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SUMMARY

Low-gravity, gas-liquid flow research can be conducted aboard the NASA Lewis Learjet, the Lewis DC–9, or the Johnson Space Center KC–135. Air and water solutions serve as the test liquids in cylindrical test sections with an inner diameter of 1.27 cm and lengths up to 1.5 m. Superficial velocities range from 0.1 to 1.1 m/sec for liquids and from 0.1 to 25 m/sec for air.

Flow rate, differential pressure, void fraction, film thickness, wall-shear stress, and acceleration data are measured and recorded throughout the 20 sec duration of the experiment. Flow is visualized by photographing at 400 frames with a high-speed, 16-mm camera.

INTRODUCTION

NASA Lewis Research Center has been conducting low-gravity, gas-liquid flow research since 1986 using an apparatus designed to fly in the NASA Lewis Learjet 25. The Learjet Two-Phase Flow Apparatus, shown in figure 1, mixes air with a water solution in metered quantities and is used to make measurements of basic, two-phase flow phenomena. The capabilities and operation of the apparatus are detailed in this report so others may utilize it.

Flying the Learjet through a Keplerian trajectory allows researchers to conduct experiments in a low-gravity environment (ref. 1). Experiments can be conducted in a near weightless environment (on the order of 10^{-2} g) or at partial gravity levels ranging from 1/20 to 3/4 g. Low-gravity periods are approximately 18 to 20 sec long; a maximum of 6 trajectories can be completed in a single flight. Similar low-gravity conditions can be achieved using either the Johnson Space Center (JSC) KC–135 or Lewis DC–9 aircraft.

The apparatus provides two-component, two-phase flow. The first component and phase is air. The other component and phase is a water solution, usually distilled water mixed with a minute amount of salt. A 50 wt% glycerin and water solution has been used to study the effects of increased liquid viscosity on flow phenomena. A 0.5 wt% solution of Zonyl FSP, a fluorosurfactant made by DuPont, in water has been used to study the effects of decreased surface tension.

The data acquisition system records measurements from various sensors to obtain the gas and liquid flow rates. Acceleration levels are measured from a triaxial acceleration head and recorded. Various two-phase flow characteristics, such as differential pressure, void fraction, liquid film thickness, and wall-shear stress are recorded at acquisition rates up to 1000 Hz. A more detailed discussion is given later in this report.

High-speed photography, at 400 frames/sec, is used to visualize the flow pattern. Time is noted on each frame.

APPARATUS LAYOUT

The Two-Phase Flow Apparatus is composed of three distinct structures, as shown in figure 2. Two of these components are standard racks designed for use aboard the Lewis Learjet and the third is a custom-designed rack. All three racks have plumbing and electrical connections for power and control. There is an additional electrical connection between the two standard racks for data acquisition.

The first standard Learjet rack, or flow metering rack, contains primarily the gas and liquid flow loops, the two-phase mixer and entry length, and the thermocouple amplifier electronics. Mounted to this rack are flow rate setting devices, such as metering valves and pressure regulators, flow rate measurement devices, such as pressure transducers and turbine flow meters, and a gas supply cylinder. The mixer housing is made of plexiglas with stainless steel inserts. An entry length of stainless steel tubing allows the flow regime to develop. There is space available on the top shelf of this rack for additional signal conditioning equipment.

The second standard Learjet rack, or data acquisition rack, contains the two-phase flow test section, the flow visualization system, the accelerometers, and the data acquisition and control systems. An operator interface panel has a liquid-crystal display (LCD), toggle switches, and two thumbwheels to select program options. The master power box and fusing are mounted to this rack as well as a research power distribution strip used to interface to the aircraft's power systems. There is space available on the middle and bottom shelves for additional signal conditioning equipment.

The custom-designed Learjet rack, or tank rack, is essentially a flat plate. The liquid supply tank, two-phase collector/separator tank, back pressure regulator, and recirculation pump are mounted to this plate. The tank rack is mounted between the other two racks in the aircraft. All three racks occupy a footprint of approximately 0.61 by 1.83 m (2 by 6 ft).

FLOW SYSTEM DESIGN

The flow system is illustrated schematically in figure 3. The system has four parts: the gas system, the liquid system, the two-phase portion, and the liquid recirculation system. An itemized listing of the individual components is given in the Appendix.

Gas is supplied as compressed air, either from a 13.2 L gas cylinder mounted on the flow metering rack or from a standard K-size bottle. The size of the Learjet cabin precludes the use of a K-size bottle; however, pressurizing the 13.2 L gas cylinder to 10 340 kPa (1500 psi) provides sufficient gas for the limited number of tests conducted in one flight. When using a K-size bottle, the delivery pressure must be decreased with a regulator.

From the gas supply tank, there are two, parallel gas metering flow legs. Each leg has its own pressure regulator, pressure gauge, solenoid valve, and square-edged orifice. After the orifice, the legs come together in a tee. Pressure and temperature are measured upstream of each orifice as well as in the common line after the orifice. If the absolute pressure upstream is at least two times greater than the pressure downstream, the gas flow through that particular orifice is choked. The mass flow rate can be determined from the following relationship (ref. 2):

$$\dot{m} = Ca\phi_i^* \left(\frac{\phi^*}{\phi_i^*} \right) \left(\frac{P_{1t}}{\sqrt{T_{1t}}} \right)$$

where $\dot{m}$ is the mass flow rate, C is the orifice discharge coefficient, a is the throat area of orifice, ϕ_i^* is the sonic flow function of an ideal gas, ϕ^*/ϕ_i^* is the ratio of the real to ideal gas sonic flow functions, P_{1t} is the inlet stagnation pressure, and T_{1t} is the inlet stagnation temperature.

Each orifice has a different diameter: 0.691 and 0.183 mm. For the same pressure range, a turndown ratio of about 250 to 1 is obtained. The superficial velocity, at atmospheric pressure for flow through the small orifice can range from 0.1 to 2.0 m/sec and through the large orifice, from 2.0 to 25.0 m/sec. Gas flow through the common leg passes through a check valve to minimize the backflow of the liquid phase into the gas supply system. Because the small orifice may be easily blocked, the flow rate is verified using a wet test meter before each flight. From the check valve, the flow enters the two-phase mixer.

The liquid supply tank holds four liters of liquid. Gas pressure is supplied from the gas supply cylinder through a regulator on top of the tank. Gas is introduced on top of a piston that travels down a shaft in the center of the tank. The gas pushes the piston downward to force out the liquid, while maintaining phase separation. Liquid exits from the bottom of the liquid tank, flows through a screen mesh that filters any large particulates or biological growth, and splits into two paths: test flow and purge flow.

The test flow path has a pair of metering valves connected in parallel. These valves are adjusted with micrometer handles so that flow settings can be easily reproduced. First the flow is metered with a turbine flow meter, then it flows through an electrically-actuated solenoid valve, past a check valve, and through a conductivity reference cell. This cell, which is made of plexiglas, contains two parallel thin wires and measures the baseline liquid conductivity. The baseline is used to correct for temperature and salt concentration differences in the liquid conductivity data. After the conductivity reference cell, the liquid flow enters the two-phase mixer.

The purge flow path is used to flush any gas bubbles trapped in the differential pressure measurement system. This flow goes through a valve that essentially sets and meters the flow rate, and then splits into two parallel lines before entering the test section. Each parallel line contains a metering valve used to minimize the pressure drop during purging and a solenoid valve used to turn on and off the flow. The flow passes through a chamber containing the pressure transducer diaphragm and then enters the test section.

Both the gas and liquid phases are introduced to the plexiglas mixer. The gas flow is injected axially down the center of the tube. The liquid phase is injected perpendicular to the test section axis and gas flow direction. If desired, the inlet lines for the gas and liquid phases can be reversed. Two schemes have been used to mix the liquid with the gas as depicted in figure 4. In the first arrangement (fig. 4(a)), the liquid is injected directly into the mixer through several small holes (diam=3.18 mm) around the circumference of the mixer. This approach promotes turbulence and mixing. In the second arrangement (fig. 4(b)), the liquid is injected into an annular region and flows in the same direction as the gas before the two flows come into contact. This approach establishes the annular liquid film more quickly in the slug and annular flow regimes and reduces the amount of liquid droplet entrainment in the annular flow.

Flow is allowed to develop along an entry length, which is a stainless steel tube with a length of 66 cm with an inner diameter of 12.83 mm. The entry length is connected to the plexiglas test section with a flange. A transducer, connected to the entry length, measures the absolute pressure within the test section so that the mass flow rate can be converted to a superficial gas velocity.

Various configurations of straight conduit test sections have been utilized, each with a different combination and placement of sensors, for measuring the flow phenomena. Sensors include differential pressure transducers, conductivity probes, and hot film anemometers.

Previously, Validyne model P40D transducers were used to measure differential pressure. These transducers had some advantages, including replaceable diaphragms sensitive to a variety of ranges, relatively small size, and the capability to flush liquid through the diaphragm chamber, which provides an additional method for removing gas bubbles from the pressure sensing lines. However, this transducer was abandoned because of difficulties with vibrations in the pressure sensing lines and a wandering zero offset.

Currently, two Druck PCDR 820 transducers with a full-scale range of 6.9 kPa (1.0 psid) are utilized. These transducers have a flush fitting and are mounted in a special receptacle affixed to the test section tube, as illustrated in figure 5. A small diameter connection between the receptacle and the test section permits pressure measurement. The Druck transducers measure differential pressures; however, the reference port of the transducer must be exposed to a dry, noncorrosive gas. To meet this requirement, the reference from both transducers are connected together and exposed to the pressure within the collector/separator tank. To prevent liquid contamination, a chamber containing a calcium carbonate dessicant is located between the ports and the collector tank. The Druck pressure transducers can tolerate pressures higher than their rating; their output signal is linear up to 68.9 kPa (10 psid). Consequently, signal conditioning electronics were developed to utilize the full range of input voltages in the data acquisition system and to permit measurement of several pressure ranges: from 0 to 1.4, 4.1, 13.8, and 41.4 kPa (0.2, 0.6, 2.0, and 6.0 psid).

Void fraction and liquid film thickness measurements are made with thin-wire conductivity probes (ref. 3). Two parallel wires are stretched across the cross section of the test section. These measurements are a function of the area between the wires when immersed in liquid. These wires are 0.0762 mm (0.003 in.) in diameter and are 87 wt% platinum and 13 wt% rhodium. To enhance the conductivity of the liquid, a small amount of sodium chloride is dissolved in the liquid solution. Typically, the amount required is approximately one gram per liter of solution. The liquid film thickness probes are coated with a nonconductive enamel along one-half of their length. Calibration of the void fraction and liquid film thickness probes are discussed in reference 3.

Wall-shear stress measurements are made with a hot-film anemometer. This probe is made on a polyimide film and has a nickel hot-film sensor. The probe has a built-in compensator to correct for the temperature of the liquid film. These probes are calibrated under annular flow conditions where waves in the liquid film are suppressed.

The flow visualization section incorporates a rectangular box around the cylindrical test section. The box is backlit and filled with water to avoid refraction. High-speed, 16-mm cameras, with a shutter speed of 1/4000 of a second, record the flow pattern at 400 frames per second.

After exiting the test section, the flow enters the two-phase collector/separator tank. This tank is a large, aluminum tank designed to retain the liquid and vent the air, through a back pressure regulator, into the aircraft cabin. The two-phase flow enters at the top of the cylindrical tank and collides with a circular plate, which has large holes to permit the liquid to drain through to the lower chamber. Around the plate and between the plate and the top of the tank is a woven mesh. The mesh retains the liquid with surface tension; air passes through it and is released by the back pressure regulator, which is connected to the top periphery of the tank.

Between trajectories, when gravity is restored to normal levels, liquid may be pumped from the collector/separator tank back to the liquid supply tank through a recirculation line. A solenoid valve is opened between the two tanks and another solenoid valve vents the pressurized air from the top of the liquid supply tank. A small centrifugal pump recirculates the liquid. Air that has been vented into the cabin is not recovered.

All nonstandard fluid devices, i.e., the liquid tank, the collector/separator tank, and the test section must be hydrostatically tested at 1.5 times the maximum working pressure differential to satisfy safety standards. The lower pressure on this differential is about 27.6 kPa to account for the possibility of the aircraft losing cabin pressurization.

ELECTRICAL POWER AND CONTROL SYSTEMS

Two types of power are supplied by the aircraft: 28 Vdc, 110 V, 60 Hz and 110 V, 400 Hz. Aircraft power is fed to a power distribution strip attached to the back of the data acquisition rack. Power connections between the experiment and the power distribution strip are made in accordance with aircraft standards (ref. 4).

The 28 Vdc power is split into two sources at the power distribution strip to provide electrical isolation and minimize noise interference. The first source powers instrumentation and signal conditioning, such as the absolute pressure transducers, the turbine flow meter, and the signal conditioning equipment for the thermocouples and differential pressure transducers. The second source powers the purge solenoid valves, the backlighting, and the high-speed camera.

The 110 V, 60 Hz source powers the gas and liquid flow solenoid valves, the data acquisition and control system, the recirculation pump, and the signal conditioning equipment for the conductivity probe and hot-film anemometers. When the experiment is mounted aboard either the KC–135 or DC–9 aircraft, additional power and space is available and an enhanced high-speed video system may be used.

The data acquisition and control system is a card cage standard (STD) bus computer system. The central processing unit is a 386 chip rated at 20 MHz. There are 4 MB of random access memory and storage capacity on a 50 MB hard drive and a 1.44 MB floppy drive. The hard drive is partitioned into two logical drives: one for programs and one for data. The BIOS may be reconfigured to accept a larger hard drive, if necessary.

Three cards are used for data acquisition. Each has 12-bit resolution and accepts either 16 channels of differential input signal or 32 channels of single-ended input. They can be configured to accept input voltage ranges of either ±10, or 0 to 10 Vdc. At least 25 μsec are required to digitize an input signal.

A digital input/output board controls and monitors the operator panel and the timing and sequencing of the valves, backlighting, camera, and other devices. The digital input/output board can output a 0 or 5 Vdc timing signal to other data acquisition systems.

The operator panel consists of a display, an "ENTER" button, two thumbwheels, an emergency stop button, and several toggle switches. The display is four lines by twenty characters. Pressing the emergency stop button turns power off to all solenoid valves; however, power to the camera, lights and data acquisition and control system is unaffected.

SOFTWARE FOR DATA ACQUISITION AND DATA REDUCTION

Two types of software are used: data acquisition and control system software, and data plotting and transmission software. The data acquisition and control system software was written in C and relies heavily on a DOS extender to maximize the use of the upper memory. This software initializes the apparatus, monitors various data channels, acquires data and controls the experiment during testing, and transfers data from the hard drive to the floppy disk.

During the experiment, the software monitors several data channels and records the outputs. Scientific measurements, i.e., the acceleration levels, the differential pressure, the void fraction, film thickness, and wall-shear stress, are recorded as voltages. Data from other sensors are recorded in appropriate units: from the thermocouples as degrees Fahrenheit, from the absolute pressure transducers as absolute pounds per square inch, and from the turbine flow meter as gallons per minute. The data acquisition system also calculates and records the gas and liquid flow rates as superficial velocities in meters per second.

A diagnostic routine performs the following functions: controls the zeroing capability of the accelerometers, controls the power to the purge control switch, and controls the 0 or 5 Vdc signal output to other data recorders.

Data plotting routines have been written to plot data on either Hewlett-Packard graphics language (HPGL) or postscript devices, such as Hewlett-Packard plotters, Paintjet XL printers, and laser printers.

INSTALLATION AND TEST PROCEDURES

The apparatus mounts into each aircraft differently. The Learjet mounting method uses two "T-rails" that run along the length of the aircraft. The first rail runs along the middle of the floor; the second rail runs along the wall, on a step that is 10 cm above the first rail. Mounting fixtures that mate to the T-rails are attached to each rack. For mounting either in the KC–135 or DC–9 aircraft, a single plate of aluminum is used to attach all three racks to the floor. Bolts are fed through the plate in a hole pattern specified in the KC–135 users guide (ref. 5).

After the apparatus has been installed in the aircraft, plumbing and electrical connections are made between the racks. Make the following plumbing connections:

- Connect the liquid feed line from the liquid supply tank on the tank rack to the connection on the flow metering rack.
- Connect the purge supply line from the liquid feed line on the flow metering rack to the purge solenoids on the data acquisition system rack.
- Connect the purge line from the purge solenoid valves on the data acquisition system rack to the entry region on the flow metering rack.

• Connect the two-phase return line from the test section exit flange on the data acquisition system rack to the collector/separator tank on the tank rack.

Make the following electrical connections:

• Connect the power and solenoid valve control cable bundle from the data acquisition rack to the flow metering rack.

• Connect the data acquisition cable bundle from the flow metering rack to the data acquisition rack.

• Connect the operator panel control cable from the data acquisition rack to the flow metering rack.

• Connect the power and control cable bundle from the data acquisition rack to the tank rack.

After these connections have been made, the test section is installed on the data acquisition rack. Complete the following steps:

• Mount the test section to the flanges on the entry section and two-phase return line.

• Connect the plumbing for the purge lines.

• Mount the differential pressure transducers.

• Connect the cabling between the signal conditioning electronics for the conductivity probes and the wall-shear stress probe.

After the experiment is over, follow the installation steps in reverse order to remove the experiment from the aircraft.

Before every flight, complete the following tasks:

• Filter the liquid. Over time, biological organisms grow and can attach to the fine-wire conductivity probes, which alters the signal. Filtering the liquid removes organic contamination.

• Adjust the zero offset of the absolute pressure transducers. Measure the ambient pressure with each transducer, then enter the local barometric pressure. The software compares the measured value with the barometric pressure and adjusts the zero offsets.

• If the small orifice will be used, check the flow with both a wet test meter and the data acquisition system. If the values differ by more than five percent, examine the flow system for leaks or a blocked orifice.

• Check the gas supply. If using the 13.2 L cylinder, pressurize the system to 10 340 kPa. If using a K-size bottle, check that the bottle pressure is greater than 922 480 kPa (13 790 psi).

• Pack a supply of floppy disks to transfer data onto during the flight.

• Load the 16 mm cameras with film. Only one camera is used at a time; however, additional cameras may be brought along. After the film is used, switching cameras is faster than reloading film.

• Update the data file containing the test names and conditions to reflect the tests planned for the flight.

Two operators are required for conducting tests. The first operator, stationed in front of the data acquisition rack, controls the acquisition software. The second operator, stationed near the flow metering rack, set the gas and liquid flow rates. Their coordinated activities, as well as the functions performed by the software, are described next.

The first operator places a label describing the test conditions in the camera's field of view. Then he or she configures the software appropriately by setting the following parameters:

• gravity level of either 1.0, 0.17, or 0.1 g
• orifice size of either small, large or none
• data acquisition rate of either 250, 500, or 1000 Hz
• full-scale range of differential pressure transducers of either 0.2, 0.6, 2.0 or 6.0 psid[1]
• test-section diameter of either 1.27 or 2.54 cm
• type of liquid solution of either water, water and glycerin, or water and zonyl
• length of camera recording and total experiment time

The second operator sets the desired superficial velocity of the gas by adjusting the appropriate regulator, then sets the liquid supply tank pressure to 207 kPa (30 psi) and adjusts the liquid flow rate with the micrometer handles on the two liquid flow valves.

After the gas and liquid flow rates have been set, the first operator instructs the software to calibrate the instruments. The software acquires the zero offsets of the accelerometers for 0.5 sec. The operator waits for the aircraft to enter a short period of zero acceleration along the aircraft thrust direction, which is indicated on the display, then instructs the software to calibrate the differential pressure transducers. The software turns off power to the purge solenoid valves and acquires differential pressure data and accelerometer data for 0.5 sec. Power is reestablished to the purge solenoid valves. The zero offsets for the differential pressure transducers are measured and corrected for residual hydrostatic forces.

The pilots are notified that the operators and apparatus are ready for a low gravity trajectory. After low gravity has been attained, the first operator instructs the software to start the experiment.

After the two-phase mixture has entered the test section and covers the last port to the differential pressure transducers, the purge switch is toggled off. During the low-gravity period, the first operator monitors the apparatus for any leaks or air bubbles in the sense lines for the differential pressure transducers, and notes the position of any air bubbles in the liquid supply tank that might be ingested into the liquid feed system. If necessary, the first operator may press the emergency stop button on the top of the control panel to close all solenoid valves and stop all flow. The camera and data acquisition system continue to operate.

After normal gravity has been reestablished, the first operator toggles the purge switch back to software control and removes and discards the old test name label. Liquid is recirculated back to the liquid supply tank. After every third trajectory, the camera is removed and traded for a fully-loaded one. The first operator mounts and plugs in the loaded camera and the second operator secures the spent camera.

After all data have been taken, they are transferred to floppy disks. The data are analyzed to see whether or not the desired flow rates were obtained, the differential pressure transducers were overranged, and if electronic noise interfered with the differential pressure transducers, conductivity probes, or hot-film anemometer probes.

The data, which are stored as integers, are converted to voltages. The flow rate data are then converted from voltages to engineering units, e.g., psia, and calculations are performed to determine the superficial velocities of the phases. The data are written to hard disk. Table I lists the file name extension, the transducer that the data was recorded from, and whether the data is stored in binary or ASCII format. Flow rate data are stored in two files. The file with the ".FIL" extension is in a format suitable for further data analysis. The file with the ".PRT" extension may be used to print out the data in tabulated columns. The contents of a typical flow rate data file is shown in Table II.

The Learjet Two-Phase apparatus has provided excellent data and photographs of low-gravity two-phase flow. Scientific results are presented in references 3 and 6.

ENHANCEMENTS

A planned enhancement to the apparatus is the integration of a high-frame-rate video system. The video camera will be controlled by the data acquisition and control system and can record motion at 500 images per second. Up to 43 min of video can be stored on a single video tape. Strobe lighting will be used to maximize the "freezing" the action of the camera, which will offset the effects of lower resolution film.

[1]These controls are labeled in English units.

CONCLUDING REMARKS

The Learjet Two-Phase Flow Apparatus has demonstrated its ability to obtain low-gravity, two-phase flow data over a wide range of flow conditions. It has excellent capability for time resolution of electronic data and has provided splendid photographs.

APPENDIX
PARTS LIST FOR THE LEARJET TWO-PHASE FLOW APPARATUS

Item no.	Description kPa (psig)	Working pressure, kg (lbs)	Weight,	Remarks
AI00	Gas cylinder	12 410 (1800)	10.44 (23)	Aluminum Cylinder
AI01	Cylinder valve	12 410 (1800)		
AI02	Globe valve	20 680 (3000)	0.45 (1)	
AI03	Filter	20 680 (3000)		
AI04	Pressure gauge	20 680 (3000)		
AI05	Relief valve	15 510 (2250)		12 410 kPa (1800) psig relief
AI06	Globe valve	20 680 (3000)	2.16 (4.75)	
AI07	Pressure regulator	41 360 (6000)		Outlet 0-17 235 kPa (0-2500 psig)
AI08	Pressure gauge	13 790 (2000)	0.57 (1.25)	
AI09	Solenoid valve	8620 (1250)		Normally closed
AI10	Thermocouple			
AI11	Pressure transducer	8620 (1250)		0-6895 kPa (0-1000 psia)
AI12	Square edge orifice			0.691 mm (0.0272 in.) diam
AI13	Pressure regulator	41 360 (6000)	2.16 (4.75)	Outlet 0-17 235 kPa (0-2500 psig)
AI14	Pressure gauge	13 790 (2000)		
AI15	Solenoid valve	8620 (1250)	0.57 (1.25)	Normally closed
AI16	Thermocouple			
AI17	Pressure transducer	8620 (1250)		0-6895 kPa (0-1000 psia)
AI18	Square edge orifice			0.188 mm (0.0074 in.) diam
AI19	Pressure transducer	1035 (150)		0-6895 kPa (0-1000 psia)
AI20	Relief valve	24 820 (3600)	1.02 (2.25)	240 kPa (35 psig) relief
AI21	Check valve	28 680 (3000)		7 kPa (1 psi) cracking pressure
AI22	Two phase mixer	275 (40)		Hydro-tested 365 kPa (53 psig)
AI23	Thermocouple			
AI24	Test section	275 (40)		Hydro-tested 365 kPa (53 psig)
AI25	Relief valve	24 820 (3600)	0.34 (0.75)	370 kPa (15 psig) relief
AI26	Back pressure regulator	1725 (250)	5.22 (11.5)	0-70 kPa (0-10 psid) range
AI27	Globe valve	20 680 (3000)		
AI28	Pressure regulator	34 470 (5000)	1.25 (2.75)	Outlet 0-1035 kPa (0-150 psig)
AI29	Pressure gauge	690 (100)		
AI30	Relief valve	24 820 (3600)	0.97 (2.13)	310 kPa (45 psig) relief
AI31	Globe valve	20 680 (3000)		
WD32	Liquid supply tank			Hydro-tested 620 kPa (90 psig)
WD33	Ball valve	20 680 (3000)		
WD34	Strainer			
WD35	Metering valve	4825 (700)		

WD36	Metering valve	20 680 (3000)		
WD37	Turbine flow meter	415 (60)		0.5-9.0 gpm range
WD38	Pressure transducer	1035 (150)		0-690 kPa (0-100 psia)
WD39	Solenoid valve	1035 (150)		
WD40	Relief valve	20 680 (3000)		240 kPa (35 psig) relief
WD41	Check valve	29 645 (4300)		7 kPa (1 psi) cracking pressure
WD42	Conductivity probe			Hydro-tested 415 kPa (60 psig)
WD43	Relief valve	10 350 (1500)		310 kPa (45 psig) relief
WD44	Metering valve	13 790 (2000)		
WD45	Globe valve	20 680 (3000)		
WD46	Solenoid valve	1206 (175)	0.14 (0.30)	
WD47	Solenoid valve	1206 (175)	0.14 (0.30)	
WD48	Metering valve	13 790 (2000)		
WD49	Metering valve	13 790 (2000)		
WD50	Pressure transducer	1035 (150)		0-690 kPa (0-100 psia)
WD51	Pressure transducer	210 (30)		0-7 kPa (0-1 psid)
WD52	Pressure transducer	210 (30)		0-7 kPa (0-1 psid)
WD53	Moisture trap	240 (35)		
WD54	Collector tank			Hydro-tested 620 kPa (90 psig)
WD55	Pump	520 (75)	2.95 (6.5)	

REFERENCES

1. User's Guide to Learjet for Low Gravity Research. NASA Lewis Research Center.
2. Bean, Howard S., ed.: Fluid Meters; Their Theory and Application. ASME, 1971.
3. Bousman, W.S.: Studies of Two-Phase Gas-Liquid Flow in Microgravity. NASA CR–195434, 1995.
4. Yaniec, John S.: Users Guide for NASA Lewis Research Center DC–9 Reduced-Gravity Aircraft Program. NASA TM–106755, 1995.
5. White, Linda G.: JSC Reduced Gravity Program Users Guide. NASA Johnson Space Center, 1991.
6. Bousman, W. S.; and Dukler, A. E.: Studies of Gas-Liquid Flow in Microgravity: Void Fraction, Pressure Drop and Flow Patterns. Proceeding of the 1993 ASME Winter Meeting, Fluid Mechanics Phenomena in Microgravity, AMD–Vol. 174/FED–Vol. 175, 1993, pp. 23–36.

TABLE I.—OUTPUT DATA FILES

File extensions	Format ASCII or binary	Data rates (Hz)	Parameter or sensor designation	Parameter or sensor description	Units
*.dp	Binary	100–1000	G_x	Longitudinal acceleration	V
			WD51	Differential pressure #1	│
			WD52	Differential pressure #2	│
			SS	Shear stress probe	▼
*.col	Binary	100–1000	∝	Void Fraction	V
			h	Film thickness	V
*.g	Binary	100–1000	G_y	Lateral acceleration	V
			G_z	Vertical Acceleration	V
*.fil	Binary	1	AI11	Large orifice pressure	psia
			AI10	Large orifice temperature	°F
			AI17	Small orifice pressure	psia
			AI16	Small orifice temperature	°F
			AI19	Downstream pressure	psia
				Liquid temperature	°F
			WD50	Test section pressure	psia
			AI23	Test section temperature	°F
			WD37	Turbine flow meter	gpm
				Liquid conductivity	V
			WD38	Liquid line pressure	psia
				Superficial gas velocity	m/sec
				Superficial liquid velocity	m/sec
*.prt	ASCII	1	Either		
			AI11	Large orifice pressure	psia
			AI10	Large orifice temperature	°F
			Or		
			AI17	Small orifice pressure	psia
			AI16	Small orifice temperature	°F
			AI19	Downstream pressure	psia
				Liquid temperature	°F
			WD50	Test section pressure	psia
			AI23	Test section temperature	°F
			WD37	Turbine flow meter	gpm
				Liquid conductivity	V
				Superficial gas velocity	m/sec
				Superficial liquid velocity	m/sec

TABLE II.—TYPICAL FLOWRATE DATA PRINTOUT[a]

FLIGHT 154, TRAJECTORY 6, DATA FLOPRINT
RUN DATE: 11–24–1993 TIME 13:12
SMALL ORIFICE: 0.01 g's: 1.27 cm ID: 1000 Hz: DRUCK 1.6 DELTA-P: WATER AND ZONYL

Pressure large orifice (psia)	Temperature large orifice (F)	Pressure downstream of orifice (psia)	Temperature liquid line (F)	Pressure test section (psia)	Temperature test section (F)	Liquid flowrate (gpm)	Conductivity reference cell (volts)	Superficial gas velocity (m/s)	Superficial liquid velocity (m/s)
817.7	71.4	15.5	69.2	14.81	70.7	1.02	3.723	2.03e+00	0.508
816.2	71.6	15.4	68.7	14.59	69.9	1.03	3.760	2.05e+00	0.511
817.7	71.5	15.4	68.4	14.85	69.4	1.04	3.748	2.01e+00	0.518
812.3	71.7	15.3	68.4	14.76	68.9	1.04	3.726	2.01e+00	0.520
814.2	71.8	15.3	68.3	14.66	68.7	1.03	3.718	2.03e+00	0.515
813.3	71.7	15.4	68.2	14.68	68.2	1.04	3.740	2.02e+00	0.520
811.3	71.6	15.4	68.0	14.59	68.4	1.04	3.689	2.03e+00	0.519
813.3	71.7	15.4	68.0	14.59	68.2	1.04	3.713	2.04e+00	0.520
811.8	71.6	15.2	67.9	14.29	68.2	1.03	3.730	2.08e+00	0.515
811.8	71.7	15.4	68.0	13.54	68.1	1.05	3.726	2.19e+00	0.521
811.3	71.6	15.2	67.9	14.00	68.0	1.05	3.730	2.12e+00	0.522
811.3	71.5	15.2	67.9	14.54	68.1	1.05	3.735	2.04e+00	0.524
810.8	71.5	15.3	67.9	14.61	67.9	1.05	3.730	2.03e+00	0.525
810.8	71.5	15.3	67.9	14.27	68.1	1.04	3.726	2.08e+00	0.518
810.8	71.4	15.3	67.9	14.54	68.0	1.06	3.733	2.04e+00	0.528
811.3	71.3	15.4	67.9	14.51	68.0	1.07	3.757	2.04e+00	0.531
806.4	71.2	15.3	67.9	14.37	68.1	1.05	3.723	2.06e+00	0.523
809.8	71.2	15.1	67.9	14.59	67.9	1.05	3.726	2.03e+00	0.523
808.9	71.2	15.4	67.9	14.27	69.8	0.05	3.748	2.08e+00	0.023
809.4	71.2	15.1	68.0	14.15	68.0	0.00	3.726	2.09e+00	0.001

[a]Header and unit designations are reproduced as they appear in the data file.

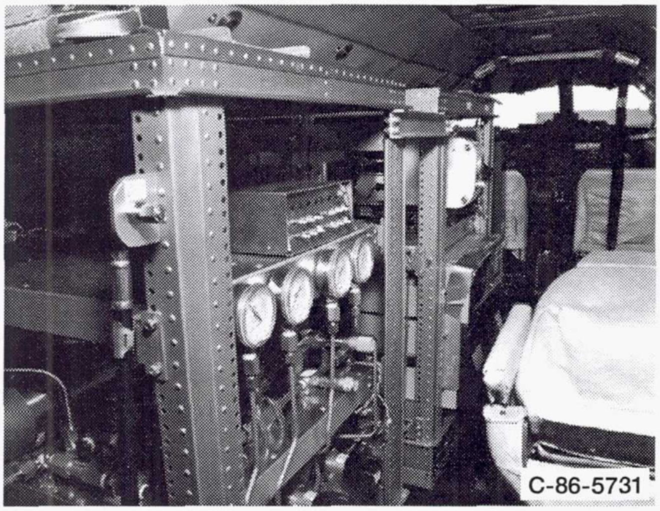

Figure 1.—Learjet two-phase flow apparatus mounted in the Lewis Learjet.

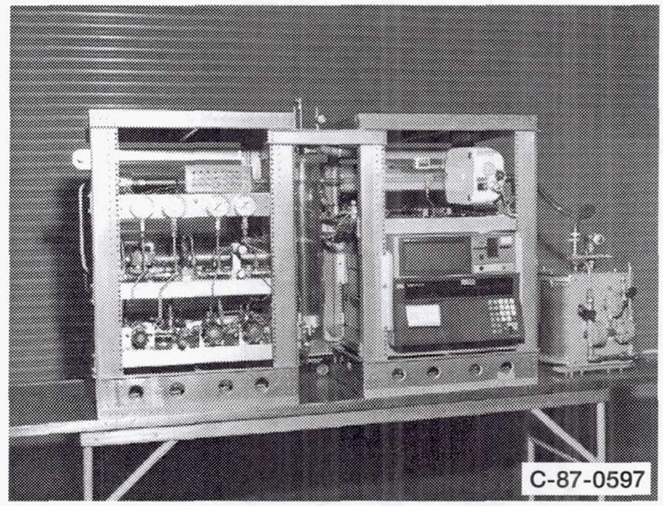

Figure 2.—Learjet two-phase flow apparatus rack layout.

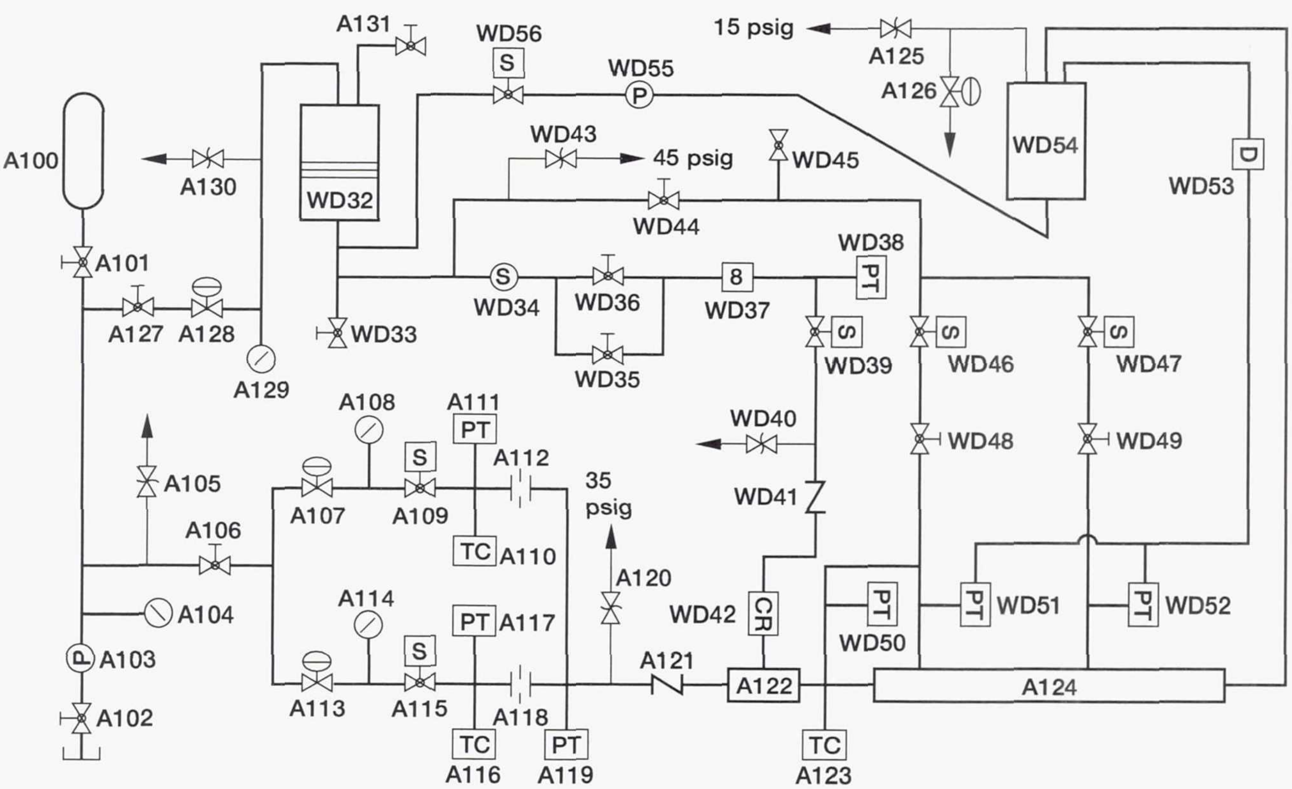

Figure 3.—Flow system for the Learjet two-phase flow apparatus.

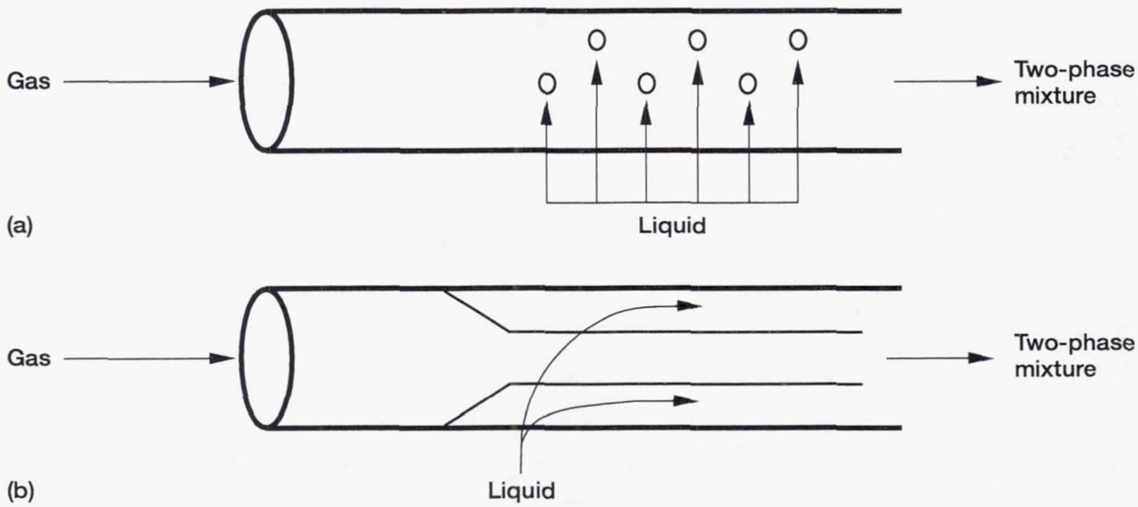

Figure 4.—Two-phase flow mixer configurations. (a) Radial. (b) Annular.

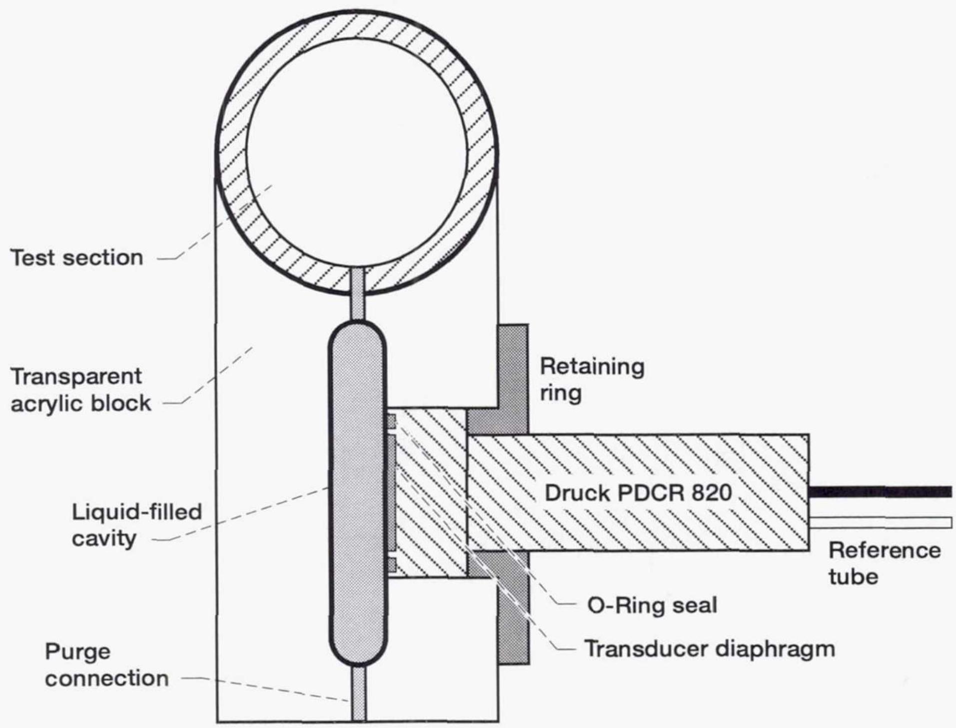

Figure 5.—Differential pressure transducer mounting receptacle.

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13. ABSTRACT *(Maximum 200 words)*

Low-gravity, gas-liquid flow research can be conducted aboard the NASA Lewis Learjet, the Lewis DC-9, or the Johnson Space Center KC–135. Air and water solutions serve as the test liquids in cylindrical test sections with an inner diameter of 1.27 cm and lengths up to 1.5 m. Superficial velocities range from 0.1 to 1.1 m/sec for liquids and from 0.1 to 25 m/sec for air. Flow rate, differential pressure, void fraction, film thickness, wall-shear stress, and acceleration data are measured and recorded throughout the 20 sec duration of the experiment. Flow is visualized by photographing at 400 frames with a high-speed, 16-mm camera.

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Two-phase flow; Microgravity; Pressure drop; Voids; Film thickness

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