Development of the Packed Bed Reactor ISS Flight Experiment

Martin O. Patton[1] and Anthony E. Bruzas[2]
ZIN Technologies, Cleveland, Ohio 44130, USA

Enrique Rame[3]
National Center for Space Exploration Research, Cleveland, Ohio 44135, USA

and

Brian J. Motil[4]
NASA Glenn Research Center, Cleveland, Ohio 44135, USA

Packed bed reactors are compact, require minimum power and maintenance to operate, and are highly reliable. These features make this technology a leading candidate as a potential unit operation in support of long duration human space exploration. On earth, this type of reactor accounts for approximately 80% of all the reactors used in the chemical process industry today. Development of this technology for space exploration is truly crosscutting with many other potential applications (e.g., in-situ chemical processing of planetary materials and transport of nutrients through soil). NASA is developing an ISS experiment to address this technology with particular focus on water reclamation and air revitalization. Earlier research and development efforts funded by NASA have resulted in two hydrodynamic models which require validation with appropriate instrumentation in an extended microgravity environment. The first model developed by Motil et al., (2003) is based on a modified Ergun equation. This model was demonstrated at moderate gas and liquid flow rates, but extension to the lower flow rates expected in many advanced life support systems must be validated. The other model, developed by Guo et al., (2004) is based on Darcy's (1856) law for two-phase flow. This model has been validated for a narrow range of flow parameters indirectly (without full instrumentation) and included test points where the flow was not fully developed. The flight experiment presented will be designed with removable test sections to test the hydrodynamic models. The experiment will provide flexibility to test additional beds with different types of packing in the future. One initial test bed is based on the VRA (Volatile Removal Assembly), a packed bed reactor currently on ISS whose behavior in micro-gravity is not fully understood. Improving the performance of this system through an accurate model will increase our ability to purify water in the space environment.

---

[1] Software Engineer, ZIN Technologies, 6745 Engle Rd # 105, AIAA Member.

[2] Project Manager, ZIN Technologies, 6745 Engle Rd # 105.

[3] Research Engineer, National Center for Space Exploration Research, 21000 Brookpark Rd/MS 110-3.

[4] Chief, Fluid Physics and Transport Branch, NASA Glenn Research Center, 21000 Brookpark Rd/MS 77-5, AIAA Member.

I. Introduction

MULTICOMPONENT mass transport in porous media is one of the most widely studied areas of chemical reaction engineering. It is an important process typically found at the core of a number of industrial and geophysical systems. As a result, two-phase flow in porous media has received considerable research attention[1-3]. However, because of the complex transport phenomena involved, the models in use today are empirical or semi-empirical. In almost every situation, the most important mass transfer parameters are controlled by the hydrodynamics which is determined by capillary forces, viscous forces, and buoyancy forces.

From the human space exploration perspective, a reliable predictive model for gas-liquid flow in porous media under reduced gravity is critical to developing the next generation life support and thermal systems as well as for materials processing and in-situ resource utilization. Experimental studies from ground-based low gravity platforms (aircraft and drop towers) have clearly shown the profound influence of gravity on flow regimes and pressure drop[4]. Fundamental studies, under extended periods of microgravity are needed to access the realistic flow rates typically found in space systems in which flows require longer to transit the test section than is attainable in the ground-based platforms.

To address this technology gap, NASA is designing an experiment to fly on the International Space Station (ISS) in 2014. The experiment will address some of the most important design and operational issues such as pressure drop, liquid holdup, and flow regime transition. This paper discusses the key features of this experiment including the diagnostics.

II. Experiment Objectives

Previous experiments[4] in the reduced gravity airplane demonstrate that gravity plays a crucial role in two-phase flow in porous media. Gravity affects the flow regimes and the regime flow boundaries at which transitions take place. In addition, the lack of gravity increases the pressure drop in a packed bed when compared to normal gravity and is attributable to the enhanced role of surface tension in the absence of gravity[4]. The long periods of microgravity available in the ISS will allow us to access the small flow rates that are relevant to water purification bioreactors under steady, fully-developed conditions.

The objectives are summarized as follows:

1) Examine the role of gravity on gas-liquid flow through porous media in the extended range of flow rates available in the ISS. The goal is to determine robust flow regime boundaries and pressure drop correlations relevant to water recovery bioreactors using the most effective set of dimensionless groups. A practical, general result of this work will be the development and validation of scaling laws that can be used as design tools for future fixed packed bed reactors in zero gravity and partial-gravity environments, including start up and transient operations.

2) Since the fluid displacement process in zero gravity is fundamentally different from that in normal gravity, carefully identify the best conditions to purge undesired gas bubbles from single liquid phase beds, and to most efficiently flood an initially dry bed with liquid.

3) Develop and validate fluid holdup models developed in Ref. 5 for both wetting and non-wetting fluid flow rates.

In addition, a design feature of this platform allows for removable test sections, so other types of reactors or two-phase components can be tested in zero gravity. Examples of alternative test sections range from membrane reactors to piping components such as tees and elbows.

III. Experiment Design

The Packed Bed Reactor Experiment (PBRE) will provide a wide range of gas (nitrogen) and liquid (water) flows. The flow range will encompass flow rates anticipated in thermal and life support systems and will span liquid and gas Reynolds numbers up to two orders of magnitude. The experiment will allow for interchangeable test sections. In addition to the test sections, the experiment package will include the Gas Control Module, the Water Control Module, the Data Acquisition and Control Unit (DACU) and the Avionics Unit. Each are discussed in more detail here.

A. Test Sections

Three test sections will be flown initially. Two of the test sections will be identical except for the packing material, and will be used to perform Fundamental Hydrodynamic Studies (FHS). The third column will mimic the Volatile Removal Assembly (VRA) already in operation in the ISS. Each column will have a circular ID of 5 cm and an overall bed length of 61 cm and will be filled with 3 mm diameter beads. One bed will contain hydrophilic beads while the other one will contain hydrophobic beads. Including the end cap, the overall length of the column will be approximately 69 cm. A screen or drilled plate in both end caps holds the spherical packing within the column. Both of these columns will be instrumented for pressure measurement and imaging data. Two needles will be introduced through the inlet plate a few centimeters into the packing to deliver discrete gas bubbles into a liquid-filled packing. The needles will only be used with very low gas flow rates.

Each FHS reactor column will be instrumented with 5 pressure transducers having temperature measurement capability and cameras at two positions along the length of the column. The pressure transducers will be evenly spaced along the column length and sample at a frequency of 200 Hz to within an accuracy of 0.1 psi. Fig. 1 shows a preliminary unit built for breadboard testing.


Figure 1. FHS breadboard column.

In order to image the flow regimes, video at up to 170 frames per second will be recorded at two locations, the first one starting at about 5 cm from the inlet to the column and the other one in the last third of the column. Digital images of two-phase flow will be captured using two GigE Vision cameras with Gigabit Ethernet links to a DACU for data transfer and camera control. The cameras nominal 1024 x 1024 pixel sensor array provides user-selectable frame rates from 2 to 112 fps at full resolution, and higher frame rates when sensor region-of-interest (ROI) readout is implemented. Two view ports are planned, each 7.6 cm in the flow direction by 3.8 cm across and inscribed with a scale to facilitate analysis. Camera optics will be capable of remote focus, iris and 6x zoom control from the 7.6 cm field of view down to 1.2 cm. A 2:1 aspect ratio is maintained throughout the zoom range by programming the camera sensor to readout a 1024 x 512 pixel ROI. By reducing the number of pixel rows during readout, the maximum frame rate can be increased to 170 fps. It is possible to reprogram the camera on orbit to record other ROI and frame rate settings as needed.

To accommodate the transfer rate necessary to meet the steady transfer and storage of video, disk drives operating at up to 10,000 rpm and solid state drives are being investigated . In addition, the data generated on the ISS must be transferred to the ground for evaluation. Options for downlink and down-mass are under consideration as well.

In order to better understand the fluid displacement processes within the packing, the science team is evaluating imaging diagnostic options that can provide information about the phase distribution at a given cross section in the column. Due to mass, volume and safety concerns, conventional high-resolution techniques such as Magnetic Resonance Imaging, X-Ray tomography and gamma densitometry have been ruled out.

Lower resolution process tomography exists in several forms which may be suitable for the PBRE. Electric Resistance Tomography[6] (ERT) and Electric Capacitance Tomography[7] (ECT), respectively exploit differences in resistivity or permittivity between the phases. In both methods, electrodes are arranged around a cross section of the flow channel. Each electrode in sequence is energized with a voltage while the remaining electrodes are grounded. In ERT, the current in the grounded electrodes is measured; while in ECT, the charge is measured. An inverse problem is solved in order to extract the resistivity (ERT) or permittivity (ECT) spatial distributions from the current or charge measurements. Several algorithms for inverse problems are described in Ref. 8. Process tomography techniques have resolution on the order of 5% of the diameter of the vessel. Experiments are under way in an X-Ray system at En'Urga (West Lafayette, IN). to verify the results obtained from ERT or ECT,. The X-Ray system images one plane in the center of our packed bed column which is near the process tomography sensor. The X-Ray/packed bed correlation system is shown in Fig. 2.

Figure 2. X-Ray ERT Calibration Flow Loop at En'Urga.

The Volatile Removal Assembly (VRA) test section is designed to simulate an actual reactor used on ISS for water processing. The test section will have an ID of 3.5 cm and an overall bed length of 31 cm. A 60 x 60 mesh retaining screen is required to simulate the VRA design with a retainer on both the inlet and outlet. The gas will be injected into the inlet tube immediately upstream of the retainer. The VRA column will have three equally spaced pressure transducers of the same type as those used on the FHS columns. The packing will be crushed alumina, with an average diameter of 2 mm.Two downstream filters will be provided (in parallel) to trap fines generated during launch and operation. The VRA test section will have the capability of switching (with a three-way valve) the flow through either filter. It is anticipated that after a short startup period the first filter will capture most of the fines generated during launch. After this startup period, it will be necessary to switch to the second filter to conduct the full test matrix. The top end cap has one inlet for gas and liquid, and a needle injector that will be used for low gas flow only. The gas and liquid from the primary inlet will mix in the first few inches of the column and yielding an uniform flow distribution. Liquid flow rates in the VRA columns will range from 5 to 9 liters/hour with gas flow rates from 0.001 to 0.003 kg/hr.

B. Gas Control Module

The PBRE gas flow hardware will be housed in the Gas Control Module and consists of the pressure regulator, solenoid valves, pressure transducers, mass flow controllers and relief valves. The experiment requires accurate and flexible control and measurement of the gas mass flow rate from 0 to 3 kg/h. Furthermore, the flow rate must be provided in very fine incremental flow rates. Mass flow controllers that operate on the Coriolis principle rather than the thermal principle were chosen because of concerns about zero-offset with thermal mass flow controllers in microgravity. Nitrogen from the ISS will be delivered to the experiment at 120 psia, so no compressor will be required.

Because of the wide range of required gas flow rates and the tight tolerances required, a two-tier system has been designed. The larger flows will be controlled by a single controller, which is immediately downstream of the high flow/high pressure regulator. Lower flows are controlled by one or both of the low flow controllers, and can either be sent directly to the column or to one or both of the needles in the FHS columns (or the single needle in the VRA column) depending on the rate required. For operations, the solenoid valves and flow control are commanded to the desired rate. This regulated flow is then transferred to the Test Module through a flexible line equipped with quick disconnects to allow the assembly of the system on orbit.

Gas is sent to the end cap of the FHS reactor columns in the Test Section and is mixed with the fluid within the first few bead diameters then flows through the reactor column in a two-phase condition. The flow through the needles in those columns injects a steady stream of bubbles. The mixing in the VRA column occurs just outside of the column, and it also contains a single needle to support low-rate bubble flow.

The gas exits the packed bed column within the two-phase flow and is sent to a phase separator located within the Water Control Module. The gas output pressure in the phase separator is controlled by a back pressure regulation system. The gas then exits the Water Control Module and reenters the Gas Control Module to be vented to the cabin. Just prior to venting a water trap is used to ensure that all vented moisture is in the form of vapor.

C. Water Control Module

The PBRE Water Control Module manages the liquid flow rates. When not flowing, the liquid will be stored in the separator and the line leading from it to the test section during launch. Once installed, the rest of flow loop will be filled with the fluid after assembly and will reuse the liquid during operation. The fluid system hardware will be housed inside the Water Control Module and includes three pumps, solenoid valves, liquid filters, pressure transducers, and flow meters. Mass flow meters based on the Coriolis effect were also chosen for the liquid flow. Magnetic drive gear pumps are used to generate smooth and continuous liquid flow. The pump motor speed control is used to vary the liquid flow in a feed back control loop using the pump tachometer signal the flow meter reading. Water mass flow will be varied from 1 to 150 liters/hour.

The two-phase packed bed effluent flows to a vortex phase separator initially developed at Texas A&M[9]. All three pumps are connected to the fluid outlet of the phase separator. One is used to recycle liquid directly back into the phase separator to keep the appropriate vortex momentum. The other two pumps circulate the liquid through the packed bed for the entire range of flow rates. These pumps are controlled with input from a mass flow meter located in the fluid system just downstream from the pump outlets.

Controlling the voltage to the pumps controls their speeds and therefore the flow rate of the water that they deliver to the packed beds. The flow meters provide feedback that will be used to fine tune the settings determined by ground based testing. The amount of fluid in the phase separator is determined by the amount of the fluid transferred to the rest of the system. A video camera will monitor the amount of liquid in the separator to assure sufficient liquid remains to maintain the vortex during all phases of the operations.

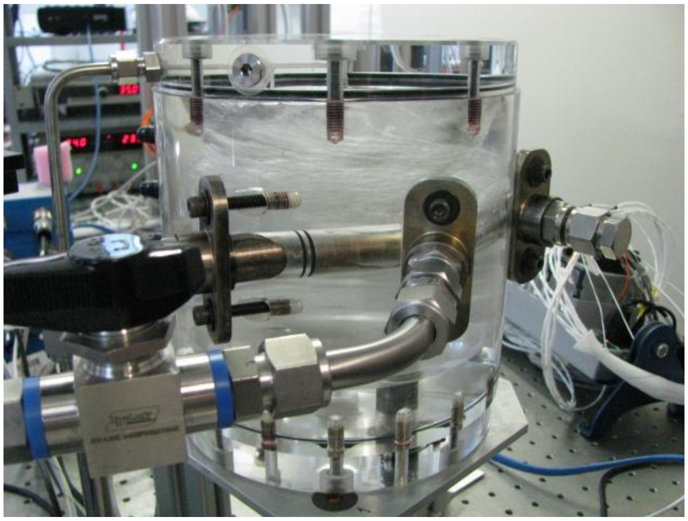

Figure 3. **Phase separator installed into the PBRE breadboard.**

The vortex phase separator shown in Fig. 3 will recycle the water and vent the gas. Water vapor and the nitrogen gas will vent to the cabin during each test. It is estimated that the system will lose 0.02 kg of water for each kg of nitrogen gas used. Executing the current test matrix will release approximately 2.6 kg of nitrogen gas so the total water loss in the system will be approximately 0.052 kg or 52 ml.

The water holdup in the columns will also deplete the water resource. Once a particular column has completed its testing, it will be purged with pressurized nitrogen, but an unknown amount of liquid will remain in the test section. Ground tests will be conducted prior to the flight to provide estimates of water not recovered.

The vortex phase separator has a number of design challenges. Briefly, the separator consists of a cylinder with a pump-driven vortex that swirls liquid next to its wall. The vortex operates over a range of thicknesses by design, which is a fraction of the cylinder radius. The two-phase mix is injected into the vortex, which provides the acceleration to drive gas into the center core. A baffle disk, with diameter smaller than the cylinder, is located near one of the cylinder ends and allows pure liquid to collect between the disk and the cylinder end. The gas is vented from the core, the gas-free liquid is taken from the baffle/cylinder end volume.

D. Other Design Considerations

In addition to the modules discussed above, there will also be a Data Acquisition and Control Unit (DACU) which will use a two-CPU approach. The main CPU will be used to handle all of the data acquisition and functions associated with the sequential control of the other modules:

- Experiment Sequencing and Operations
- Gas Flow Control
- Liquid Flow Control
- Gas / Liquid Separation
- Status and Safety Monitoring
- Data Acquisition & Storage
- Carrier Interfacing

The second CPU will support digital imagery analysis through a Vision System implementation, which combines a Dual Giga Bit Ethernet Camera interface and illumination.

The filtering, power conversion, power conditioning and electrical isolation and safety are performed in the Avionics Module (AM) and then the DC Voltages are distributed to the Data Acquisition and Control Unit (DACU); Test Sections; and Gas and Water Control Modules. The power distribution system is responsible for delivering power to the electronic devices in the PBRE. This filtered input is converted to DC Voltage levels of +5 V, +12 V and +24 V. The system is designed to distribute the load and condition the power to satisfy the instrumentation needs. The power distribution system also provides single point ground isolation and a circuit breaker.

IV. Summary

The PBRE has successfully passed through a Preliminary Design Review at NASA and is expected to be ready for flight in 2014. This will be the first test of this kind on the ISS and is expected to provide important information for design and operation of fixed bed reactors. As new designs for human exploration evolve, the PBRE will also provide a simple test platform to verify the performance of microgravity sensitive components.

REFERENCES

[1] Dullien, F.A.L., *Porous Media: Fluid Transport and Pore Structure*, 2nd edition, Academic Press, Inc., San Diego, 1992.

[2] Wang, C.Y. and Cheng, P., "Multiphase Flow and Heat Transfer in Porous Media", *Adv. Heat Transfer*, Vol. 30, 1997, pp. 93-196.

[3] D.A. Nield and A. Bejan, *Convection in Porous Media*, Springer, New York, 1992.

[4] Motil, B.J., Balakotaiah, V., and Kamotani, Y., "Gas-Liquid Two-Phase Flows Through Packed Beds in Microgravity", *AIChE J.*, Vol. 49, No. 3, 2003, pp. 557-565.

[5] Guo, B., Holder, D.W., and Carter, L., "Distribution of Flowing Fluids in a Confined Porous Medium Under Microgravity Conditions", Phys. Fluids, Vol, 16, No. 8, 2004, pp. 3045-3050.

[6] Lucas, G.P., Cory, J., Waterfall, R.C., Loh, W.W., and Dickin, F.J., "Measurement of the solids volume fraction and velocity distributions in solids–liquid flows using dual-plane electrical resistance tomography", *Flow Meas. Instrum.*, Vol. 10, No. 4, Dec. 1999, pp. 249-258.

[7] Jaworek, A., and Krupa, A., "Phase-shift detection for capacitance sensor measuring void fraction in two-phase flow", *Sensors and Actuators A: Physical*, Vol. 160, No. 1-2, May 2010, pp. 78-86.

[8] Soleimani, M., "Computational Aspects of Low Frequency Electrical and Electromagnetic Tomography: a Review Study", Int. J. Numer. Anal. Mod., Vol. 5, No. 3, pp. 407–440.

[9] Ellis, M., Kurwitz, C. and Best, F., "Development of a Unique, Passive, Microgravity Vortex Separator", *Proceedings of the ASME 2005 International Mechanical Engineering Congress and Exposition (IMECE2005*, ASME, 2005, pp. 763-770.