Development of the Two Phase Flow Separator Experiment for a Reduced Gravity Aircraft Flight

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The recent hardware development and testing of a reduced gravity aircraft flight experiment has provided valuable insights for the future design of the Two Phase Flow Separator Experiment (TPFSE). The TPFSE is scheduled to fly within the Fluids Integration Rack (FIR) aboard the International Space Station (ISS) in 2020. The TPFSE studies the operational limits of gas and liquid separation of passive cyclonic separators. A passive cyclonic separator utilizes only the inertia of the incoming flow to accomplish the liquid-gas separation. Efficient phase separation is critical for environmental control and life support systems, such as recovery of clean water from bioreactors, for long duration human spaceflight missions. The final low gravity aircraft flight took place in December 2015 aboard NASA's C9 airplane.

I. Introduction

THE Two Phase Flow Separator Experiment (TPFSE) is an International Space Station (ISS) investigation of the behavior of the separation of gas and liquid from a gas/liquid stream in microgravity using the cyclonic separation concept. When the cyclonic approach was first considered by NASA in the 1960's, there were very limited reduced gravity platforms and limited laboratory diagnostic tools (1). New developments in Computational Fluid Dynamics (CFD) codes, as well as new developments in experimental diagnostic instruments such electrical capacitance tomography, have generated a renewed interest in investigating how this technology might behave in a microgravity environment (2). Before final ISS experiment hardware development begins for most ISS fluids/thermal experiments, parabolic aircraft flights are performed in order to test the hardware operation in reduced gravity. As the aircraft flies a parabolic trajectory, the aircraft can offer about 20 seconds of reduced gravity, on the order of 0.01 g. The pilot's skill at guiding the aircraft along a parabolic trajectory affects the fluctuation, which is often bounded by minus 0.05 g to plus 0.1 g. The atmospheric conditions during the flight also play a role in determining the fluctuation. After flying in a subsequent high g pullout, the aircraft then repeats the cycle of a low gravity parabolic arc followed by a high g pullout. Typically, around 40 parabolas can be accomplished within a day. Even though only about 20 seconds of low gravity is available, some portion of a modified ISS test matrix can be completed and qualitatively observed.

Developed over the last three years at the NASA Glenn Research Center, the TPFSE breadboard test rig allows the change-out of various types of separator test sections. For the initial test sections, two types of separator are being built; one by DYNAFLOW, Inc. of Jessup, Maryland, and the other one by Case Western Reserve University in Cleveland, Ohio. It is hoped that the future operation of the TPFSE aboard the ISS will accommodate additional test sections from new principal investigators selected from future solicitations.

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Potential beneficiaries of the TPFSE include the design of future large spacecraft Rankine and fuel cell power systems, spacecraft life support, and spacecraft water recovery systems. Also, CFD techniques to model air/liquid separation of flows with widely varying void fraction, such as cyclonic separators, can be benchmarked with this data.

The proposed space based Rankine cycle schematic, shown in Figure 1, identifies the location and function of a microgravity vortex separator (MVS). For the MVS located downstream of the boiler, the function is to assure that only vapor reaches the turbine. For the condensing separator located downstream of the radiator condenser, the function is to assure complete condensation with no vapor, such that the liquid pump only receives liquid and not vapor (3).

A different space-based power application is for the separation of gas and water from a PEM fuel cell (4). This concept uses an ejector to remove unused gas and liquid generated in the reaction.

In the area of life support, gas/liquid separators are very important. For example, the Sabatier carbon dioxide reduction system aboard the ISS currently uses a non-passive, spinning rotary drum concept to separate desired water from the waste methane gas. It has operated successfully aboard the International Space Station (ISS) for several years. Figure 2 shows the picture of the engineering development hardware used in the Sabatier concept. Although there are no plans to replace this rotary drum separator with a passive separator, this example illustrates the utility for a microgravity capable gas/liquid separators for life support systems (5). A passive version of this separator would, in principle, be acoustically quieter, and therefore more desirable for long term human exploration missions. The TPFSE version of a vortex separator is passive in that it requires no dedicated motor or rotating drum.

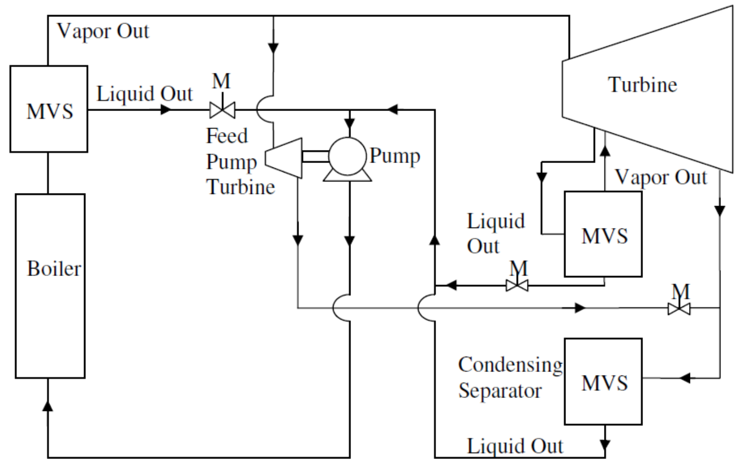

Figure 1. MVS locations in a proposed space based Rankine power generation cycle.

Figure 2. Rotary pump phase separator for the Sabatier carbon dioxide reduction system. (9)

Another life support application for a gas-liquid separator is the proposed Heat Melt Compactor (HMC) (6) (7). This device will use astronaut trash produced from long-term human exploration missions to extract valuable water. The water will be directed to a water recycling system aboard the spacecraft. To affect water recovery from trash, the HMC is heated to a temperature that causes the residual water in the trash to evaporate. This water vapor is then sent to a downstream condenser. Along with the water vapor will follow non-condensable gases and possible some errant liquid droplets. The liquid water would contain undesirable organic compounds that may foul a condenser. Therefore, it is necessary to separate the water from the gas and water vapor before entering the condenser. A gas-liquid separator, either passive or active, is appropriate for this task. Thus, the TPFSE has potentially wide ranging application to many microgravity space processes.

II. Background and Basic Physics

The TPFSE is an ISS microgravity flight experiment to study the operational limits of gas and liquid separation using a cyclonic separator. The allowable void fraction of gas within the flow may be limited depending on flow rate and separator design characteristics. The number of small air bubbles remaining in the liquid outlet will define the effectiveness of the separator design. As such, the diagnostics to characterize the spectrum of bubble diameters is important. Large bubbles approaching the free liquid surface may have such a large velocity that they burst through the liquid surface and cause secondary droplets to form. These liquid droplets would normally fall back into the liquid under the influence of gravity. In microgravity, theses droplets may entrain and become part of the gas outlet stream.

The basic element of a cyclonic phase separator is a cylindrical chamber with one outlet in each end-plate for liquid and gas, respectively. As shown in Figure 3 the gas-liquid mixture enters the separation chamber tangentially and sets up a swirl layer against the cylinder wall. A gas core develops in the center. The gas core diameter and swirl layer thickness depends on the gas and liquid flow rates and the pressures at each phase outlet. Surface tension is usually neglected in analyses, owing to the high flow rates that give rise to large centrifugal forces. However in the very low flow rates likely to arise in space applications, designs must ensure that surface tension is still small, in order to maintain operation with a mostly straight gas core. Figure 4 shows an actual picture of the separator flow. A gas core is formed in the center of the cylindrical separator as gas is moved to the center of the cylinder by centrifugal force.

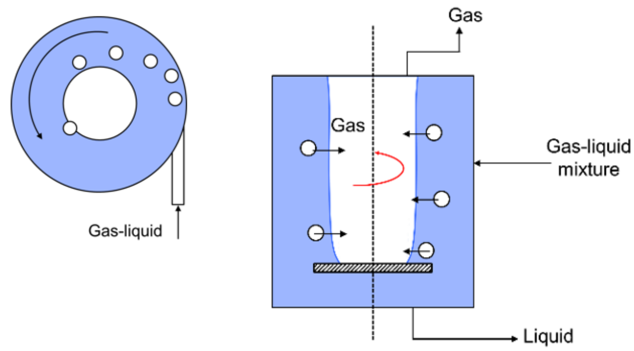

Figure 3. Diagram of vortex flow within a separator.

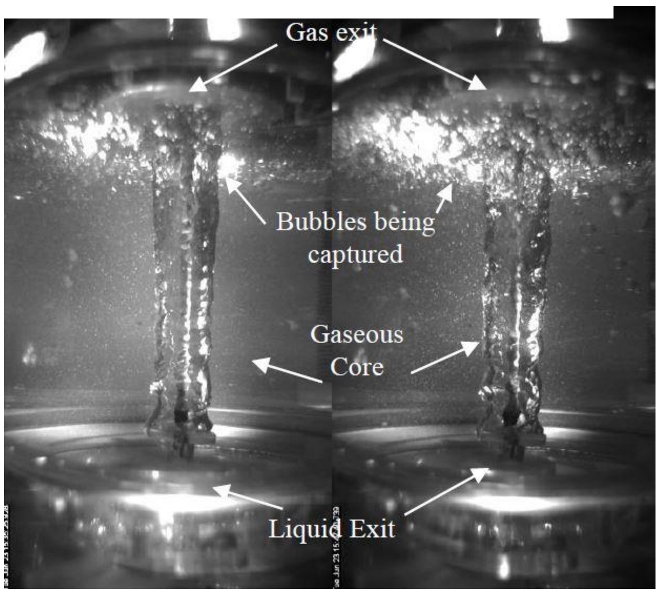

Figure 4. The gas core within the cyclonic liquid flow (8).

III. Hardware Description

A. Mechanical Design

The flow schematic for the reduced gravity flight system is shown in Figure 5. It consists of a recirculating liquid loop, and a non-recirculating gas injection system which takes breathable air from a K-bottle. The air is afterwards vented from the system to the aircraft cabin. The flow configuration can be easily reconfigured for either the CWRU separator, or the DYNAFLOW separator, which have different gas outlet requirements.

A mechanical pump drives a liquid stream which is later injected with air generated by a carefully calibrated air mass flow controller. This co-flowing stream of gas bubbles in liquid water travels through a development tube before being injected into the cyclonic separator. The development tube length is determined by an estimate of how much time and distance is needed for fully developed gas/liquid flow. The definition of fully developed flow for relatively large bubbles is not precise. The polycarbonate development tube diameter is 2.54 cm O. D. and 0.32 cm wall thickness. Polycarbonate was chosen for the development tube to allow for viewing of the two-phase mixture. The interface to the test section is a ¾ NPT quick connect (McMaster Carr 52495K47). In this way, different test sections can be changed out easily. As shown in Figure 6, a centered coaxial air injection tube is located at the entrance end of the 0.64 m long development tube. This 0.635 cm X 0.165cm air injection tube is capped by a bronze porous metal muffler (McMaster Carr 8226T11). This type of mini-muffler was originally designed as a sound muffler/filter to trap particles above 40 microns. For this application, this muffler effectively generates a uniform field of small bubbles. As shown in Figure 7, these small gas bubbles are entrained by a co-flowing water stream and quickly coalesce into larger gas bubbles. After some time, and at some point in the development tube, the flow would be fully developed. This point in the tube and therefore the necessary length of the tube is not easily determined. It is difficult to predict how this coalescence process will work in microgravity and hence, it is difficult to design the test rig for operation in low gravity without at least some low gravity experience. The goal of the low gravity flights is to learn about global behavior of the rig and its subsystems in low gravity, such that good design decisions for the eventual ISS hardware can be made. While the test sections are of primary interest, other subsystems are also important for reliability. The water pump is of special consideration, since it must operate in low gravity. It is possible that at some time during low gravity operation, the pump could be void of liquid, because in low gravity it is not always possible to keep the pump primed with liquid. This operational constraint called for a positive displacement pump. The Oberdorfer model S2101CCB was chosen. Estimates of flow resistance of the anticipated flow paths allowed for a pump selection with the proper pressure-flow rate curve.

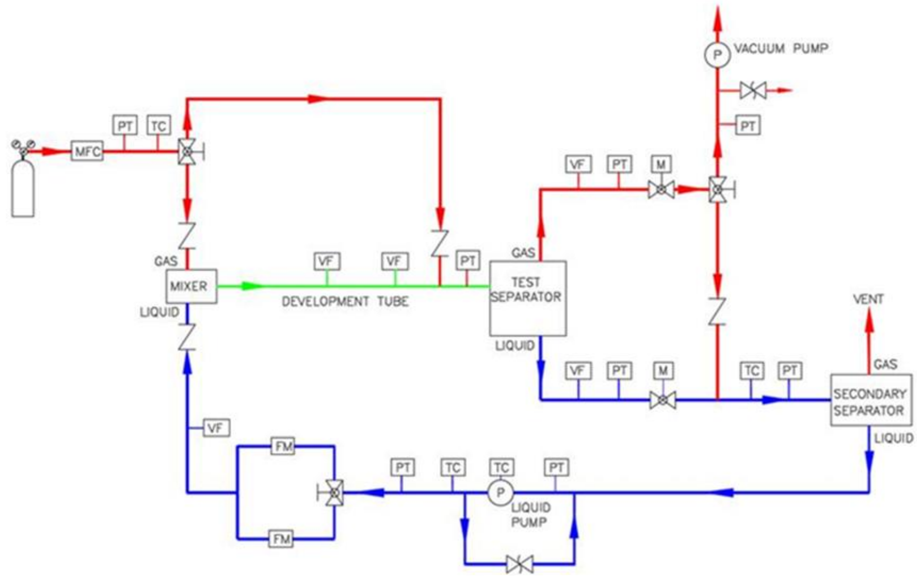

Figure 5. Flow schematic for the two phase flow separator experiment reduced gravity hardware.

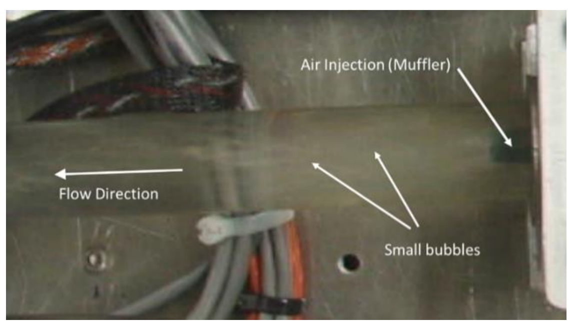

Figure 6. Air injection from muffler forms small bubbles (seen on the right of the picture).

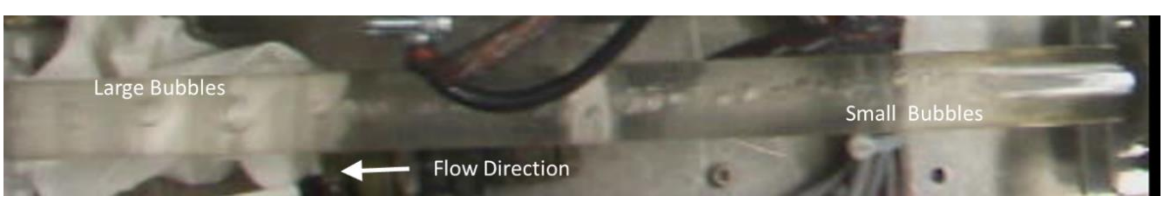

Figure 7. Small bubbles coalesce into the desired larger bubbles (Flow direction is from right to left).

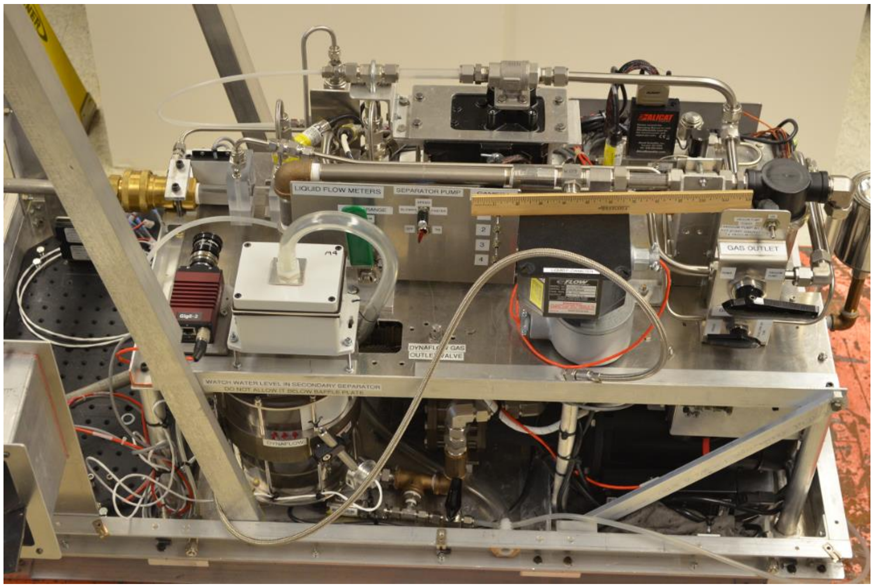

Figure 8. TPFSE reduced gravity flight hardware.

A photograph of the as-built hardware is shown in Figure 8. A 3D CAD model of the reduced gravity hardware is shown in Figure 9.

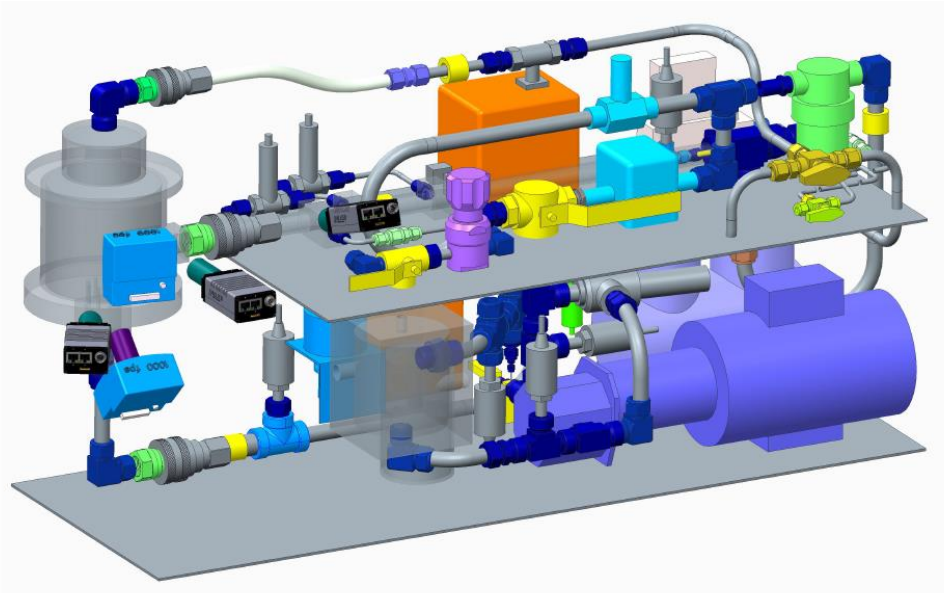

Figure 9. 3D CAD model of the Two Phase Flow Separator Experiment reduced gravity hardware.

The liquid flow in the loop is initiated by a gear pump driven by a DC motor. A variable power supply allows the pump to be driven at variable speeds, providing a liquid flow range from 0.25 to 20.0 lpm. The flow is monitored on one of two flow meters, selected with a 3-way valve. One flow meter is used for flow rates below 1.9 lpm and the other for flow rates above 1.9 lpm, due to the limited valid range of each flow meter. From the mixer, the two-phase flow travels through a straight, 0.64 m long tube where the flow is allowed to develop. The gas is injected into the system from a pressurized cylinder. The flow is controlled with a mass flow controller, providing a flow of 0.25 to 50 slpm. It is then directed to either the mixer, or a location at the end of the development tube.

After the two-phase mixture is separated, the liquid leaves by the separator's liquid exit and the gas leaves by the gas exit. Both exits have a void fraction sensor, and a motorized valve that can be adjusted to balance the gas and liquid pressures in the separator. Balancing the exit pressures is necessary for stable operation of both tests sections.

The gas exit line downstream of the motorized valve is configured differently for the CWRU and DYNAFLOW separators. This is done by switching a 3-way valve. For the CWRU separator, the gas flow is sent back into the liquid flow, where it is then sent to a secondary separator. This ensures that any liquid that errantly exits the gas outlet of the test separator, gas that exits the liquid outlet of the test separator can be accommodated (i.e., liquid exiting the gas vent or gas entering the liquid returning to the pump). From the secondary separator, the liquid returns to the pump and the gas is vented.

The liquid pump is a gear pump, chosen because it allows for very accurate control of the flow rate, while also providing a nearly-constant flow rate that is independent of pressure. The pressure from the pump is limited to 500 kPa by a relief valve which opens at this pressure and vents the flow back into the liquid system. The liquid flow meters are turbine meters, chosen because of their compatibility with liquids and their quick response time (3-4 ms).

The vacuum pump is a diaphragm pump, chosen for its compatibility in low-gravity. It does not provide a high vacuum, but a vacuum level of only approximately 50 Torr is required.

B. Optical Diagnostics

Several types of cameras were used to provide video data. Special lighting and camera diagnostic equipment are needed to image the gas core size as well as bubble injection dynamics. For the low gravity flight, a standard frame rate camera streamed video data to the electronics rack for later data reduction.

In total, four cameras were used to visualize the flow loop and test sections. Two standard rate 30 frames per second (fps) GigE-Vision cameras from Allied Vision were used to visualize the development pipe and the overall flow separator test section (Figure 10). Two additional high-speed cameras from Mikrotron, utilizing the CoaXpress (CXP) streaming interface, were installed to visualize specific regions of the test section cores using higher magnification optics.

For the GigE-Vision cameras, the development pipe camera captured at a sensor resolution of 1024 x 1024 at 30 fps, while the overall view camera captured at a sensor resolution of 1920 x 1080 at 30 fps. Depending on the test section installed, the CXP cameras were set to capture at sensor resolutions of 960 x 960 at 1000 frames per second, or 512 x 1024 at 500 frames per second. All standard rate and high-speed cameras were controlled by custom-built PC-based data acquisition recording system, which simultaneously recorded all streaming data from the two Allied Vision GigE-Vision cameras and the two Mikrotron CXP cameras. The rack-mount PC system was designed to maximize throughput using all solid state disc's (SSD's), a dedicated RAID (Redundant Array of Independent Discs) controller for each CXP channel, and 4 terabytes (TB) of storage per CXP camera. The system was designed with enough storage capacity to control and store all camera data streams, synchronized to IRIG-B (Inter Range Instrumentation Group) time code, for two days of zero-gravity aircraft operations.

Figure 10. The Gig-E camera field of view allows for capture of a small portion of the development tube at the point just before the entrance to the vortex test section.

Illumination for the development pipe camera was provided using a COTS LED back-light panel connected via a strobe controller synchronized to the 30 fps Allied Vision camera. For the test sections, custom LED backlights and compact LED spot units with beam-shaping optics were designed and fabricated at GRC. To minimize dispersion through the polycarbonate test sections, single wavelength LED emitters were selected during the development process. The completed LED assemblies were placed behind and around both test sections to provide illumination for the overall 30 fps view and the high-speed cameras during all test operations.

C. Analog Data Acquisition

Temperature, pressure and flow rate histories were recorded using LabVIEW® software. All the electronic equipment (NI control box, NI connector boxes, Agilent 100 VDC power supply, MicroDisk video storage, control PC, E-Stop, and associated relays) were mounted in the "electronics rack". The electronics rack was located next to the flow rig on the airplane floor. The LabVIEW® software controlled the liquid flow, the air flow, and the different cameras used on the rig. The DAQ also synchronized together the three data rates (1000 hz, 100 hz, and 10 hz) requested for the different sensors. Select data was displayed for the operators while all data was stored for each test point. Figure 11 shows a CAD model of the electronics rack.

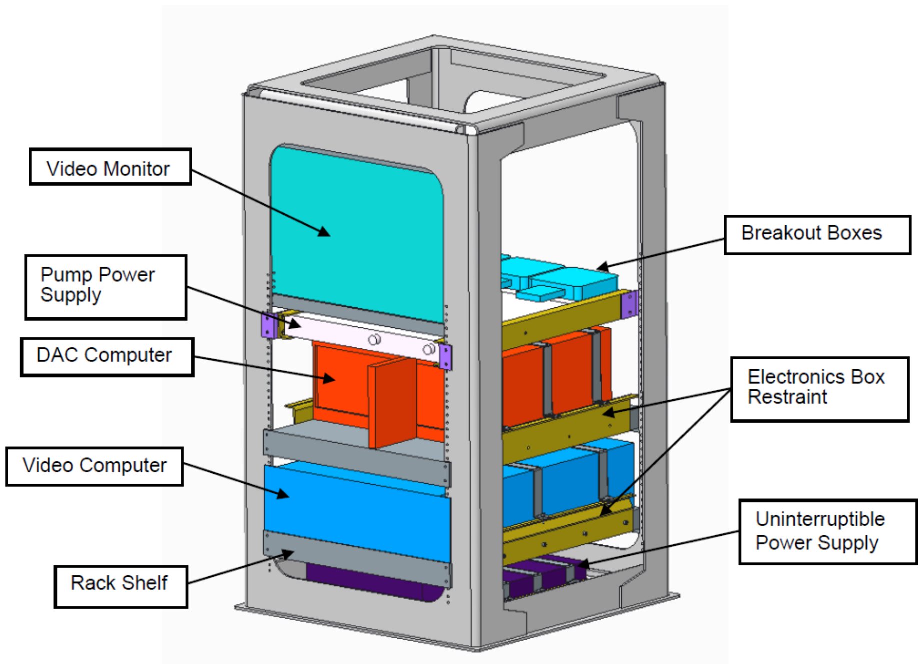

Figure 11. Model of the electronics rack.

IV. Reduced Gravity Flight Results

The results of the December flight campaign using the DYNAFLOW test section provide guidance for achieving a good design for the eventual ISS TPFSE hardware. The flight campaign consisted of two days, with each day providing one flight. There were approximately 40 parabolas for each flight. Each parabola offered about 20 seconds of reduced gravity. The results of the each flight on Tuesday and Wednesday showed good performance of the rig. The test matrix included a flow rate that ranged from 1.5 to 4.5 gallons per minute and a gas flow rate that ranged from 0.5 to 6 liters per minute. Some interesting observations can be documented here. For the Tuesday flight, the GigE-Vision camera was unavailable for the first 10 parabolas, because the plane power breaker that supplied electrical power to the camera was in the off position. A system check at parabola 10 discovered the error. As the flight progressed, the temperature of the water increased to 41° Celsius, due to the high heat load of the vacuum pump and other equipment. For the ISS experiment, detailed thermal analysis and testing will be performed for all hardware items. The gas flow meter display stopped working from parabolas 23 to 44 for an unknown reason. However, the flow meter was still sending data to the data acquisition equipment. For the ISS experiment, all hardware will be vibration and thermal cycle tested to rigorous standards to flesh out any possible loose connections or other possible causes of the intermittent behavior. For the Wednesday flight, during parabola 28, water was noticed leaving the vacuum pump. During all ground testing, this did not occur, because gravity retained the water in a water trap. For the ISS hardware development, a different type of vacuum pump will be selected, with consideration of the pump's susceptibility to eject water in a microgravity environment.

V. Conclusion

The low gravity flight results showed the hardware concept is a viable approach and valid for further development of the ISS experimental hardware. Some interesting observations during the flights showed areas of possible improvement that may be incorporated in the eventual ISS design and testing plans. Without these low gravity flights, the design of the hardware for the ISS would be risky, since unknown microgravity effects would not be discovered until the actual ISS flight.

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