Performance and Life Tests of a Regenerative Blower for EVA Suit Ventilation

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Ventilation fans for future space suits must meet demanding performance specifications, satisfy stringent safety requirements for operation in an oxygen atmosphere, and be able to increase output to operate in buddy mode. A regenerative blower is an attractive choice due to its ability to meet these requirements at low operating speed. This paper describes progress in the development and testing of a regenerative blower designed to meet requirements for ventilation subsystems in future space suits. The blower includes a custom-designed motor that has significantly improved its efficiency. We have measured the blower's head/flow performance and power consumption under conditions that simulate both the normal and buddy mode operating points. We have operated the blower for TBD hours and demonstrated safe operation in an oxygen test loop at prototypical pressures. We also demonstrated operation with simulated lunar dust.

I. Introduction

Ventilation is a critical function of a space suit's portable life support system (PLSS), vital for controlling the environment inside the suit's pressure garment. The blower that circulates ventilation gas through the pressure garment and PLSS must meet challenging requirements for flow performance, size, weight, power consumption, and safety of operation in an oxygen environment. As part of the effort to develop a PLSS for future exploration suits, NASA has sponsored programs to develop blowers that can meet these demanding requirements. This paper describes recent developments in the program to develop a regenerative blower for space suit ventilation.

Regenerative blowers have inherent head/flow characteristics that are attractive for space suit ventilation. The most important feature is the ability to generate relatively high pressure rise while rotating at low speed, which is a good match for the flow rates and pressure losses needed in future PLSSs. Operation at low speed simplifies the blower's design and contributes to oxygen safety. The low rotating speeds (less than 5,000 rpm under normal operation) enable the blower to be assembled with low tolerances from plastic materials that are inherently oxygen-safe. Furthermore, operation at low speed during normal operation enables the blower to accommodate buddy mode operation while still rotating at a speed less than 10,000 rpm.

Prior papers have reported on initial proof of feasibility, detailed fluid dynamic design, and aerodynamic performance of a first-generation prototype blower. This paper describes the design and development of an efficient low-speed motor, head/flow/efficiency performance of the final prototype blower in a simulated space suit environment, and preliminary results of life tests.

II. Requirements

The blower must force ventilation gas through the space suit pressure garment, then through a series of components in the PLSS that remove CO_2, water vapor, and heat (Figure 1). The ventilation gas must flow through

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several process components in series, leading to a relatively high pressure drop. Table 1 lists the key design requirements for the ventilation blower, which were defined by NASA at the beginning of the effort to develop a new ventilation blower.

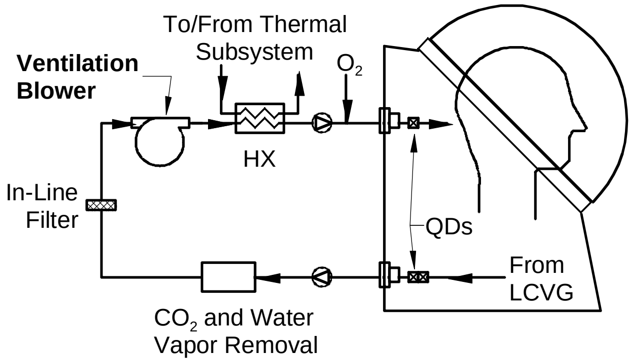

Figure 1. Ventilation Subsystem for Future Space Suits

Table 1. Design Requirements for Spacesuit Ventilation Fan[5]

Helmet Flow Rate Requirement	Current Baseline	High Flow Rate	Buddy Mode
Operating pressure (psia)	4.3	4.3	4.3
Volumetric flow rate (actual ft^3/min)	4.7	5.9	9.4
ΔP in space suit (in. H_2O)	2.7	4.1	6.75
ΔP at 1 atm pressure (in. H_2O)	9.2	14.0	23.1
Maximum power consumption (W)	8.0	—	—
Aero power at suit pressure (W)	1.5	2.8	7.4
Maximum mass (without controller) (kg)	0.91		
Maximum size (L)	0.49		
Service life (hr)	2500		

Flow Requirements. The ventilation subsystem is a circulating gas loop that transports expired CO_2 and water vapor out of the pressure garment and through PLSS components that remove expired components and add makeup oxygen. Figure 1 shows a simplified flow schematic, based on detailed schematics described by Conger et al.[6] The ventilation blower provides the motive power needed to circulate the ventilation gas through the pressure garment, CO_2 scrubber, heat exchanger, filters, valves, and quick disconnects. Ventilation gas leaving the blower flows through a heat exchanger cooled by the thermal subsystem, then enters the pressure garment. There it picks up heat, moisture, and CO_2 generated by the crew member and flows back into the ventilation gas loop via gas passages in the liquid cooling and ventilation garment (LCVG). The ventilation gas then flows through equipment to remove CO_2 and water vapor, possibly a humidity control subsystem, and then back to the blower.

Blower Requirements. The ventilation gas blower provides life-critical functions and must meet challenging requirements, particularly due to the unique conditions in the PLSS. Key requirements are:

- Safe operation in an oxygen environment. The ventilation gas flowing through the space suit and PLSS is composed primarily of oxygen. The blower must be built from materials and operate in a way that eliminates the possibility of an oxygen fire. This requirement means that the blower must be designed to prevent ignition due to possible fracture of rotating parts and resulting generation of particles and/or impact with particles that may be present in the ventilation gas.

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[5] Izenson, M. G., Chen, W., and Paul, H., “Regenerative Blower for EVA Suit Ventilation Fan,” 40th International Conference on Environmental Systems. Barcelona, Spain, AIAA.762306, July 2010.

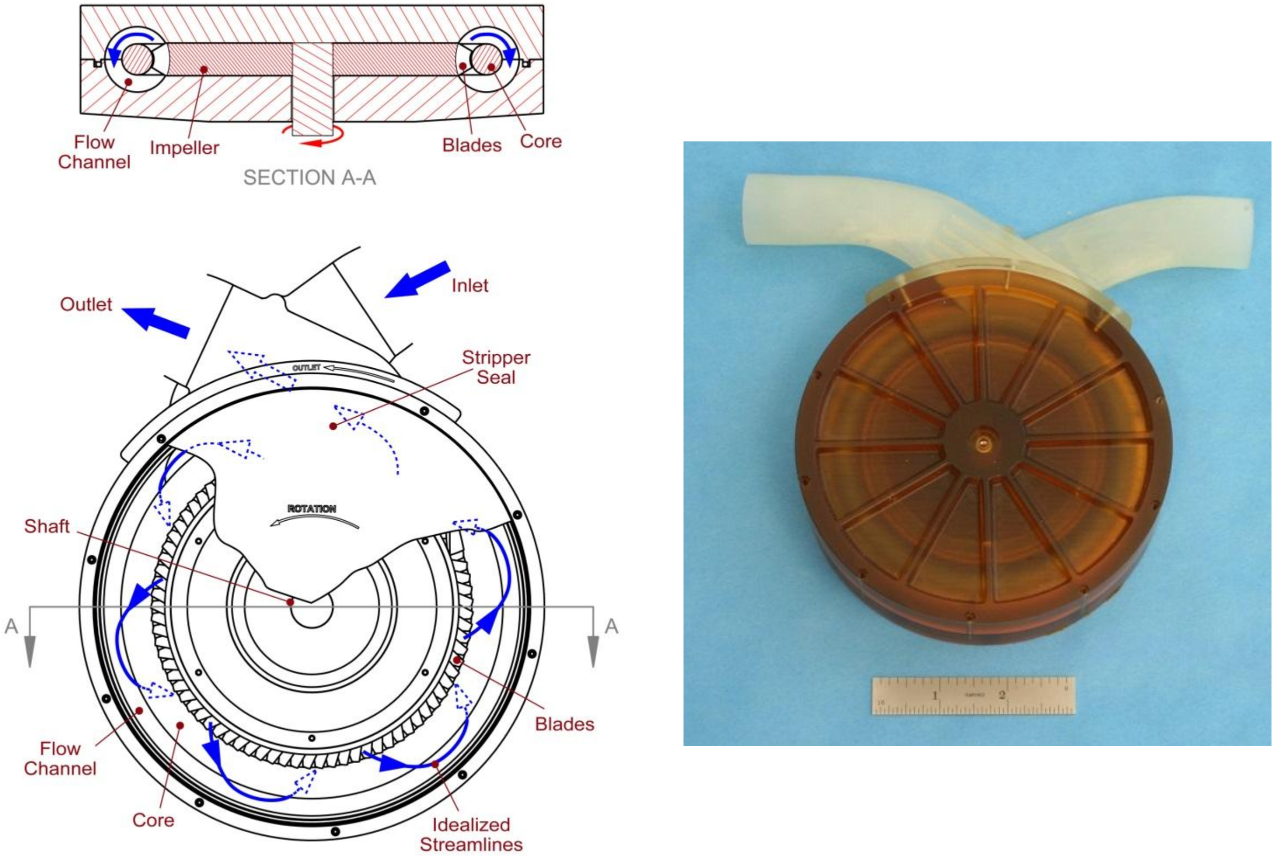
[6] Conger, B., et al., “Proposed Schematic for an Advanced Development Lunar Portable Life Support System,” 40th International Conference on Environmental Systems, Paper no. AIAA 2010-6038, Barcelona, Spain, July 2010.

- Generation of a high gas pressure. The ventilation blower must force the ventilation gas through several processing components in series, each of which requires a significant pressure difference to enable the required ventilation gas flow.
- Operation in buddy mode. EVA mission planners foresee the need for a high degree of adaptability in the event of possible hardware failure in the PLSS. In emergencies, the PLSS is required to provide "buddy mode" capability, in which the PLSS from one EVA suit sustains the environment inside a second EVA suit in case the second suit's PLSS fails. In buddy mode, the ventilation blower must provide enough aero power to force an adequate flow of ventilation gas through two pressure garments simultaneously.

Table 1 lists the primary design requirements for the ventilation blower. The current baseline requirements (4.7 actual ft^3/min with a pressure rise of 2.7 in. H_2O) correspond to the fan performance needed to properly manage CO_2 and humidity levels in the current, baseline space suit design. The high flow rate requirements correspond to an alternate space suit design with a higher ventilation flow requirement. The buddy mode requirements are based on a single ventilation fan providing enough flow for two space suits connected in series, hence twice the flow rate and a larger pressure drop. The maximum power consumption requirement (8.0 W) applies to the combined input power for the motor and motor controller. The power limit applies only to the baseline case, as buddy mode operation is expected to be very infrequent and power conservation is not a key priority. The blower mass should not exceed 0.91 kg (2.0 lb_m) and its volume should be less than half a liter. The service life of 2500 hours corresponds to 100 8-hour EVAs multiplied by an appropriate safety factor. The blower must achieve this reliability goal while operating in potentially dusty lunar or planetary environments.

III. Regenerative Blower Concept

Regenerative blowers are well-suited to meet the requirements for space suit ventilation due to their unique mechanism of imparting momentum to gas. Figure 2a shows the basic design concept for a regenerative blower, which comprises an impeller, an array of peripheral blades that impels the gas along a spiral path through an annular channel surrounding a toroidal core that extends the length of the perimeter. The gas spirals around the core, interacting with the impeller blades several times before leaving the blower. In this way the regenerative blower uses a single impeller to impart multiple stages of pumping to the gas. The total pressure of the ventilation gas increases continually as it flows around the periphery of the blower. The "stripper seal" shown in the bottom drawing of Figure 2a prevents the high-pressure gas from flowing directly back to the inlet of the blower. Figure 2b is a photograph of the first-generation prototype blower. The impeller and internal flow passages of this blower are identical to the final prototype; the main difference is the design and performance of the motor.



(a) Regenerative Blower Concept **(b) First-Generation Ventilation Blower**

Figure 2. Ventilation Subsystem for Future Space Suits

The performance of early prototypes validates the concept that a regenerative blower can meet ventilation requirements at low rotating speed. Figure 3 plots the head/flow performance of the first-generation prototype for operating speeds ranging from 4,000 to 6,500 rpm. The performance curves are fairly linear and relatively steep, showing rapid increases in head as the flow rate decreases. The baseline operating point is achieved at an operating speed of 4,630 rpm. The buddy mode operating point (9.4 ft^3/min, 6.75 in. H_2O) is very nearly achieved at a rotating speed of 6,500 rpm; scaling from these data show that buddy mode operation should be achieved at a rotating speed of 6,850 rpm.

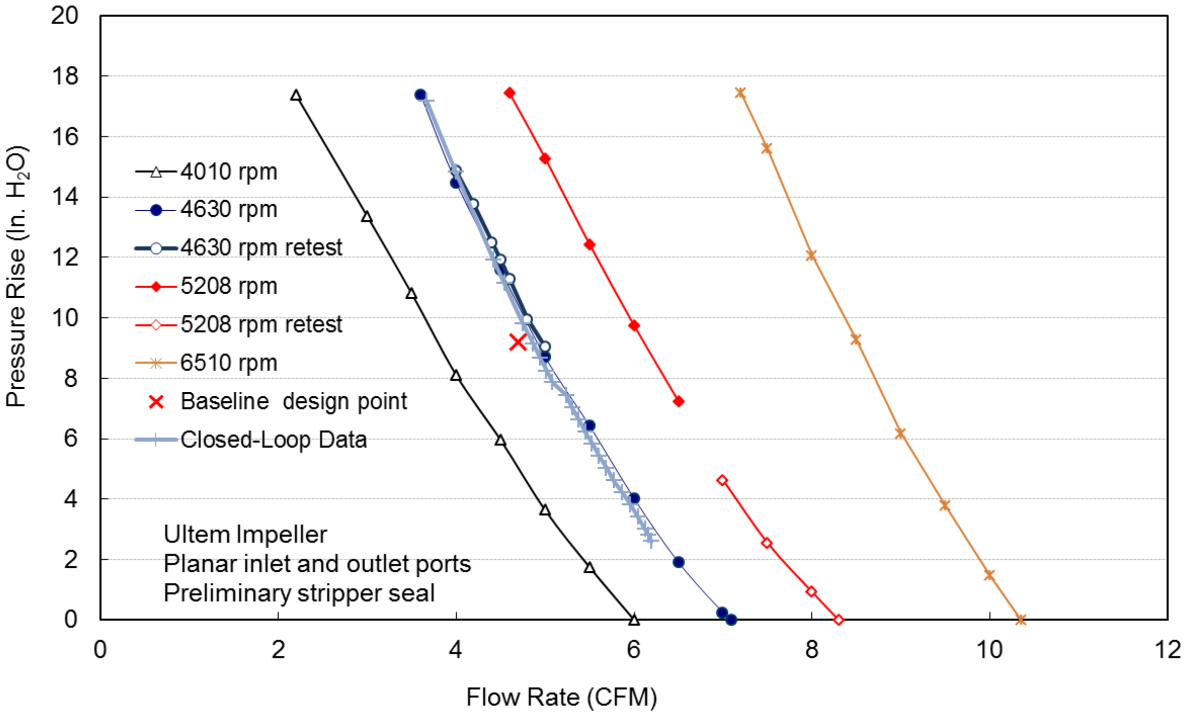


Figure 3. Head/Flow Performance of the First-Generation Ventilation Blower

IV. Motor Design and Development

The regenerative blower needs a unique motor for safe operation at high overall efficiency. A fundamental requirement is to isolate all active electrical components—including the motor coils—from the ventilation gas to prevent contact with pure oxygen. The motor must also be efficient to meet power consumption requirements.

To ensure safe operation, the stator coils of the blower's brushless DC motor are isolated in a central hub that is sealed from the ventilation gas (Figure 4). The stator is located in a recess in the blower housing, and is separated from the rotor by a very thin wall. The thin wall is necessary to ensure a high magnetic flux in the stator. To reduce the size of the stator, we use a four-pole permanent magnet motor instead of a standard three-phase motor.. The rotor is driven by an annular permanent magnet that surrounds the stator. This magnet is made of oxygen-compatible ferrite.

The blower's aerodynamic components can achieve efficiencies up to 43%, which is quite good for a small device, and is documented in prior papers. During normal operation, the aero power into the ventilation gas is 1.5 W, so the shaft power input needed to drive the blower during normal operation is (1.5 W)/(43%) = 3.5 W. The total mechanical power needed for the blower includes an allowance of 1 W for bearing losses, so the total mechanical power input required is 4.5 W. To meet the nominal requirement for < 8 W_e electric power input, the overall motor efficiency therefore must be greater than (4.5 W)/(8.0 W) = 56%. Although many commercial motors are much more efficient than this, no commercial motors are available that can meet oxygen safety requirements and efficiently provide the power needed by the ventilation blower at the low operating speeds.

To develop the high efficiency motor, we formulated a first-order analysis model for the blower and compared the model results with data from candidate motors. We used the model to determine the voltage and current waveforms in the stator windings and estimate the overall losses (Figure 5). We optimized the rotor pemanent magnet geometry and the field strength to minimize fringing and losses. We also optimized the windings parameters to minimize the total losses in the stator, and enable the motor to achieve the norminal operating speed at a 28 V power input. We adjusted the Hall effect sensor angular position to optimize the timing to switch the polarity of stator power supply for maximum motor efficiency.

Figure 6 shows the stator and the motor controller, which uses an H-bridge that can apply voltage across the load in either direction. The H-bridge uses 150 V-rated MOSFETs to withstand the switching transients produced by the motor. The motor must run at higher than normal voltage for buddy mode operation. Increased motor voltage for buddy mode operation is accomplished with a boost regulator IC that produces nominally 56 VDC. During normal operation, the boost regulator will be bypassed and un-powered, so its parasitic power drain will be zero. The controller also includes design features that enable the synchronous motor to self-start.

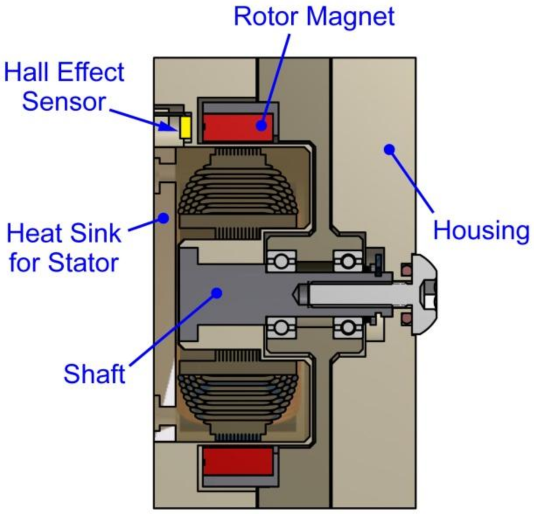
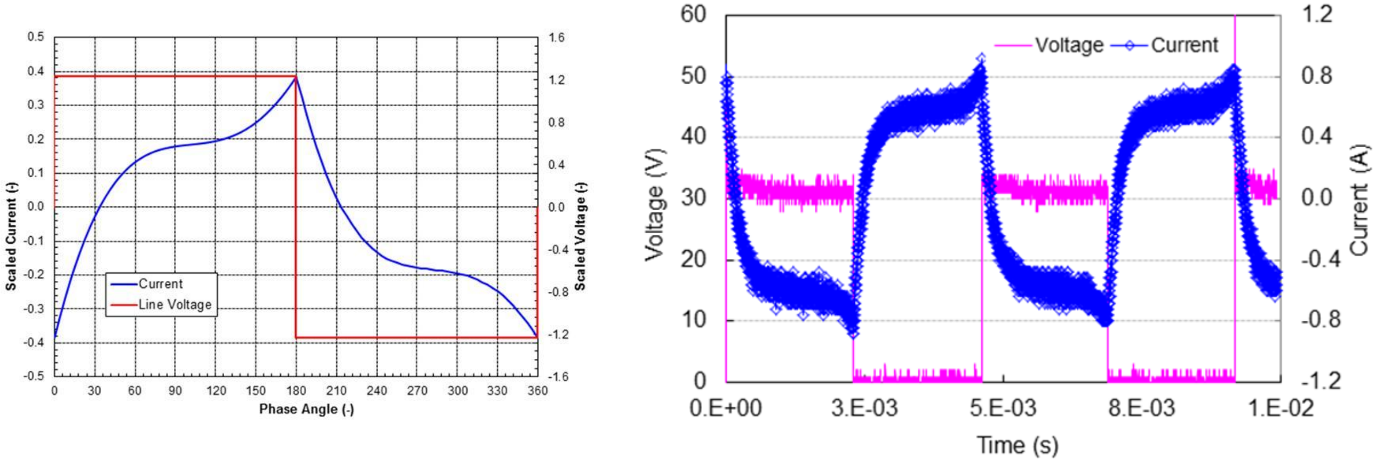
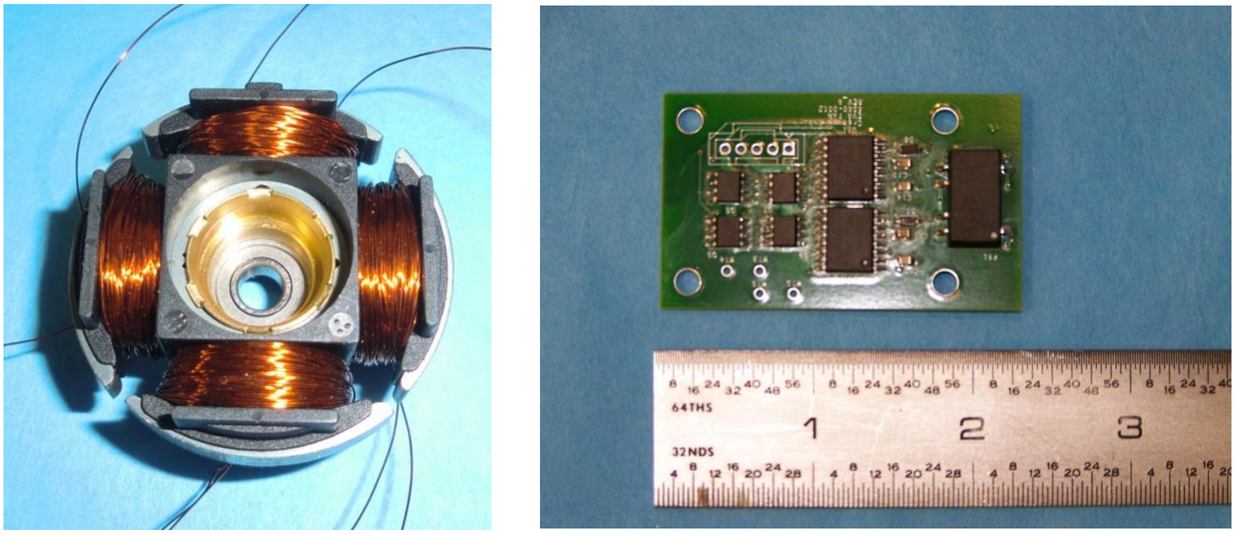


Figure 4. Oxygen-Safe, High Efficiency Motor



(a) Model Predictions **(b) Measured Current**

Figure 5. Predicted and Measured Current Waveforms



(a) Stator **(b) Motor Controller**

Figure 6. Central Stator and Motor Controller

To measure the motor-inverter efficiency, we mounted the stator on bearings so that it was free to rotate in a direction counter to the rotor. The rotor was connected to an aerodynamic brake, as shown in Figure 7. During testing, the stator was held in place by a torque arm coupled to a scale, enabling us to measure the mechanical torque output of the motor. The power supply that drove the motor provided data on the overall electric current and voltage input to the inverter, which we used to calculate the inverter power input. The mechanical power output from the motor is the product of the motor torque and its rotating speed. We measured the rotating speed by measuring the frequency of the current waveform for the stator, and calculated the torque from the force exerted by the torque arm. The motor torque is simply the product of the measured force and the length of the torque arm. The ratio of the mechanical power output to the electrical power input is the motor-inverter efficiency. The measured electrical-to-mechanical efficiency near the design operating speed and mechanical power output is about 75%, as shown in Figure 8.

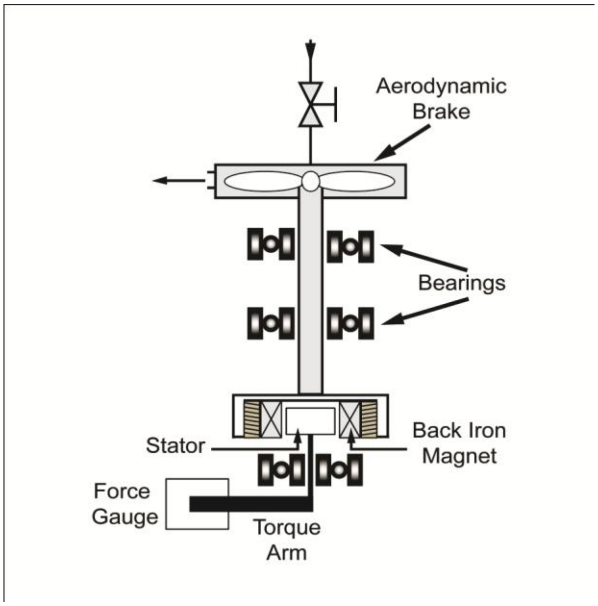


Figure 7. Measurement of Motor Efficiency

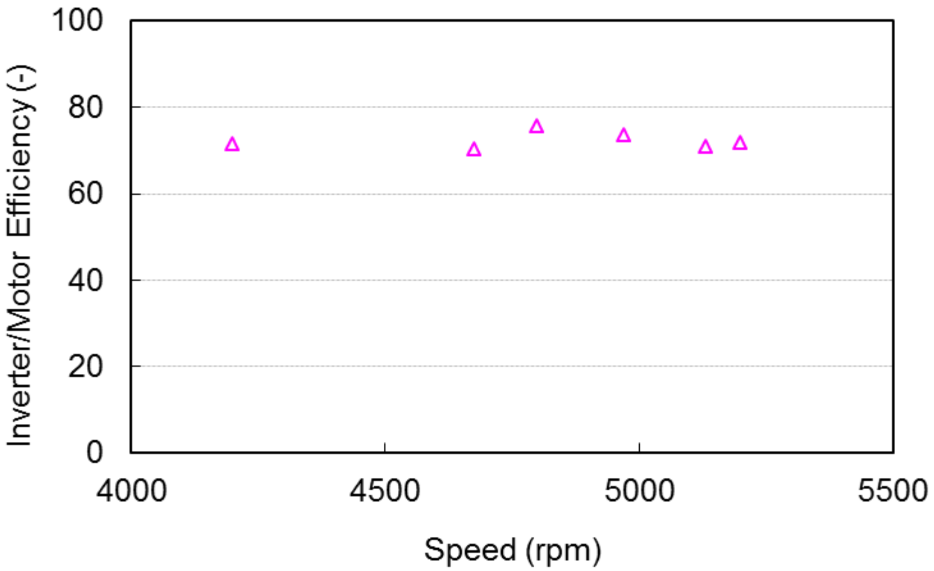


Figure 8. Motor Achieves High Efficiency at Prototypical Rotating Speeds

V. Prototype Blower Design and Performance

The design of the blower has been specified to meet the stringent requirements for operation in a PLSS. These requirements include:

- Efficient fluid dynamic performance.
- A robust structure for operation in an external vacuum.
- A mechanical design that provides leak-tight seals and enables simple disassembly and maintenance.
- Materials selected for light weight and oxygen safety.
- Cooling for the motor stator.

Figure 9 shows an exploded solid model of the blower components, illustrating the overall assembly. Figure 10 shows the impeller and the assembled blower housing, and Figure 11 shows the entire blower with inlet and exit ducts. Prior to life testing we measured head/flow performance and overall efficiency under conditions that simulated operation in a space suit ventilation subsystem. The blower performance meets NASA's requirements and is consistent with data from prior blower prototypes.

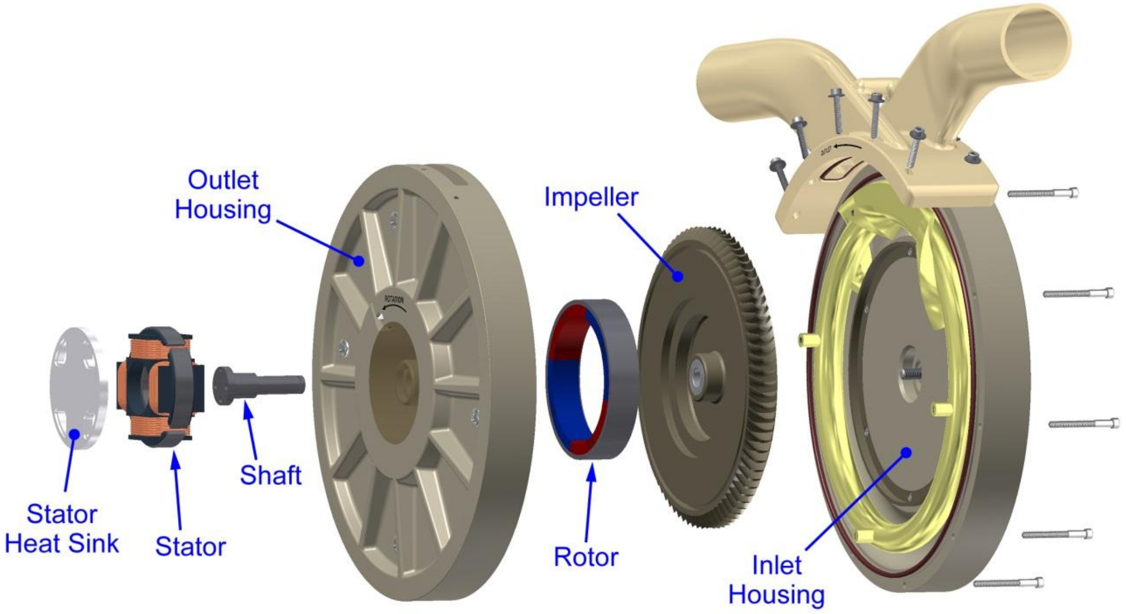
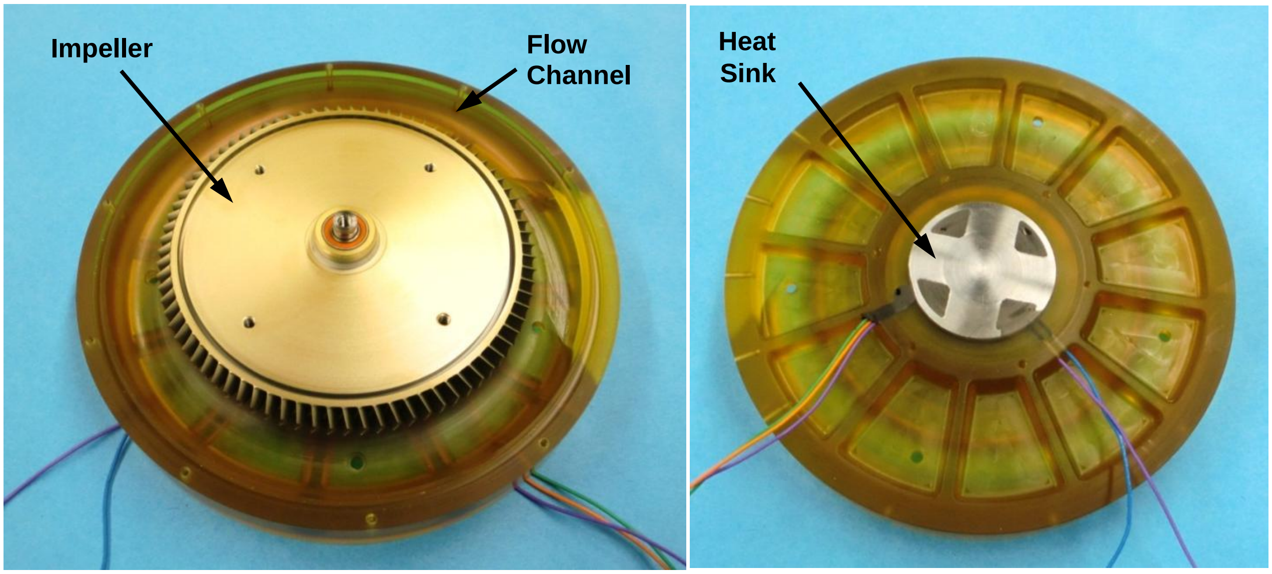


Figure 9. Exploded View of Blower Components



(a) Cover Removed Showing Impeller, Flow Channel, and Shaft

(b) Fully Assembled Showing Motor Heat Sink

Figure 10. Blower Impeller and Housing

Figure 11. Final Prototype Blower

A. Design

We specified the shapes of the impeller blades, annular flow passage, stripper seal, and inlet/exit ducts based on CFD analysis of the internal flow. As reported by the authors in an earlier paper,[7] the CFD results agreed well with the blower's head/flow performance and aero efficiency. The blade design was taken directly from the most efficient geometry modeled by CFD. The shapes of the inlet and exit flow passages near the stripper seal were specified based on the detailed predictions of gas velocity.

The blower will operate in the vacuum environment of the PLSS backpack with an internal gas pressure of 4 psia. Since the blower mass should be minimized, we designed the housing with lightweight features that minimize stresses and deflection due to the internal pressure. We analyzed the stresses and deflections in the housing due to the internal pressure using ANSYS® v12 (Figure 12). We found that the stresses were all acceptable and that the deflections were within acceptable tolerances for the mechanical and fluid components.

Materials were selected to ensure safe operation in an oxygen environment while meeting fluid dynamic, mechanical, and structural requirements. The low rotating speed of the blower reduces mechanical tolerance requirements and enables the selection of a broader range of materials with an emphasis on oxygen safety. Table 2 lists which materials were used for each component, and whether that component contacts oxygen in the ventilation loop. Some of the key materials used for the moving parts in the blower are:

- Ultem® polyetherimide is a lightweight, high strength plastic used for the blower housing and impeller. Ultem® has high wear resistance, high auto-ignition temperature, low flammability (Hirsch et al., 2007[8]), and will not generate sparks on impact with high-speed particles. The impeller is coated with a thin layer of gold to prevent buildup of static charge.
- Silicon nitride is an extremely inert material that was used in the liquid oxygen turbopumps in the space shuttle's main engines. We use miniature ball bearings with SiN balls for oxygen safety and very long service life.
- Krytox® is used to lubricate the blower's ball bearings. DuPont™ Krytox® synthetic greases comprise synthetic perfluoropolyether-(PFPE-) thickened with polytetrafluoroethylene (PTFE) powder. Krytox® is extremely inert, nonflammable, and has extremely low vapor pressure. It is used extensively by NASA in oxygen service.

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[7] Izenson, M. G., Chen, W., Hill, R. W., Phillips, S. D., and Paul, H., "Design and Development of a Regenerative Blower for EVA Suit Ventilation," 41st International Conference on Environmental Systems, Portland, OR, AIAA 2011-5260, July 2011.

[8] David B. Hirsch, James H. Williams, Susana A. Harper, Harold Beeson and Michael D. Pedley, Oxygen Concentration Flammability Thresholds of Selected Aerospace Materials Considered for the Constellation Program, <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070018178_2007017304.pdf>.

Thanks to the low rotating speed and light weight of the impeller, shaft loads are small and the impeller can be supported by a pair of miniature silicon nitride ball bearings (see Figure 4). The blower is sealed using mechanical fasteners and Viton O-rings for easy maintenance.

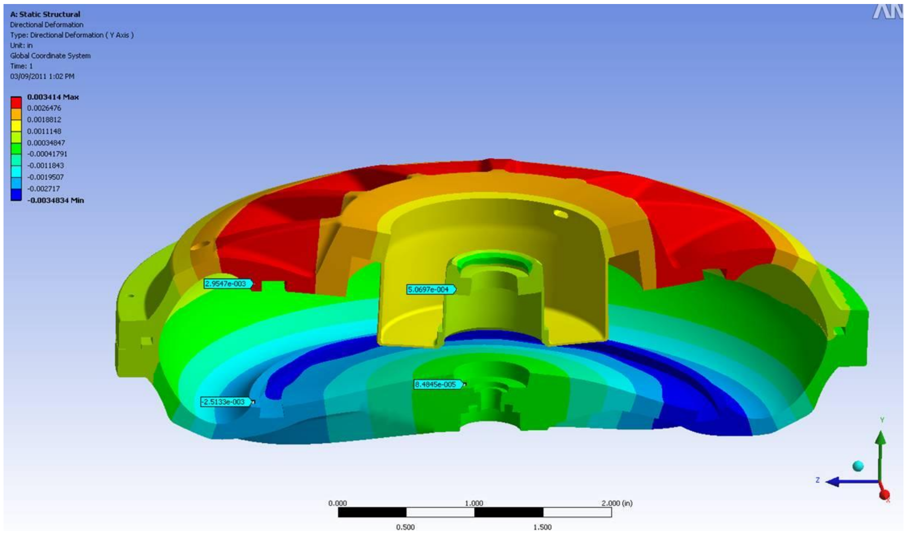


Figure 12. Calculated Deformation of Blower Housing

Table 2. Materials Used in the Spacesuit Ventilation Blower

Material	Components	Contact Oxygen?
Stainless steel	Fasteners, washers, wave springs, motor shaft	Yes
Ni-plated SLA resin	Inlet/outlet, stripper seal, flow channel core	Yes
Ferrite magnet	Motor rotor	Yes
Silicon Nitride	Bearing balls	Yes
Krytox	Bearing lubricant	Yes
Sycast epoxy	Adhesive for rotor magnet, thread sealant	Yes
Polyetherimide	Impeller, housing, labyrinth seal	Yes
Viton	O-rings	Yes
Copper	Preload washer and shim	Yes
Aluminum	Stator heat sink	No
Steel	Motor back iron,retaining ring	No

Table 3 lists the masses of the blower components. The total mass of the blower is 680 g (1.50 lb_m). The housing and flow passages (316 g) and motor and controller (195 g) account for 75% of the total mass.

Table 3. Masses of Components

Impeller	(g)	61
Housing and flow passages	(g)	316
Inlet/outlet assembly	(g)	45
Bearings	(g)	3
Motor and controller	(g)	195
Auxiliary components	(g)	60
TOTAL	(g)	680

B. Performance

Figure 13 shows the head/flow curves measured at constant voltage under conditions that simulate normal operation. In these tests, air at a pressure of 5 psia simulates pure oxygen at normal suit pressure (4.3 psia). Each curve shows the blower head/flow characteristics at a fixed voltage, ranging from 18 to 24 V. The blower achieves the nominal design point at a voltage of slightly less than 20 V. The curves are relatively shallow, so small increases in pressure rise will not dramatically reduce the ventilation flow rate. The blower speed at the normal operating point is 4,800 rpm. Figure 14 plots the blower power consumption and overall efficiency for the same data that are plotted in Figure 13. The blower's electric power consumption was 8.5 W at the design point, corresponding to an overall efficiency of (1.5 W)/(8.5 W) = 17.6%.

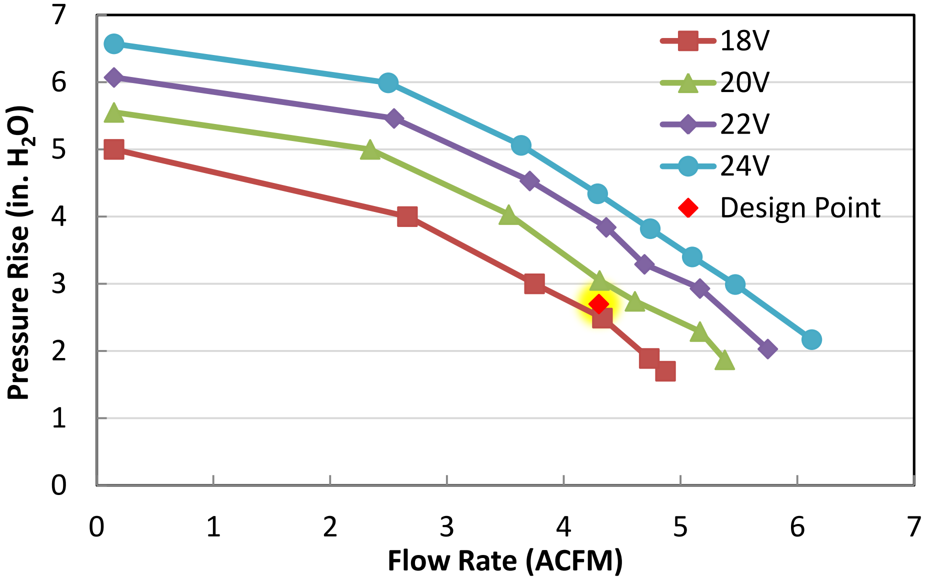


Figure 13. Head/Flow Performance During Normal Operation

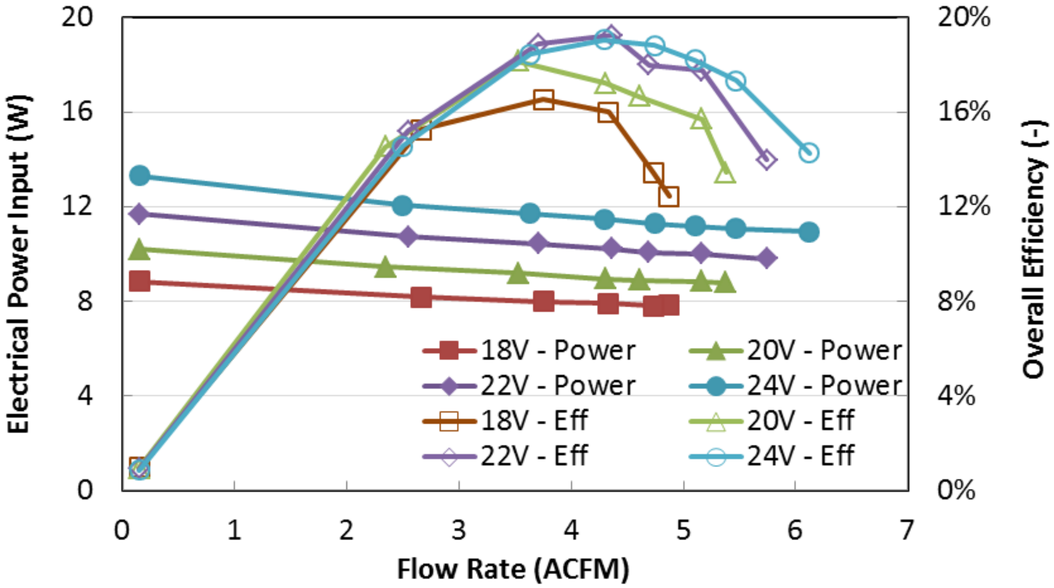


Figure 14. Blower Power Consumption and Efficiency During Normal Operation

Figure 15 shows the blower's efficiency as we increased the rotating speed by boosting the motor voltage. The speed, flow rate, and pressure rise all increased roughly linearly with the motor voltage. Over the range tested to date (up to 7,250 rpm), the motor efficiency remains essentially constant as the speed increases.

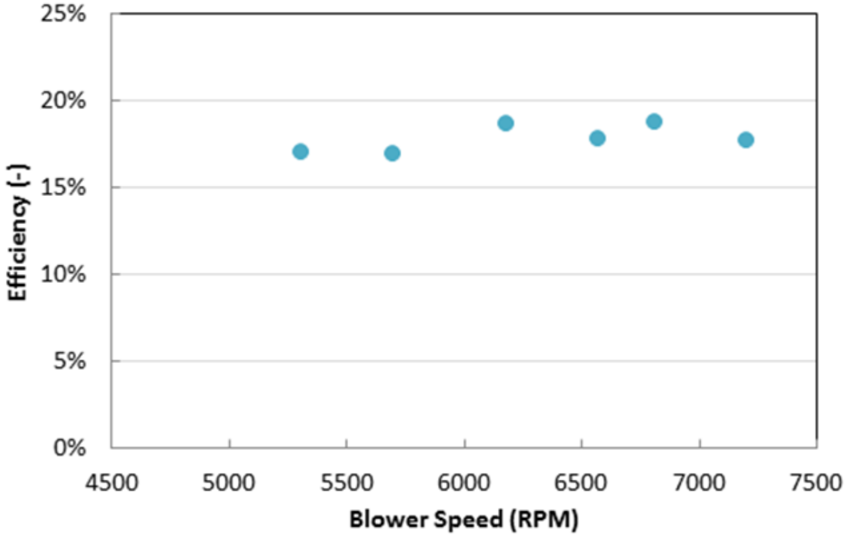


Figure 15. Blower Efficiency Remains Constant at Higher-Than Normal Rotating Speed

Table 4 lists details of the blower's power consumption at the nominal operating point. Overall power input is 8.5 W, for an overall efficiency of 17%. 1.5 W of power produces ventilation flow work , and most of the rest is consumed by flow, bearing and other mechanical losses (4.3 W), and losses in the motor (2.5 W). The inverter consumes about 0.2 W. The current power consumption of 8.5 W is slightly higher than the original design specification (Table 1). We believe that significant improvements in efficiency are still possible by optimizing the internal flow passages. Future models of the blower should be able to achieve the design point performance with power inputs less than 8.0 W.

Table 4. Blower Power Consumption

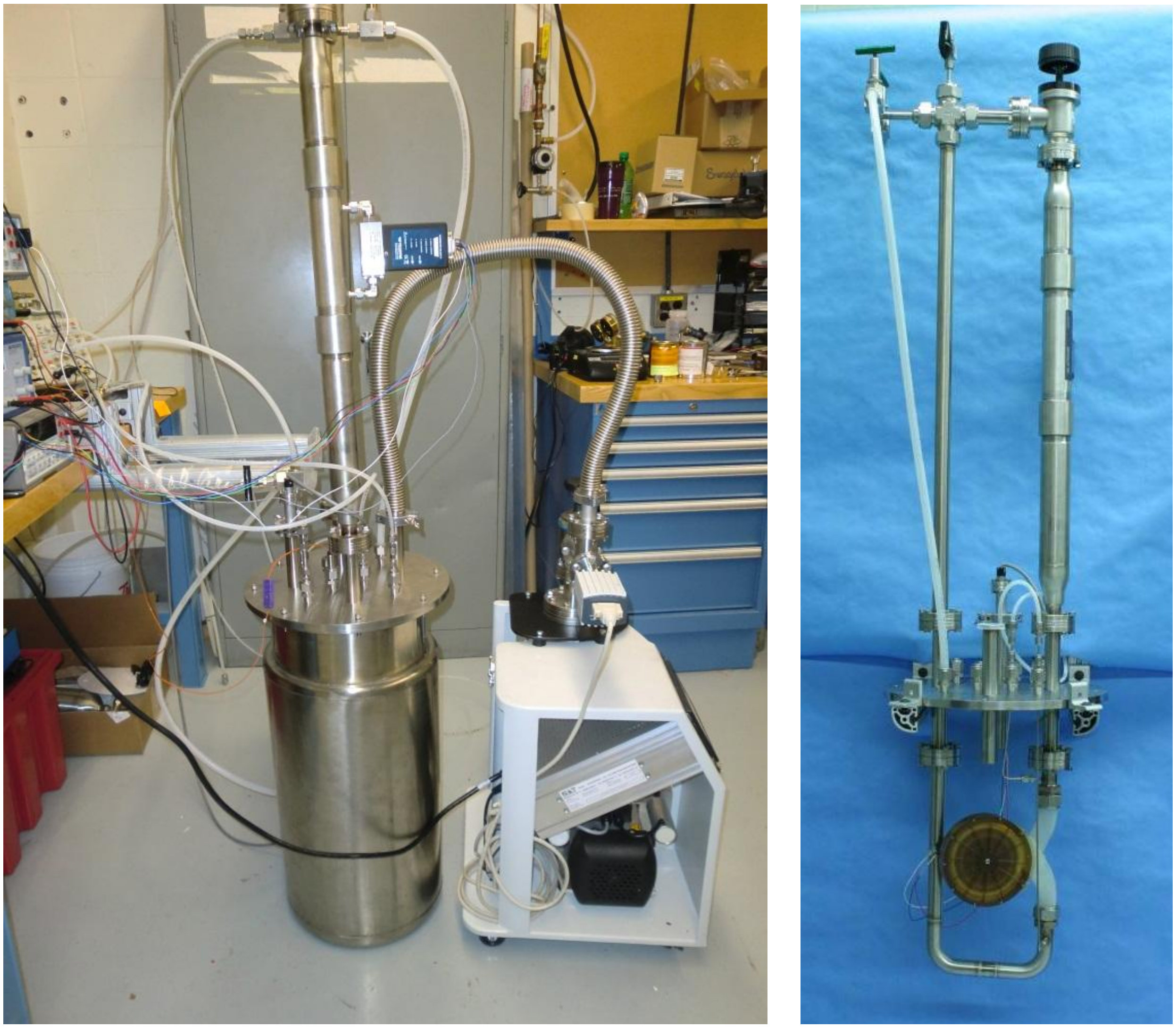
Power Consumption	
Aero power (W)	1.5
TOTAL power input (W)	8.5
Mechanical to aero efficiency	0.25
Motor efficiency	0.70
Inverter efficiency	0.98
Overall efficiency	0.17

VI. Life Testing

Future space exploration missions will require the blower to operate very reliably for hundreds of hours between routine maintenance. To demonstrate reliability in a prototypical environment, we assembled a test rig that enables long-term, unattended operation of the blower while circulating oxygen through a loop maintained at prototypical space suit pressures. To date the blower has operated for TBD hours with no signs of any performance degradation. We also ran a second prototype in the oxygen loop and introduced simulated lunar dust. The pump ran through this test without incident, demonstrating the benefits of low-speed operation for oxygen safety.

Figure 16 shows photographs of the life test rig, which comprises an oxygen flow loop and a vacuum system to simulate blower operation in space. Figure 16(a) shows an external view of the vacuum vessel and vacuum pump (only a rough vacuum is needed to simulate the effects of vacuum operation). Figure 16(b) shows the hardware that constitutes the oxygen flow loop. The blower is suspended beneath the lid of the vacuum vessel by the loop piping. The loop includes a vacuum throttle valve that enables us to vary the flow resistance and measure the head/flow performance of the blower.

Figure 17 shows a schematic of the flow loop and associated instrumentation. The loop contains a Teledyne mass flow meter and a differential pressure transducer to measure the blower's head/flow performance. We have also installed a microphone and a thermocouple to monitor the blower during life tests for signs of vibration or overheating. The absolute pressure gauge measures the oxygen inventory in the loop. Since the blower motor is synchronous, we measure its speed directly from the motor controller. A DC source provides power to the blower motor drive, and current and voltage are measured continuously by HP34401A digital multimeters. A laptop with LabVIEW® data acquisition software will continuously monitor and record signals from the blower and flow instrumentation, power supply, and the blower thermocouple.



(a) Vacuum Vessel and External Controls

(b) Flow Loop and Blower Removed from Vacuum Vessel

Figure 16. Life Test Rig

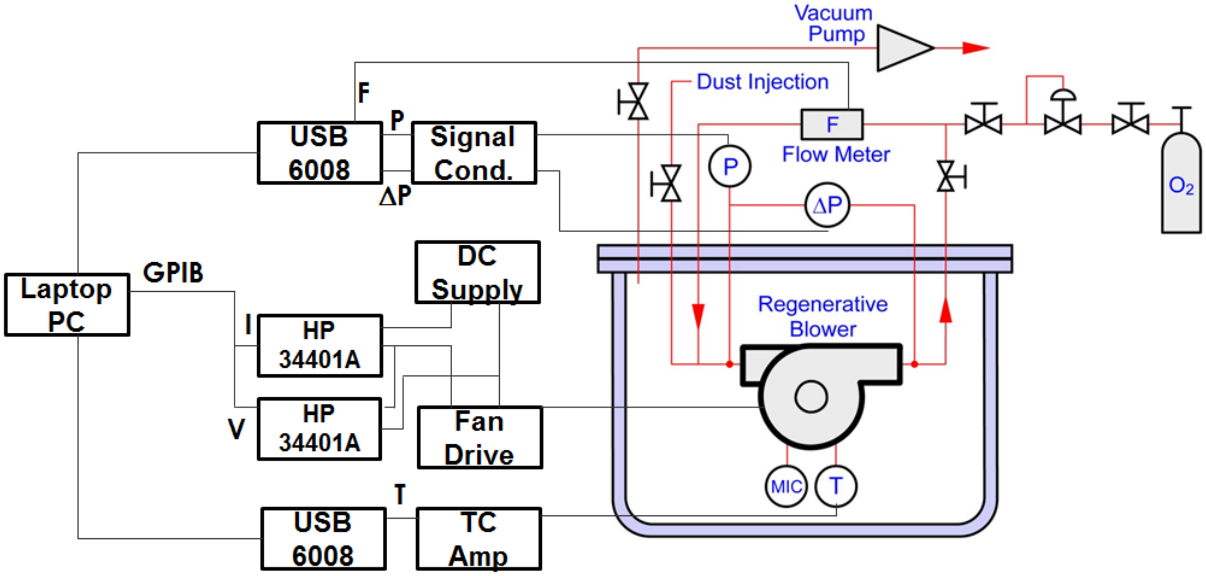


Figure 17. Flow Schematic and Instrumentation for Blower Life Tests

VII. Conclusion

A regenerative blower offers features that are attractive for ventilation subsystems in future PLSSs. We have designed, built, measured the performance, and demonstrated the reliability of a regenerative blower designed for space suit ventilation. The blower has met NASA requirements for flow rate, pressure rise, power consumption, size, and weight. The blower provides the flow rate and pressure rise needed for normal operation at a rotating speed of 4,800 rpm while consuming only 8.5 W of electric power. The blower meets the head/flow requirements for buddy mode operation at a rotating speed of only 4,800 rpm. The blower comprises an innovative fluid dynamic design based on detailed and validated CFD calculations and an efficient, four-pole, brushless DC motor in which the stator coils are isolated from the ventilation gas. The blower is built from oxygen safe materials, and has demonstrated safe operation in oxygen environment for TBD hours, including a testing in which simulated lunar dust was injected into the oxygen flow loop. The blower has been delivered to NASA for further testing in the PLSS 2.0 facility at NASA Johnson Space Center.

Acknowledgments

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