-up are a challenging task. The use of CMFD, rather than empirical correlations, is in principle applicable to a wider range of conditions and design configurations. However, this procedure calls for a solution of the coupled continuity, momentum and energy equations for two fluid phases and a dispersed solid phase. For problems of practical utility, the ensemble-averaged form of the Navier-Stokes equations are solved. This approach necessitates the use of constitutive equations (i.e., closure models) to re-introduce information that was lost through the averaging procedure. Mechanistic-based closure relations have been and are continuing to be developed [4], but require validation with experimental data obtained at conditions applicable to the FT process. To validate a CMFD based model of a SBCR, the important interfacial mass, momentum and energy transfer processes must be identified. For the SBCR under consideration, the transfer processes listed in Table 1 are considered dominant and should be validated with data.

Table 1. Important mass, momentum and energy processes in a SBCR

Mass Transfer	Momentum Transfer	Energy Transfer
• Bubble Coalescence – small bubble interaction – cap/slug bubble interaction • Bubble Breakup – cap/slug bubble breakup • Flow Topology Transition – interfacial area density transport	• Interfacial Drag Force – bubble drag – cap/slug drag – particle drag • Interfacial Lift Force • Interfacial Virtual Mass Force • Interfacial Wall Force • Interfacial Turbulence Dispersion Force • Liquid Turbulence – shear induced turbulence – bubble induced turbulence	• Reaction Kinetics • Tube Bank Heat Transfer • Interfacial Heat Transfer

The purpose of this review is to identify available experimental facilities, techniques and data to validate CMFD models of gas-liquid-solid flows through SBCRs. The following sections will review results from our database and internet searches. In this paper, we refer to "integral" experiments as pertaining to a system, whereas "fundamental" experiments provide the capability to isolate separate effects occurring within a system.

Experimental Facilities, Techniques and Methods Available

The experimental facilities, techniques and methods listed cover both integral and fundamental testing. Capabilities span the scale from bench-top or laboratory SBCs to pilot or production scale slurry bubble column reactors. Available integral test facilities and data available in the open literature are shown in Table 2. Testing performed at these facilities has provided gas, liquid, and solid phase velocity field data; turbulence parameters (turbulent dispersion coefficients, Reynolds stresses); effect of process variables and component properties on gas and solids holdup; bubble size, distribution, and frequency data; as well as heat and mass transfer coefficient data. The data includes bubble column flows between large flat plates (i.e., 2D bubble column experiments) and cylindrical test sections. The 2D bubble column experiments listed were typically smaller in scale than the cylindrical SBCs and range in depth (i.e., distance between the large flat plates) from 5.08 to 15.0 cm and width from 15.0 to 30.48 cm. Although the 2D tests are less expensive to build and operate due to lower flow requirements (which translates to reduced pump and compressor requirements), the effects of the large flat plate walls may significantly influence the two-phase flow phenomena.

The cylindrical bubble columns found in the literature ranged in size from bench-top or laboratory scale to pilot and production size units. The laboratory scale integral tests ranged in diameter from 5.0 to 63.0 cm. The pressure and gas flow rate was typically limited by the material structural integrity and the size of gas compressors used. Therefore, the available data in the churn-flow regime was limited and additional experiments may be needed.

Available open source data (integral and fundamental) is listed in Table 3. The fundamental data is needed to validate individual mechanistic models or closure laws used in a CMFD simulation of a SBC. The fundamental data set is generally taken in more simple geometries (i.e., flow between parallel plates or vertical cylindrical pipes) or custom-designed tests to maximize selected interfacial phenomena. Data available in open literature includes gas, liquid, and solid phase velocity fields; turbulence parameters (liquid phase turbulent dispersion coefficients, Reynolds stress, turbulence intensity); gas and solids holdup distributions; bubble rise velocity, bubble drag coefficient, interfacial area; bubble size distribution and frequency; bubble coalescence and break-up parameters; heat and mass transfer coefficients; and residence time distributions. Test configurations were found to range from simple geometries to more prototypic vessels. The fundamental tests are typically done at low pressure and most times used air-water for the modeling fluids. The 2D test sections used for fundamental testing ranged in depth from 1.2 to 4.0 cm and width from 20 to 30 cm. More recent fundamental testing also includes local velocity and void fraction data in cylindrical vessels and pipes. The diameter for these tests ranged from 3.7 cm to 80 cm. The majority of experiments found in the literature were performed using air-water systems. To validate performance of FT SBCs, it will be necessary to include the effect of operating conditions (e.g., temperature, pressure, etc.) on fluid properties (e.g., density, viscosity, surface tension, etc.) and behavior (e.g., turbulent mixing, gas hold up, etc.).

Summary and Conclusions

This study reviewed existing experimental facilities and available data that can be used to validate a CMFD based model of a SBC. The review included searching the Web of Science, ISI Proceedings, and Inspec databases, internet searches as well as other open literature sources. Experimental facilities, techniques and methods, including bench-top or laboratory scale bubble columns and pilot or production scale slurry bubble column reactors, used to obtain hydrodynamic data relating to SBCs has been summarized. Available experimental data, both integral and fundamental, has also been summarized. Fundamental data is needed to validate individual mechanistic models or closure laws used in a Computational Multiphase Fluid Dynamics (CMFD) simulation of a SBC. The fundamental data set is generally taken in more simple geometries (i.e., flow between parallel plates or cylindrical pipes) or a custom designed tests to maximize selected interfacial phenomena. Integral data can be used to validate the performance of an entire SBC system. The goal of this effort is to produce a validated CMFD based model of a FT SBC that can be used as a numerical test bed. With such a tool, new concepts can be assessed virtually and optimized for FT process improvement.

The authors recognize that an enormous amount of work has been done pertaining to SBCs. The tables provided in this review are meant to be a starting point and are not exhaustive. Future experiments should build upon the work already done and existing data should be used to guide further experimentation.

Table 2. Experimental Capabilities to Validate CMFD-Based Model.

Experimental Facility	Test Section(s)	Measurement Technique	Information Provided	Ref.
Aalborg University Esbjerg, Denmark	0.15 m width × 0.15 m depth × 1 m height	Particle Image Velocimetry (PIV), laser Doppler anemometry (LDA)	gas and liquid phase velocity fields, gas and liquid velocity fluctuations	[5]
Advanced Fuels Development Unit (AFDU), LaPorte, TX	0.46 m dia × 15.24 m height	Radioactive tracer measurements employing NaI scintillation detectors	radioactive tracer response, mean liquid phase axial and radial eddy dispersion coefficient, centerline liquid velocity, mean recirculation velocity	[6]
Beijing Institute of Petrochemical Technology, China (Haibo Jin)	0.3 m dia × 6.6 m height, 0.54 m/s gas velocity, 1.0 MPa system pressure	gamma ray attenuation	effects of superficial gas velocity, static liquid height, liquid surface tension, liquid viscosity, acid concentration, solid and antifoam agents, and system pressure on the axial and overall gas holdup	[7]
Delft University of Technology, The Netherlands (Robert F. Mudde, Wouter K. Harteveld)	15.2 cm, 23.4 cm, 38.4 cm dia columns; 15.0 cm dia × 1.2 m column	LDA, glass fiber probe	axial and tangential liquid velocity components, Reynolds stresses, turbulence power spectra, gas fraction profiles, axial mean liquid velocity, axial normal stress profiles	[8] [9] [10]
Florida Atlantic University (D. Moslemian)		Computer Automated Radioactive Particle Tracking (CARPT)	Mean circulation profiles, turbulence parameters (Reynolds normal and shear stresses, turbulent eddy dispersion coefficient),	[11]
Humboldt University Berlin, Germany (U. Kertzscher)	104 mm dia × 100 mm height SBC	XPTV	local solid velocity and the local solid hold-up in three-phase flows	[12]
Illinois Institute of Technology (Dimitri Gidaspow)	30.48 cm width × 5.08 cm depth × 213.36 height	PIV with γ- and x-ray densitometer	Flow profile, particle concentration profiles and Reynolds stresses PIV – time-averaged particle velocities and concentrations	[13]
Iowa State University (Theodore J. Heindel)	32.1 cm dia × 4.88 m height acrylic SBC	X-ray Computed Tomography (CT)	cross-sectional gas holdup distribution	[14]
NASA Glenn Research Center	25 mm dia × 20 cm height tube	MRI	void fraction distributions	[15]
Sandia National Laboratories (Tim O'Hern, Rob Tachau, John Torczynski, Joel Lash)	Industrial-scale riser testbed; 48 cm dia, ~3 m height, T≤200°C, P≤100 psig	Gamma densitometry tomography, electrical impedance tomography, electrical and optical probes	gas volume fraction, three-phase profiles	[16]
Technische Universität Braunschweig, Germany	0.63 m dia × 6.1 m height Plexiglas bubble column	DPM/TDR, DPM/ECM	local gas and solids holdup	[17]

Experimental Facility	Test Section(s)	Measurement Technique	Information Provided	Ref.
Texas A&M University (Dragomir B. Bukur)	0.05 and 0.21 m inside diameter by 3 m tall stainless steel bubble columns	Gamma ray densitometry	radial gas holdup distribution, radial and axial gas and solid volume fraction distributions, flow regime transitions	[18]
Ohio State University (L. S. Fan)	10 cm dia × 100 cm height bubble column; 10.2 cm width × 10.2 cm depth × 150 cm height Plexiglas square SBC	Electrical Capacitance Tomography, LDV, PIV	real-time cross-sectional gas and solids holdup distributions, instantaneous and average velocity distributions, turbulent energy distributions, Reynolds stresses, liquid-phase power spectra, bubble-induced turbulence, effect of gas distributors and solids on the turbulence field, bubble sizes and distributions	[19] [20] [21] [22] [23]
Purdue University (M. Ishii)	10 mm × 2950 mm high	conductance probe, high speed video, LDA	void fraction, interfacial area concentration, bubble size, gas and liquid velocity	[24]
University of Amsterdam, The Netherlands (R. Krishna)	0.1 m dia, 0.174 m dia, 0.19 m dia, 0.38 m dia, 0.63 m × 4 m height polyacrylate columns	dynamic gas disengagement, pitot tube	total gas holdup; small bubble holdup; dense-phase gas voidage; large bubble (dilute phase) holdup; influence of column diameter, liquid properties, gas distributor, and gas density; rise velocity and average size of large bubbles; centerline liquid velocity; radial distribution of liquid velocity; liquid phase dispersion coefficient	[25] [26]
University of Cambridge, UK (A.J. Sederman)	50 mm dia.	magnetic resonance imaging	gas phase volume fractions, distributions of gas bubble length and velocity	[27]
University of Liege, Belguim (E. Fransolet)	0.24 m dia × 2.75 m height	electrical resistance tomography, wall mounted pressure probes	influence of liquid rheology on gas flow pattern in bubble column reactor, average gas holdup, gas phase distribution, bubble size distribution	[28]
University of Mumbai, India (J. B. Joshi)	385 mm dia × 3.2 m height Perspex bubble column, $u_G = 0.06 – 0.3$ m/s	gamma ray tomography	radial variation of gas holdup	[29]
Washington University (Muthanna Al-Dahhan, Milorad P. Dudukovic)	0.162 m dia × 2.5 m height SBC, P≤1.2 MPa; 30.5 cm dia plexiglass SBC	Computer Automated Radioactive Particle Tracking (CARPT), Computed Tomography (CT), four-point probe, optical oxygen probe	Axial and radial eddy diffusivities, solids residence time, ensemble-average velocities and eddy diffusivities, incipient particle motion, flow regime identification, cross-sectional gas holdup distribution, bubble frequency, specific interfacial area, bubble chord length, bubble velocity, volumetric gas-liquid mass transfer coefficient (k_La), liquid side mass transfer coefficient	[30] [31] [32] [33] [34]

Table 3. Experimental Data to Validate CMFD-Based Model.

System gas/liquid/solid	Column Dimensions	Operating Conditions	Data Acquired	Ref.
air/water	0.15 m dia × 0.66 m height	ambient T and P	bubble pulsation count and frequency, bubble size and distribution	[35]
nitrogen/hydrocarbon waxes/iron oxide and silica particles	0.05 m dia × 3 m height; 0.21 m dia × 3 m height	T = 265°C, atmospheric pressure	radial gas holdup distribution, radial and axial gas and solid volume fraction distributions, flow regime transitions	[18]
nitrogen/FT-300 paraffinic wax	0.051 m dia × 3.05 m height	T = 230-280°C, atmospheric pressure	average gas hold-up, flow regime transition	[36]
Air/water/solids; Air/water, ethanol/solids	30.5 cm dia × 100 cm height		cross sectional gas and solids holdup distribution, time-averaged particle velocities	[30]
dimethyl ether synthesis SBC reactor	0.46 m dia × 15.24 m height	T = 250°C, P = 5.27 MPa	radioactive tracer response, mean liquid phase axial and radial eddy dispersion coefficient, centerline liquid velocity, mean recirculation velocity	[6]
air/water	200, 400, 800 mm dia × 3 m height	u_G = 20-90 mm/s	instantaneous local heat transfer rates	[37]
nitrogen, carbon dioxide/ cyclohexane, water	0.2 m dia × 1.6 m height	T = ~20°C, P_{atm}, $u_G \leq 0.14$ m/s	mass transfer efficiency, volumetric mass transfer coefficient (k_La)	[38]
air/water/500 µm acetate particles	10.2 cm width × 10.2 cm depth × 150 cm height	u_G = 0.025-7.5 cm/s	turbulent energy distributions, average velocity and Reynolds stresses, liquid-phase power spectra, bubble-induced turbulence, effect of gas distributors on the turbulence field, effect of solids on the liquid-phase turbulence	[39] [22]
air/water	14 cm dia; 19 cm dia; 44 cm dia	u_G = 2.0-12.0 cm/s	time-averaged spatial flow structure, axial liquid velocity profiles, Reynolds shear stress, and turbulence intensities profiles	[40]
air/water, K_2SO_4/poly-methyl methacrylate, polyoxymethylene	0.63 m dia × 6.1 m height Plexiglas bubble column	u_G = 0.02-0.09 m/s	local gas and solids holdup	[17]
air/various Newtonian and non-Newtonian fluids	0.24 m dia × 1.60 m height; 0.30 m dia × 0.50 m height	T = 293K	bubble rise velocity, drag coefficient	[41]
air/aqueous xanthan solutions	0.24 m dia × 2.75 m height	u_G = 0.02-0.15 m/s	influence of liquid rheology on gas flow pattern, average gas holdup, gas phase distribution, bubble size distribution	[28]
air/water	0.162 m dia	P ≤ 1.0 MPa	overall gas holdup, volumetric gas-liquid mass transfer coefficient (k_La), interfacial area, liquid side mass transfer coefficient	[34]
air/water	0.4 m dia × 9 m height	atmospheric pressure	gas-liquid mass transfer, total gas hold-up, small bubble hold-up in the liquid–small bubble mixture, large and small bubble hold-up	[42]
H_2, N_2, CO, CH_4/hexane mixture/FT Fe catalyst	0.316 m dia × 2.8 m height	P ≤ 0.8 MPa	effects of gas velocity, system pressure, and catalyst loading on gas holdup	[43]
air/water, Drakeol 10	48 cm dia × ~3 m height	P ≤ 50 psig $u_G \leq 0.25$ m/s	spatially resolved gas holdup	[16]
air/water; air/acetic acid	0.3 m dia × 6.6 m height	P ≤ 1.0 MPa $u_G \leq 0.4$ m/s	effects of superficial gas velocity, liquid surface tension, liquid viscosity, and system pressure on the axial gas holdup	[7]

System gas/liquid/solid	Column Dimensions	Operating Conditions	Data Acquired	Ref.
nitrogen, helium/ethanol, 1-butanol, toluene, decalin, tap water	0.1 m dia × 2.4 m height	T = 293K, P = 0.1-4.0 MPa, u_G = 0.01-0.20 m/s	effect of gas density on the gas hold-up structure in a bubble column with organic liquids	[44]
nitrogen/distilled water, sodium gluconate/carbon particles	0.3 m width × 0.015 m depth × 2 m height	T = 293 K, P = 1 bar	local and overall gas holdup in homogenous, transition, and heterogeneous regimes	[45]
air/water	0.174, 0.38, 0.63 m dia × 4 m height	P = 101.3 kPa	radial distribution of liquid velocities, liquid-phase axial dispersion coefficients, bubble drag coefficient	[46]
air/paraffin oil/porous silica particles	0.1, 0.19, 0.38 m dia	P = 1 bar	gas holdup, gas voidage, rise velocity and average size of large bubbles, centerline liquid velocity, radial distribution of liquid velocity, liquid phase dispersion coefficient	[26]
air/water, isopropanol	0.10, 0.14, 0.19, 0.26, 0.30 m dia	u_G = 0.02-0.12 m/s	effect of column diameter, superficial gas velocity, distributor type, static liquid height, axial distance from distributor, and liquid properties on gas-holdup	[47]
air/water, inorganic industrial solution	0.078 m dia × 4.6 m height	T = 45°C, u_G = 1-8 cm/s	average gas holdup, bubble size distribution, method to estimate coalescence and break-up parameters in bubble columns	[48]
air/1.5 wt% polyacryamide in water	30 cm width × 1.2 cm depth × 120 cm height		coalescing mechanism of two in-line oblate-cusped bubbles rising in a non-Newtonian fluid	[49]
air/water, glycerin	68 mm width × 88 mm depth × 450 mm height		turbulence intensity, Reynolds stress, liquid velocity profile associated with bubble induced flow structure	[50]
nitrogen/water, ethanol, 1-butanol	0.1 m dia × 2.1 m height	T = 298-323K, P = 0.1-0.5 MPa, u_G = 0.01-0.21 m/s	gas holdup, axial liquid velocity, liquid axial dispersion coefficient, CFD model developed for the prediction of flow pattern in terms of mean velocity and eddy diffusivity profiles. Model also predicts residence time distribution and axial dispersion coefficient.	[51]
air/water/calcium alginate beads	0.14 m dia		effect of presence of solid phase on homogeneous–heterogeneous flow regime transition, regime transition critical point, voidage as function of gas flow rate	[52]
air/water, n-butanol, glycerin	10 cm width × 10 cm depth × 150 cm height	ambient T and P	effect of liquid properties on average gas holdup values, bubble size distributions and Sauter diameters	[53]
air/water	0.2 m width × 0.04 m depth × 1.2 m height	ambient T and P	flow regime identification, Reynolds stresses, global gas hold-up, liquid velocities, liquid flow macrostructures	[54]
coal-to-liquids reaction	1 m dia × 11.8 m height pilot plant	T = 313-733 K, P = 16.6-16.8 MPa	residence time distribution curves	[55]
air/water, cationic and anionic surfactant aqueous solutions	0.05 m dia × 0.40 m height glass bubble column	T = 20°C, dynamic bubble regime	effect of liquid properties (surfactants) on bubble generation phenomenon, interfacial area, and liquid-side mass transfer coefficient	[56]
air/clay particles suspended in water	0.3 m dia × 3 m height		effect of power input, fluid phase viscosity and solids loading on the mechanical stress on suspended particles	[57]

System gas/liquid/solid	Column Dimensions	Operating Conditions	Data Acquired	Ref.
nitrogen/cyclohexane	0.3 m dia × 4 m height	T = 30-160°C P = 0.2-1.1 MPa	bubble size distribution, mean gas holdup, interfacial area, bubble swarm velocity	[58]
air/water; steam/water	195.3 mm dia	20° C < T < 30° C P = 120 kPa; T=180-280° C 1 < P < 6.5 MPa	gas fraction, gas velocity, bubble size	[59]
air/water/glass beads (150 μm)	0.162 m dia × 2.5 m height	P = 0.1-1.0 MPa u_G = 0.08-0.45 m/s	effect of reactor pressure and superficial gas velocity on solids phase velocity and shear stress	[32]
air/water/glass beads (150 μm)	0.162 m dia × 2.5 m height	P = 0.1-1.0 MPa u_G = 0.08-0.45 m/s	cross sectional holdup distribution of gas, liquid, and solid phases	[60]
air/water	0.1 m width × 0.1 m depth × 1.0 m height	u_G = 0-8 cm/s	bubble velocity, diameter, void fraction, and liquid velocity, influence of the void fraction on the relative velocity of a swarm of gas bubbles, experimental drag correlation proposed	[61]
nitrogen/water/glass beads	8.89 cm dia × 290 cm height	u_G = 0.5-12 cm/s, 5-30 wt% solids	solid holdup	[62]
nitrogen/Tellus oil, aqueous glucose solutions	0.15 m dia × 1.22 m height; 0.23 m dia × 1.22 m height	ambient temperature, P = 0.1-1 MPa	effect of high liquid viscosity, column diameter and operating pressure on the total gas hold-up	[63]
air, nitrogen/water, organic oil/activated carbon, silica particles	0.15 m dia	ambient temperature, P = 0.1-1.3 MPa	influence of particle lyophobicity on gas hold-up, homogeneous to churn-turbulent regime transition, and gas–liquid mass transfer	[64]
air/C_9-C_{11} paraffin oil/porous catalyst	0.1 m dia	ambient T and P, u_G = 0-0.4 m/s	gas holdup and volumetric mass transfer coefficient in homogeneous and churn-turbulent flow regimes	[65]
air/aqueous solutions of n-butanol	0.385 m dia × 3.2 m height column	u_G = 0.06-0.24 m/s	effect of superficial gas velocity on radial gas hold-up profiles	[29] [66]
air/water	0.1 m dia × 2 m height column	ambient T and P, u_G = 0.6-15 cm/s	axial and tangential mean and RMS liquid velocity values	[67]
air/water	0.16 m dia × 2.5 m height column	P ≤ 10 bar u_G = 0.03-0.30 m/s	time-averaged local heat transfer coefficients	[68]
water, hydrocarbon liquids	5.08 cm dia × 55.88 cm height, 10.16 cm dia × 91.44 cm height columns	room temperature, P ≤ 10.3 MPa u_G ≤ 0.4 cm/s	liquid phase axial dispersion coefficients	[69]
nitrogen, carbon monoxide, hydrogen/liquid paraffin/silica gel powder	37 mm dia × 480 mm height SBC	T = RT-300°C, P = atm-6 MPa u_G ≤ 0.02 m/s	bubble sizes, interfacial areas and volumetric mass transfer coefficients	[70]
air/water	10 mm thick × 2950 mm high	T = 70 °C, P = 24-49 kPa	void fraction, interfacial area concentration, interaction mechanisms	[24]
air/water	0.114, 0.190, 0.292 m dia columns	u_G = 2-18.4 cm/s	axial dispersion coefficients (eddy diffusivities)	[71]

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