High-Accuracy Oxygen Flow Meter for the Exploration Portable Life Support System

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The Exploration Portable Life Support System (xPLSS) requires a high-accuracy instrument to measure the rate of oxygen flow in the ventilation system. The sensor must produce accurate readings across a wide range of flow conditions while consuming very little volume and power and introducing very little pressure loss to the ventilation loop. We have developed an innovative flow sensor built around a commercial off-the-shelf MEMS flow-sensing chip that is designed for oxygen service. The sensor comprises a custom housing that channels gas flow over MEMS sensing elements and uses custom electronics to control the sensor and generate signals compatible with Exploration Extravehicular Mobility Unit (xEMU) requirements. The flow sensor operates in parallel with the ventilation loop heat exchanger, so it introduces no additional pressure loss to the ventilation system. The unit meets size and shape requirements for service in the xPLSS and is replaceable in space if necessary. Data from separate-effects tests and tests of the integrated xPLSS heat exchanger/flow meter system show that the flow meter is capable of generating high-accuracy flow measurements across the range of specified operating conditions. We built and tested a proof-of-feasibility prototype in mid-2019, followed by a "rapid-turn" demonstration sensor that meets form, fit, and function requirements in late 2019. Fully qualified Design Verification Test (DVT) units are scheduled for delivery in mid-2020.

Nomenclature

ADC	=	analog-to-digital converter
DVT	=	Design Verification Test
xEMU	=	Exploration Extravehicular Mobility Unit
FM-HX	=	flow meter-heat exchanger
OML	=	outer mold line
PCB	=	printed circuit board
PLSS	=	Portable Life Support System
xPLSS	=	Exploration Portable Life Support System

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I. Introduction

THE xEMU requires an xPLSS that meets performance requirements and operates in environments that are quite different than the PLSS used for the space station EMU. As a result, new components that provide new capabilities are currently under development for the xPLSS. One of these new components is a high-accuracy flow meter that measures the actual volumetric flow of the circulating ventilation gas. This flow meter operates in parallel with the ventilation gas heat exchanger and uses the heat exchanger as a pressure drop element. In NASA's schematic for the xPLSS, the flow meter designation is FM-321 and the heat exchanger is HX-340, and the two devices comprise a single FM-HX hardware item.

Figure 1 is a photograph of an FM-HX prototype delivered to NASA in March 2020, and Figure 2 is a schematic illustrating the operation of the device. The flow meter is connected to the ventilation loop in parallel with the vent loop heat exchanger. The flow meter inlet draws gas from the inlet plenum of the heat exchanger, and the flow meter exit exhausts to the heat exchanger's exit plenum. The flow path through FM-321 has a flow resistance that is quite high compared to the heat exchanger, so that only a tiny fraction (roughly 0.1%) of the ventilation flow passes through the flow meter. This bypass flow can be used to deduce the flow rate of ventilation gas as follows:

- Nearly all the ventilation gas flows through the heat exchanger core. The heat exchanger flow produces a pressure difference between the inlet and exit plena.
- This pressure difference drives a small bypass flow of gas through the flow meter.
- This bypass gas flows across a MEMS sensor in the flow meter and generates a voltage signal that is a function of the mass flow rate of the bypass gas.
- Sensor electronics convert this voltage to a digital signal that expresses the flow in engineering units and transmit this signal to the suit's caution and warning system.
- The caution and warning system then computes the ventilation loop flow rate based on the flow meter signal, calibration equations for the flow meter, and separate measurements of the gas temperature and pressure.

The flow meter is designed to achieve high accuracy across a wide range of potential operating conditions. It must also be highly compact, replaceable in situ, and meet numerous requirements related to operation in a safety-critical spaceflight oxygen system. We have designed and built a prototype flow meter integrated with a ventilation loop heat exchanger. The device was thoroughly characterized in the laboratory and delivered to NASA for use in the first integrated xPLSS build. This paper describes the design and performance of the first flow sensor.

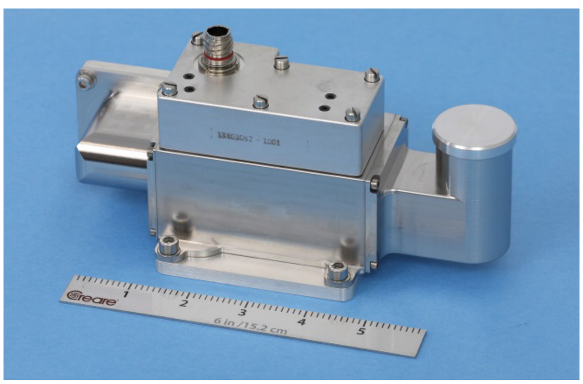

Figure 1. Flow sensor integrated with ventilation loop heat exchanger.

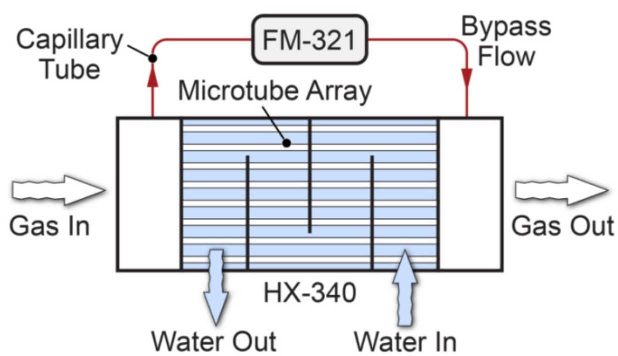

Figure 2. Schematic showing flow meter (FM-321) and ventilation loop heat exchanger (HX-340) components.

II. Need for an Accurate, Compact Flow Sensor

Although flow sensors that satisfy some of the FM-321 requirements are available commercially, they are packaged in a way that is not suitable for flight applications, and they are too large for integration with HX-340 and the xPLSS. The combination of accuracy, size, and flight requirements implies that a custom sensor is needed for the FM-321.

High Accuracy. One reason for requiring high accuracy is the fact that the xPLSS is a compact and highly integrated system. Accurate measurements of overall system performance need to be made using an integrated system, and the ventilation gas flow rate is a critical parameter needed to evaluate component performance. Measuring the flow with an external flow meter would significantly disrupt the overall system performance, so the best way to measure the flow during system development and initial checkout will be with the built-in flow meter.

As a result, the flow meter must be able to measure ventilation flow rates with a total accuracy better than 3% full-scale output over the range of 1 to 7 actual ft^3/min. (0.47 to 3.3 actual L/min.). The sensor must achieve this accuracy across a wide range of conditions that spans all modes of xPLSS operation. These modes include normal operation in a vacuum, operation when the suit is used as a hyperbaric chamber, and operation on lunar and planetary surfaces with a wide range of thermal environments. This means that the sensor must be designed to function across a temperature range of 35°F to 125°F (1.7°C to 51.7°C) and a pressure range of 3.1 to 25 psia (21.4 to 172 kPa). Note when expressed in terms of the mass flow rate of ventilation gas, this is a very wide dynamic operating range (56:1 mass flow ratio).

Compact Size. The flow sensor and associated electronics must fit within the volume left over between the vent loop heat exchanger and the OML specified for the FM-HX component. Sensors that are available commercially cannot meet this requirement.

Figure 3 is a photograph of an early prototype FM-HX that used a commercial flow sensor. The sensor and electronics are installed in an enclosure mounted above the heat exchanger. The enclosure is too large to meet the OML requirements for integration with the xPLSS, because the sensor itself is an awkward size and shape for integration with the FM-HX. Figure 4 shows the sensor and electronics with the enclosure removed The COTS flow sensor (purchased from Posifa[9]) is coupled to the heat exchanger through two capillary tubes (labelled "Bypass Flow Lines" in the photograph) and is connected to a small circuit board that conditions the output to meet NASA requirements.

Figure 5 shows a cutaway view of the current FM-HX design, showing the compact enclosure (1×2×3.44 in.) that meets the OML requirements. The custom sensor has been specially designed to fit inside this small volume.

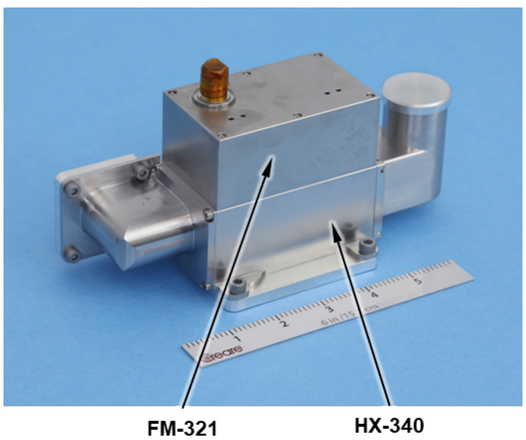

Figure 3. Base phase FM-HX does not meet the OML requirement.

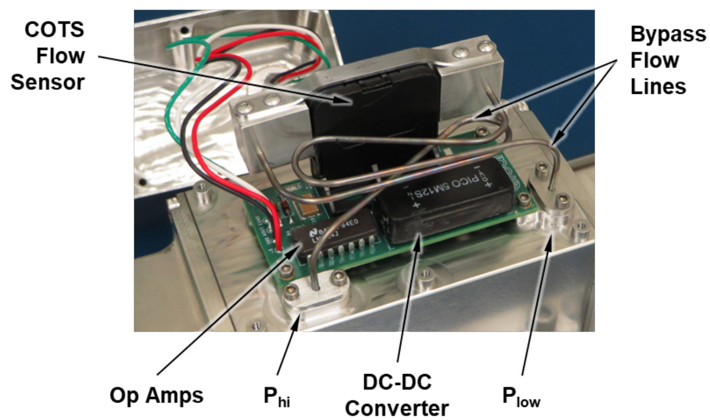

Figure 4. COTS mass flow sensor and electronics used in Base phase FM-HX.

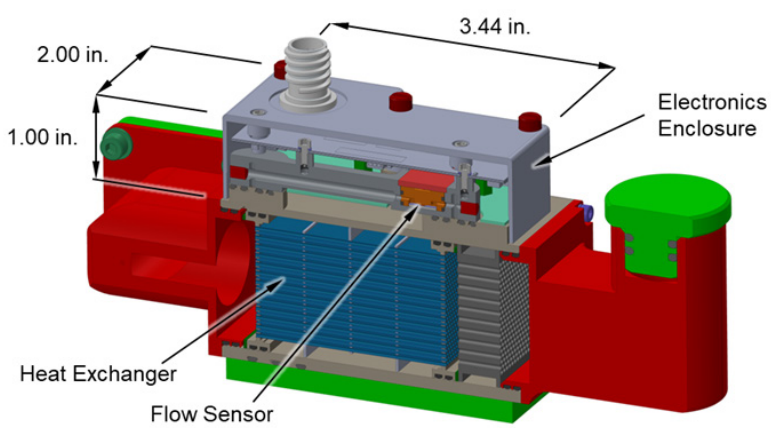

Figure 5. Current FM-HX design, showing the envelope available for the flow sensor and electronics.

[9] Posifa Microsystems Inc., San Jose, CA, www.posifamicrosystems.com

Additional Requirements and Specifications. The sensor must also be designed to function in challenging flight environments and meet numerous additional requirements:

- Material compatibility with all operating modes, including use with pure oxygen.
- Long service life and thousands of qualification and operating cycles.
- Dynamic loads for launch and operation.
- Low power consumption.
- Electrical interface requirements for xPLSS integration (physical connector, input voltage requirements).
- Electrical and ionizing radiation environment.
- Fastener and soldering requirements for assembly.
- Standard flight requirements for electronic, electrical, and electromechanical parts.

Replaceable Unit. The flow sensor, electronics, and housing are an integral assembly that can be removed from the vent loop heat exchanger using only captured mechanical fasteners. The bypass gas flow lines couple to the vent flow through two ports that line up with corresponding ports in the heat exchanger body. Each port connection is sealed with a set of captured double O-rings in the sensor body that make a face seal with the heat exchanger housing. FM-321 is therefore essentially an orbital replacement unit that can be swapped out in space if necessary.

III. MEMS Flow Sensor Design and Construction

We have designed and built a custom flow sensor comprising a commercial flow-sensing chip in a custom housing and integrated with custom, flight-qualifiable electronics. The flow-sensing element is the FS1010-C01, which is a new part available from Renesas. The FS1010-C01 uses the same die-level flow sensor device as the Renesas FS1012 series of analog gas flow sensors. The difference is that the sensor element in the FS1010-C01 is mounted on an alumina ceramic carrier and does not include any elements to shape the fluid flow over the sensor face. To complete the flow sensor, we designed a housing and flow shapers to direct the bypass flow from the HX-340 across the flow sensor.

Sensor Configuration and Operation. Figure 6 shows the MEMS thermal flow sensor. It operates on a thermal mass flow principle, in which the fluid is heated by a polysilicon resistive heater and the resulting temperature gradients upstream and downstream from the heater are monitored by thermopile sensors. The thermopiles consist of multiple aluminum-polysilicon thermocouple junctions that are fabricated in series to increase the voltage generated for a given temperature gradient. The heater and “warm junctions” of the thermopiles are fabricated on a porous silicon substrate, which provides improved thermal isolation compared to normal silicon. A multilayer silicon carbide/silicon nitride and glass coating protects the active face of the flow sensor.

With heater power applied and no flow, the temperature field across the sensor is dominated by conduction and will be symmetrical on either side of the heater (subject to small variations in device symmetry). Thus, in an ideal device at no flow, the thermopile temperature gradients on either side of the heater are identical and the thermopiles generate the same voltage. For 5 V applied to the heater of the FS1010-C01, the thermopiles generate ~120 mV each. When gas flows across the sensor face, the temperature distribution is modified by the forced convection and the temperature field skews away from the upstream thermopile (i.e., the upstream sensor is cooled), resulting in a voltage difference between the thermopiles. It is possible to use a single thermopile to sense flow in a similar way, but the differential measurement between the upstream and downstream thermopiles provides some inherent compensation for device temperature.[1] This fundamental measurement, the voltage difference, is expressed as ΔV or DV. Our custom electronics provide a scaled and offset version of DV.

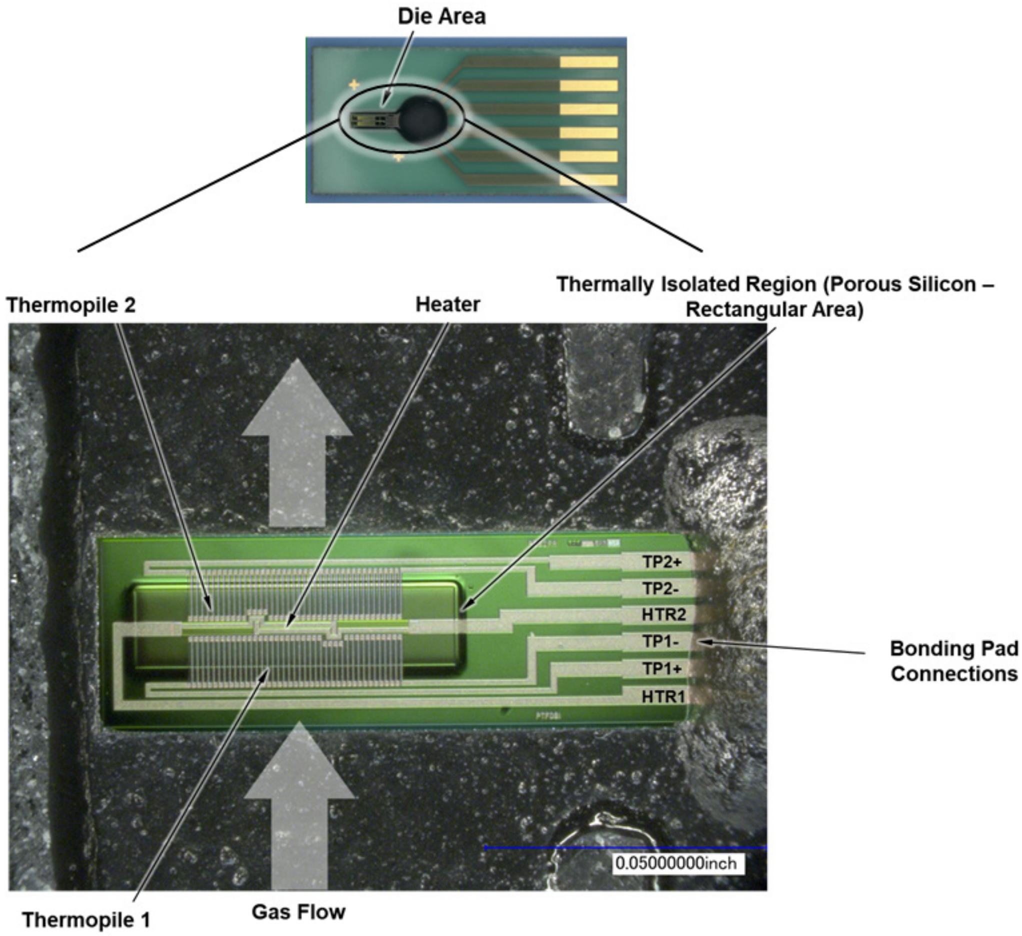

Figure 6. Image of Renesas FS1010-C01 die-level flow sensor (top) with enlargement to show details of the sensing element (bottom).

The advantage of the FS1010-C01 flow sensor is that it can be integrated with custom flow sensor packaging to meet xEMU PLSS volumetric, environmental, material, and performance requirements. Self-contained commercial mass flow sensors, such as the Posifa device used in the first prototype, also contain highly integrated electronic circuits that are not necessarily screened for high reliability and radiation tolerance. Use of the FS1010-C01 flow sensor enables the development of custom electronics to meet these program needs. Another important benefit of custom electronics is that the firmware is completely under developer control, so that NASA can apply a CMMI Level 3 software development process appropriate to safety-of-life critical applications.

Figure 7 shows the FM-321 custom flow sensor. It is designed to have pins soldered to a PCB and to be mounted on standoffs. Four standoffs from the FM-321 housing pass through the flow sensor PCB and screw into the sensor body to hold the sensor in a known position. When the FM-321 housing is placed on the HX-340, the inlet and outlet ports of the sensor mate with the bypass flow orifices using double O-ring seals. Sensitivity can be adjusted by altering the size of the flow gap over the sensor, with the goal of producing a full-scale voltage difference (DV) of ~14 mV for the maximum expected rate of bypass flow. Note that the calibration will vary depending on the gas used and its thermal properties,[1] so we expect somewhat different calibrations depending on whether nitrogen or oxygen is the test gas.

Sensor Reliability. The alumina substrate was selected by Renesas for operating temperatures up to 125°C and operating voltages up to 5V. Because the sensor housing is closely coupled thermally to the heat exchanger body and the sensor power is very small (<< 1 W), there are no reasonable conditions under which thermal expansion mismatches can cause high stresses in the sensor / carrier assembly. The sensor has been designed and demonstrated to operate reliably in normal, Earth-surface ambient conditions including particles that may be found in ordinary environments. Therefore, there is good basis for assuming that sensor performance will not be sensitive to the small number of particles that may be present in the controlled spacesuit environment, although future testing and verification should be considered as the technology matures.

The basic elements of the sensor (polysilicon heater and aluminum-polysilicon thermocouple junctions) should not be susceptible to disruption from single ionizing radiation events, but may be sensitive to accumulated radiation dose that could cause a slow calibration drift over time. No data are currently available to quantify these potential long-term effects. The development team and NASA plan to work together to investigate and assess radiation effects as the technology matures. Note that since the sensor is removeable and replaceable, the sensor unit could be changed out as part of regular maintenance if necessary.

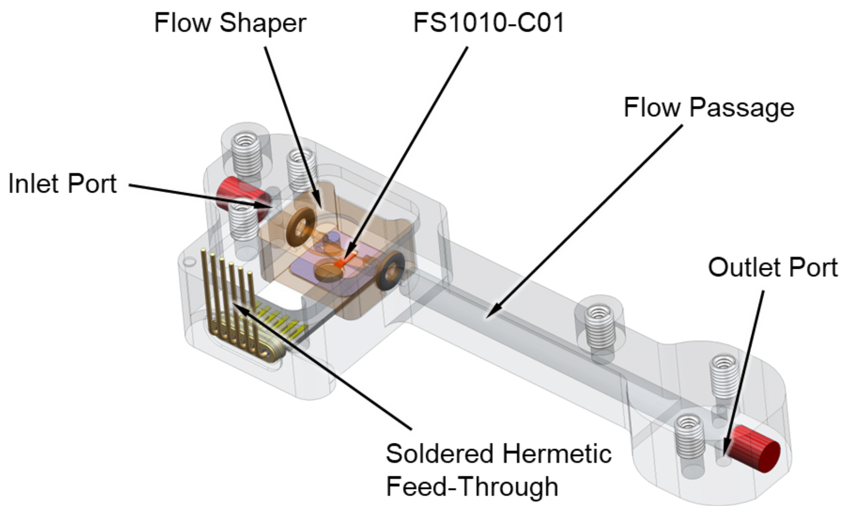

Figure 7. FM-321 custom flow sensor based on the FS1010-C01.

IV. Flow Sensor Electronics

Custom electronics are needed to power the sensor, convert sensor outputs to a format useful for the xPLSS, and meet all other NASA requirements for spaceflight operation and integration with xPLSS sensing and control systems.

Some key design decisions are driven by the very limited space available inside the FM-321 housing. Compactness is especially limiting because space-grade components, such as integrated circuits in ceramic packages and MIL-PRF-123 capacitors, tend to be bulkier than their commercial equivalents. Power consumption is also a concern. As a result, the sensor electronics are designed with streamlined functionality to conserve both real estate on the PCB and electrical power. For example, in the rapid-turn units, the 5 VDC power is applied directly to the ~280 Ω heater due to size and efficiency constraints, rather than being converted to a lower voltage like 3 VDC. In the DVT units, the 5 VDC input power will be applied to the sensor's heater through a soft-start circuit with filtering and surge limiting. Ideally the heater would be operated under feedback control based on heater power or temperature,[1,2] but due to size and efficiency constraints we settle for monitoring the heater's power consumption.

Figure 8 shows a simplified schematic of the flow-sensing circuit, and Figure 9 is a simplified solid model showing the entire sensor and electronics package. The electronics package is based around a Microchip ATmegaS64M1-KH-SV 8-bit processor. The processor is radiation tolerant and produced in a hermetically sealed package with a reported reliability level that is comparable to QML-V integrated circuits. The processor reads the sensor output, performs computations, generates a serial data stream representing the mass flow rate, and sends the data stream to the caution and warning system. Inputs to the processor include a scaled and offset version of sensor DV, heater voltage and current, and PCB temperature. The "rapid-turn" version of the flow sensor used an external 12-bit ADC for the measurements, but we have determined that the 10-bit ADC aboard the ATmega processor can provide sufficient accuracy for the DVT sensors when configured properly. In the current rapid-turn version, the processor simply passes DV, heater power, and temperature measurements to the caution and warning system. The current plan for the DVT electronics is to convert the measured voltage difference to the bypass mass flow rate aboard the sensor, then report this flow rate in engineering units to the caution and warning system. In this mode of operation, the FM-321 units become swappable because each unit is calibrated to yield an accurate ΔP measurement across the heat exchanger, which can be converted to the vent loop flow rate in the caution and warning system.

Based on testing to date, open-loop (constant voltage) control of heater power has proven adequate. The resistance of the heater increases with temperature, which provides some feedback stabilization. Looking ahead, the latest hardware design for DVT units to be delivered in 2020 includes overvoltage protection and current limiting features to mitigate potential problems with fault conditions.

V. Flow Sensor Performance

Measurements of sensor performance across a wide range of conditions that simulate operation in the xPLSS show the potential for high-accuracy measurement of the ventilation flow rate. These tests were run using a separate-effects test rig in which the sensor was coupled to a high-precision syringe pump instead of the vent loop heat exchanger. The performance when coupled to the vent loop heat exchanger shows degraded accuracy at higher static pressures. Work is under way to identify the cause of these performance changes and to modify the custom sensor to achieve high performance at all specified conditions.

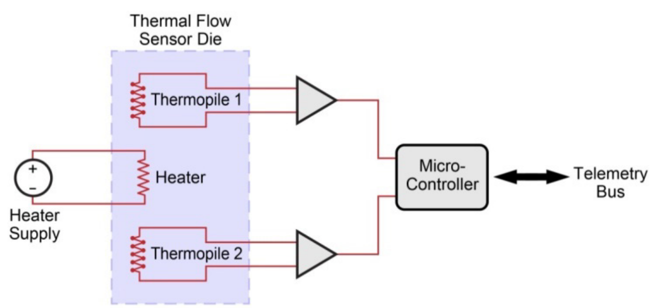

Figure 8. Basic flow measurement technique.

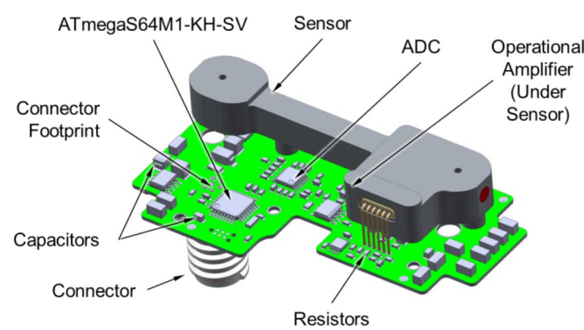

Figure 9. Sensor and electronics layout for rapid-turn sensor.

Figure 10 shows the overall test setup. Gas flow through the sensor is measured and controlled using a precision syringe pump that provides flow rates up to 100 cm^3/min. The syringe pump is plumbed directly to an aluminum test block that contains the flow sensor. The sensor is coupled to a small PCB that allows electrical access to the circuit elements for powering the heater and monitoring the thermopile voltages. Test temperature is controlled by circulating water through the block from a laboratory chiller (water lines are visible at the bottom center of the photo).

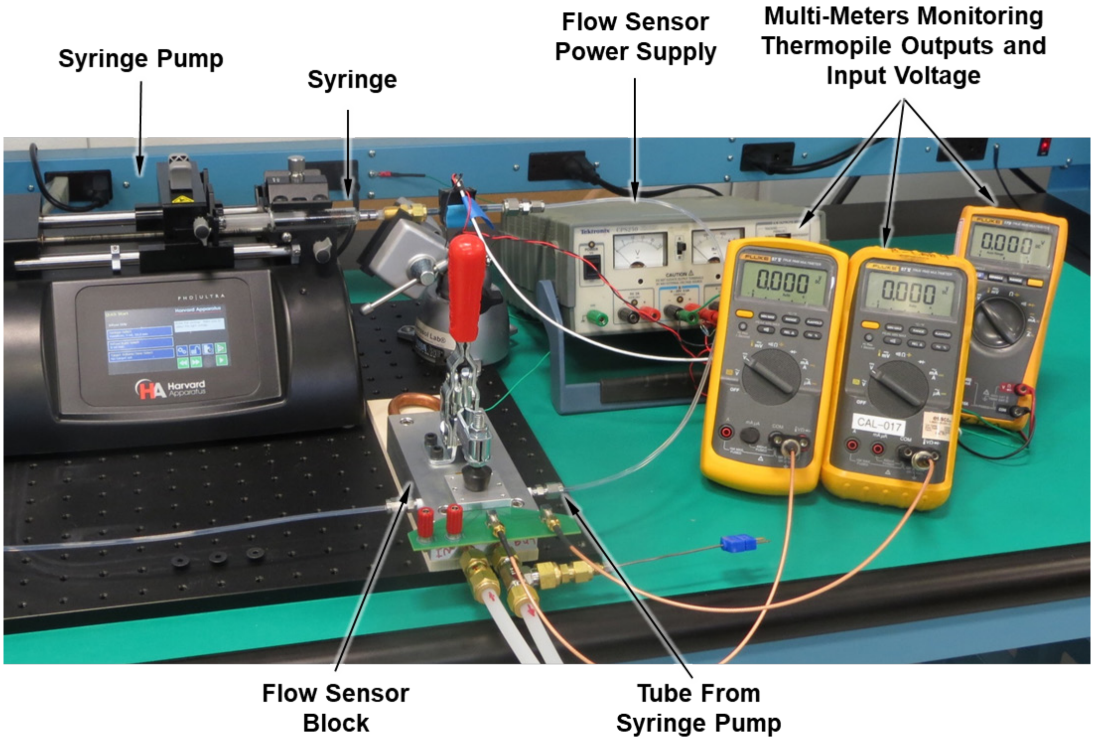

Figure 10. Syringe-pump test setup.

Figure 11 shows a test sensor installed in the test block. The sensor itself is located on a small PCB that enables electrical access to the sensor components. Nitrogen enters and leaves the test block through the fittings visible on the left- and right-hand sides of the photo. Passages inside the test block feed the nitrogen into the test chamber, where a machined block (not shown) forces the flow through a prototypical passages above the thermal sensing element.

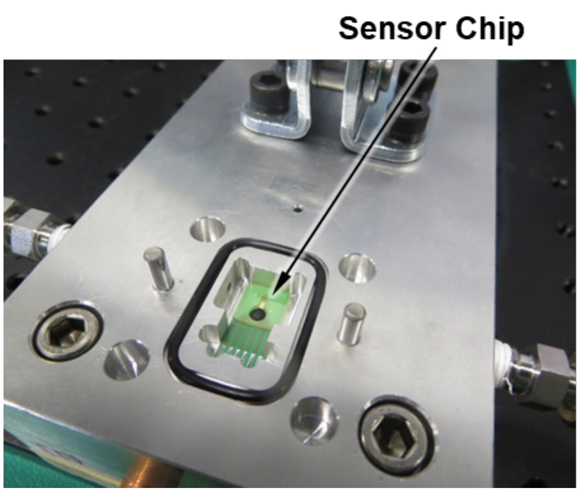

Figure 11. Flow sensor chip installed in syringe pump test block.

Figure 12 shows the sensor performance measured in the syringe pump rig. These data span pressures that range between 4.3 and 25 psia and temperatures that range from 6°C to 25°C, consistent with the operating range of the FM-321. Results from this series of tests show that the sensor performance is highly consistent across the entire range. The difference in voltage generated by the thermopiles in the sensor is a single-valued function of the mass flow rate of nitrogen, which is consistent with the expected performance of a thermal flow sensor.

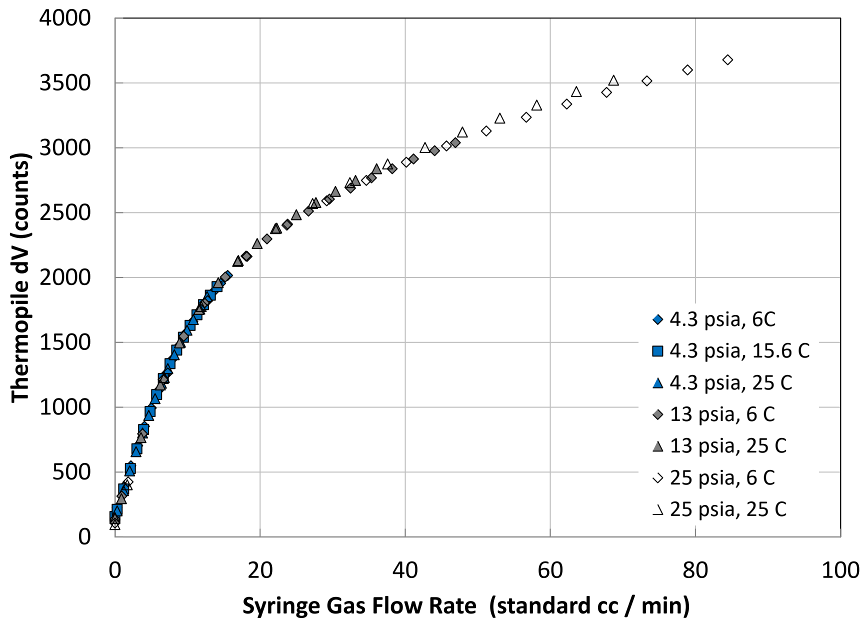

Figure 12. Extremely consistent output across operating range when tested with syringe pump.

After characterizing a sensor in the syringe pump rig, we assembled the integrated FM-HX by installing the sensor in a custom housing coupled to the vent loop heat exchanger and integrated with the flow sensor electronics package. Figure 13 shows the sensor output in ADC counts as a function of the simulated ventilation gas flow at 4.3 psia and across the range of 0 to 70 std L/min. At this operating pressure (corresponding to normal suit pressure), this flow range corresponds to 0 to 8.8 actual ft^3/min. and covers the range of ventilation loop flow. The sensor output at 4.3 psia is highly consistent and matches the expected output based on the syringe pump results shown in Figure 12.

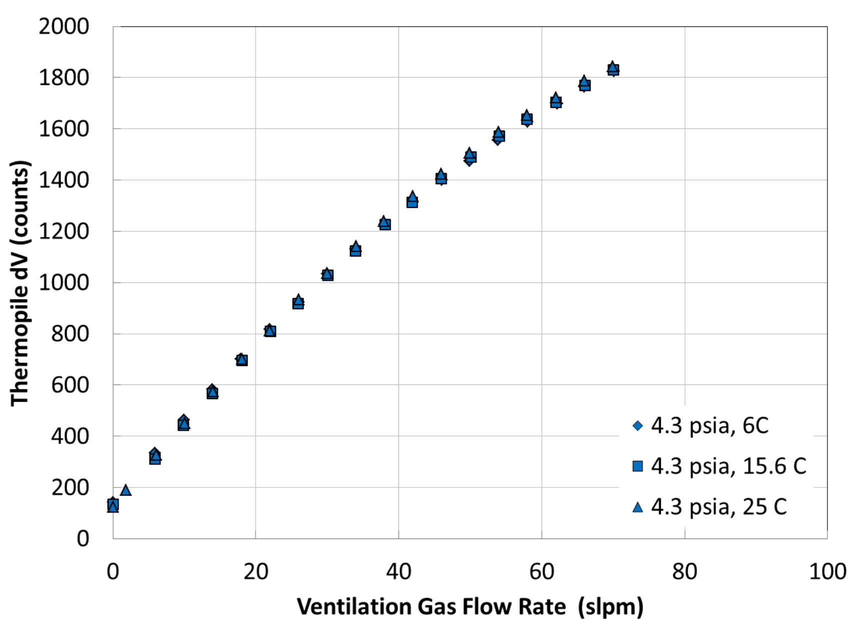

Figure 13. Output at low pressure when installed with vent loop heat exchanger.

Further testing of the integrated FM-HX unit showed that the sensor output deviated from the syringe pump data when operating pressures of 13 and 25 psia. The critical difference between the two test setups (syringe pump vs.

integrated FM-HX) is the flow boundary condition for the sensor. The syringe pump is a positive displacement device that fixes the mass flow rate through the sensor. In the FM-HX, however, it is the pressure drop across the sensor that is fixed by the large flow of gas through the heat exchanger. Results show that at higher pressures, where the mass flow rate through the sensor and the Reynolds number are relatively high, there is more than one gas flow pattern and flow rate that correspond to the same pressure drop across the sensor. Preliminary data suggest that under these conditions, the flow is unstable and shifts between these patterns, causing the flow rate and sensor output to fluctuate.

Figure 14 shows the approach for converting sensor output to vent gas flow rate and how the sensor response at higher pressure affects accuracy. The left-hand plot shows how the inverse of the sensor calibration curve can be used to calculate the pressure drop across the heat exchanger based on the sensor output. The right-hand plot shows data for the pressure drop across the heat exchanger as a function of the volumetric flow rate of ventilation gas. The basic process for estimating the vent loop flow is indicated by the arrows in the figure: (1) use the left-hand plot to convert the sensor output to pressure drop, and (2) use the right-hand plot to convert the pressure drop across the heat exchanger to the actual volumetric flow rate of gas through the heat exchanger.

If the sensor behaved the same way in the FM-HX as it did in the syringe pump tests, then this would be a highly accurate calculation. The error inherent in the HX pressure drop to flow rate estimation is only about 3% based on the data shown in the right-hand plot of Figure 14 and including second-order corrections based on operating pressure. However, due to the inconsistent sensor response at high pressure, current data show a range of possible pressure losses corresponding to the same sensor output. This increases the flow estimation error to about 1 actual ft^3/min. or ~13% of full scale using the current data. Work is currently under way to diagnose the cause of the flow instabilities at higher pressure and to redesign the custom sensor to provide a more consistent output.

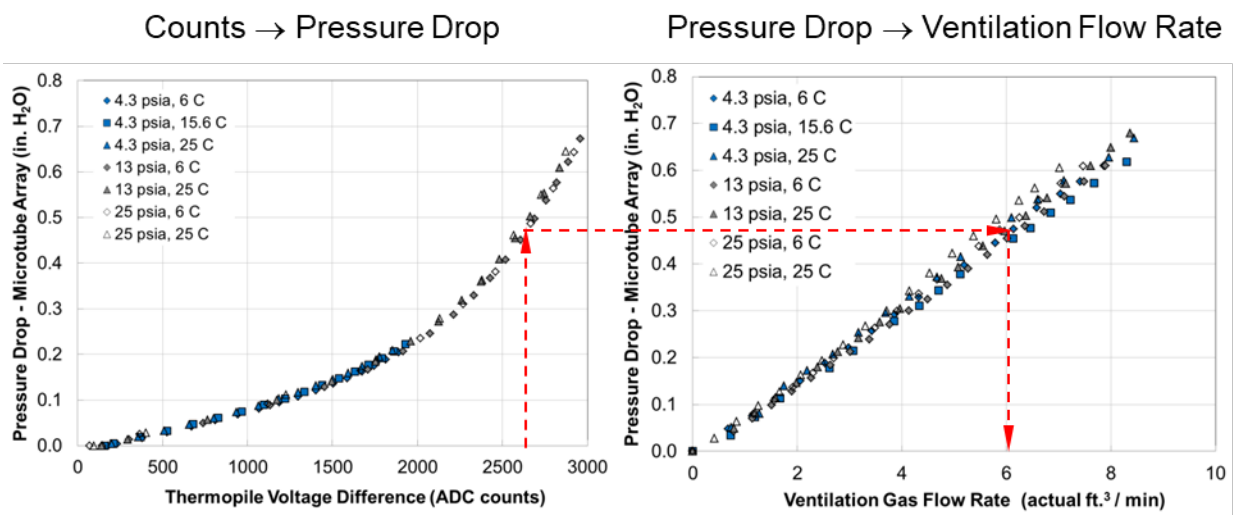

Figure 14. Calculating ventilation loop flow rate from sensor output.

VI. Forward Work and Conclusions

Work to date has shown the feasibility of using a custom, compact, high-accuracy flow sensor that meets requirements for operation in the xPLSS to measure the flow rate of ventilation gas. The sensor uses a commercial thermal flow-sensing chip, a custom housing for the sensor, and a custom electronics package for control, measurement, and signal processing. All components must ultimately meet requirements for spaceflight and xPLSS integration. The most recent sensor includes commercial electronic components that mimic the performance of flight-worthy components.

The next-generation electronics for DVT will be built exclusively from components that either are already flight-qualified or can be shown to meet all the specified requirements. The next-generation device will also incorporate a redesigned flow sensor that incorporates lessons learned from the first build to provide a more stable output at high pressure and meets accuracy requirements across the entire range of xPLSS operation.

Acknowledgments

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References

[1] Kalstas, G., Nassiopoulos, A. A. and Nassiopoulou, A. G., "Characterization of a Silicon Thermal Gas-Flow Sensor With Porous Silicon Thermal Isolation," *IEEE Sensors Journal*, Vol. 2, No. 5, 2002, pp. 463–475.
[2] van Oudheusden, B. W., "Silicon Thermal Flow Sensors," *Sensors and Actuators A*, Vol. 30, Jan 1992, pp. 5–26.