NOISE-CON 2023
May 15-18 | Grand Rapids, MI

Quiet Spacecraft Cabin Ventilation Fan: Aerodynamic Measurements Results

David B. Stephens[1] and L. Danielle Koch[2]
NASA Glenn Research Center
21000 Brookpark Road
Cleveland OH 44135

ABSTRACT

A spacecraft cabin ventilation fan suitable for aerodynamic and acoustic ground tests was designed and two copies of the fan assembly were fabricated. Both fans were tested for aerodynamic performance and acoustic levels in the NASA Glenn Research Center Acoustical Testing Laboratory. A new test rig for small axial flow fans was designed to accommodate the instrumentation and back-pressure adjustments. Measurements acquired were from: static pressures for measuring performance, a 72-channel in-duct microphone array, external microphone measurements for acoustics, and inter-stage hot wire measurements of the fan wake. This report documents the aerodynamic measurements as part of a series of reports.

1. INTRODUCTION

Advances in modern society such as manned spaceflight sometimes come with significant penalties, such as an uncomfortable noise environment. People need clean air to breathe and a quiet place to work, whether they are living on the surface of the earth or inside an aircraft or spacecraft. What we know about quiet high-performance air moving devices and ventilation systems on earth can help us to create systems that perform well in spacecraft. Likewise, what we learn about creating atmospheric revitalization systems for long duration space exploration missions can help us to improve air moving devices and ventilation systems on earth, too. Fans are critical components in spacecraft atmospheric revitalization systems to maintain the chemical and biological composition of the gases at levels that can sustain human life.

Beginning in 2006, the NASA Glenn Research Center (NASA GRC) Acoustics Branch has been conducting research to examine the aerodynamic and acoustic performance of small fans. A central research question was formed: Could the tools and techniques that had primarily been used to develop quiet and efficient fans for aircraft propulsion systems could be put to broader use to support long duration human exploration missions? A fan was designed by Tweedt [1], first adapted for additive manufacturing in plastic using stereolithography [2] and then in Aluminum using laser powder bed fusion [3]. The result is termed the Quiet Space Fan (QSF). This paper describes the aerodynamic results from this test campaign. A photograph of the metal fan is given in Figure 1 with an annotated diagram given in Figure 2. Companion papers present the acoustic performance [4], the acoustic design [5], the wake measurements [5], vibration characteristics [6], as well as a paper describing the motivation behind the overall effort [8].

[1] david.stephens@nasa.gov
[2] l.danielle.koch@nasa.gov

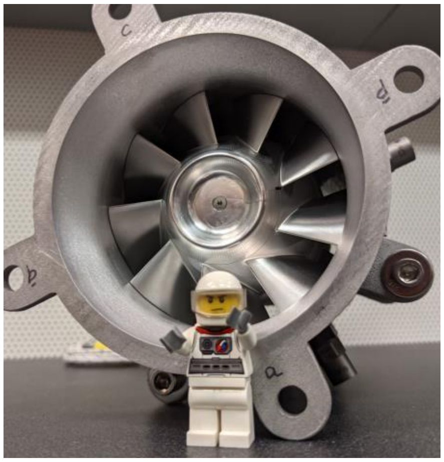

Figure 1: Quiet Space Fan inlet side showing rotor and a minifig

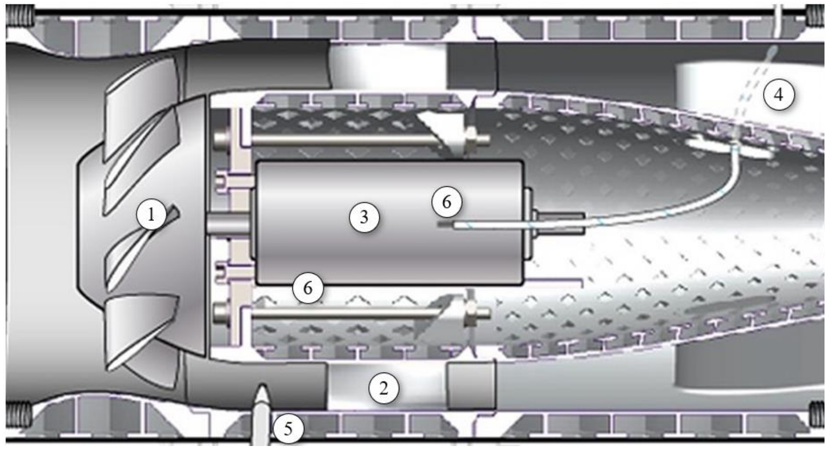

Figure 2: Cutaway of fan unit. Diagram indicates 1. Rotor, 2. Stator, 3. Motor, 4. Strut, 5. Hot wire probe, 6. Thermocouple

2. TEST RIG

A test rig was designed and assembled so that small fans could be throttled through their operating envelopes so that aerodynamic and acoustic measurements could be acquired. The rig was operated in the Acoustical Testing Laboratory at NASA GRC [4] [5]. The acoustic chamber features an adjacent control room allowing safe testing of the fan prototype aerodynamics while also enabling radiated sound measurements, which are presented in a companion paper.

2.1. Standards

The test rig design largely followed ISO 5801 third edition [5] for an aerodynamic test bed. ASHRAE 68 [6] was also a valuable reference and applicable. Similarly, ISO 5136 second edition [7] was used to guide the design and methods for noise testing of a ducted fan. The test rig size was constrained slightly by the dimensions of the test chamber, but this is expected to be a minor effect. The completed test rig is shown in Figure 3.

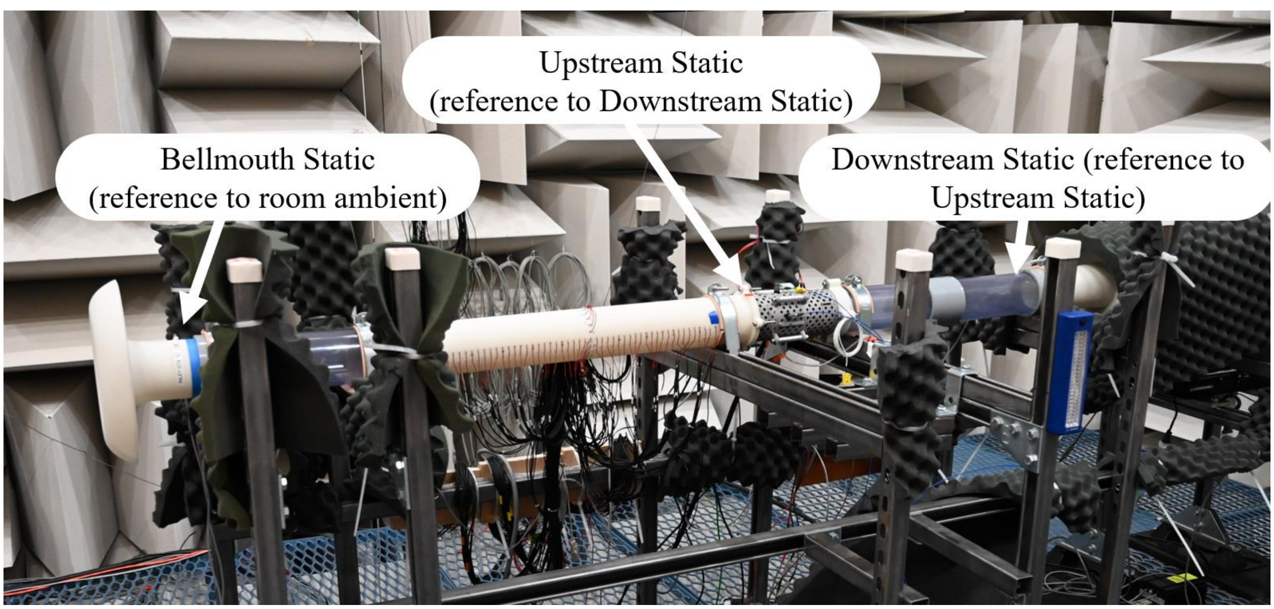

Figure 3: Test rig showing bellmouth and mode array

2.2. Bellmouth

A bellmouth inlet was designed for the 3.5 inch duct section, based on the ISO standard recommendations and prior experience. A profile of the intersection of two elliptical shapes was chosen for the lip and thickened into a solid part. The inlet static pressure was simulated using Solidworks Flow Simulator software. A 150 CFM airflow was pulled through the simulated bellmouth and the static pressure on the wall was evaluated. The straight part of the duct was the logical place to put a wall static tap, but the availability of easy to use CFD confirmed that about an inch downstream of the end of the curvature was suitable for a wall tap. The size of the part turned out to be a good fit for printing in SLA as a single piece. The inlet mounted on the test rig is shown in Figure 3.

2.3. Throttle

A critical part of testing the QSF was applying an appropriate amount of flow resistance to the duct in order to push the fan to the design point on the fan map. This system also needed to be adjustable so that different setpoint could be achieved. The adjustment should be controlled remotely so that test points could be varied without entering the test chamber or interrupting the test. A Velmex BiSlide linear actuator and controller were already available and were determined to have more than sufficient range of motion and load capability. A string potentiometer was used to measure the position of the BiSlide. A few accessories were procured, and a throttle cone was 3-D printed in SLA. The cone was inserted into the outlet of the anechoic termination to block airflow. The throttle assembly is shown in Figure 4.

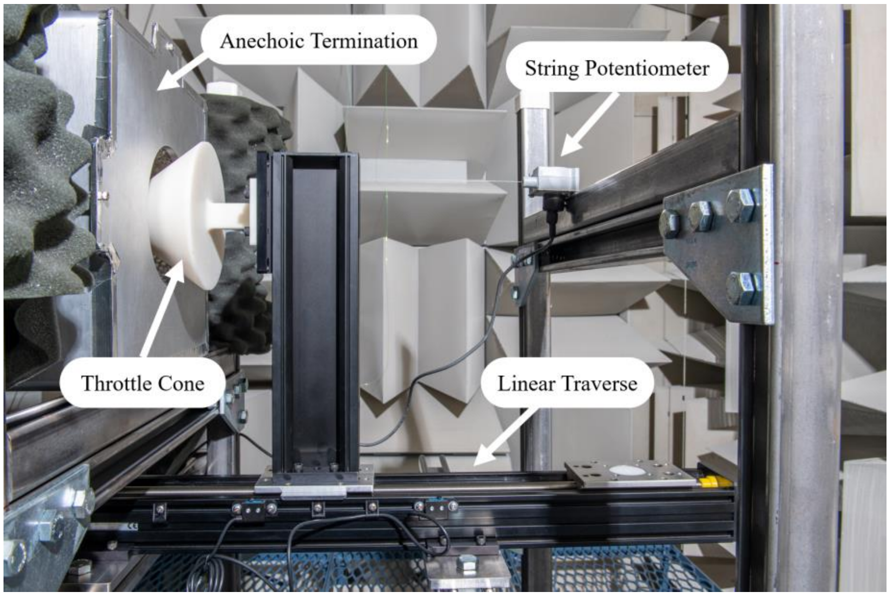

Figure 4: Throttle assembly on downstream end of test rig

A Labview program was developed to control the throttle, which communicates to the motion controller by requesting motor steps in a serial command string. The linear motion is by a lead screw with pitch of 1 mm per rotation driven by a stepper motor with 400 steps per revolution. Prior to any testing experience, this seemed like sufficiently small steps. The test rig operator inserted or withdrew the throttle to achieve the desired fan back-pressure. In practice, this was sufficiently usable for a manually conducted test. If many test runs were to be conducted, either a feedback-loop could be used to set a precise backpressure or a look-up table could be generated.

2.4 Pressure Instrumentation

To quantify the aerodynamic performance of the QSF, steady pressure measurements were used. Duct airspeed was calculated from the difference between room ambient pressure and a static tap in the throat of the inlet bell mouth. A second airspeed measurement was calculated from a pitot-static probe inside the duct, upstream of the fan. This in-flow probe is a potential source of unwanted noise, as the wake from the probe causes turbulence which convects into the fan blades. To eliminate the extraneous noise source, the probe was removed during acoustic testing and flow measurement relied on the bellmouth static tap previously described. The third pressure transducer measured the pressure rise with static taps on each side of the fan. The first two units were 0-1” H_2O range and the third was 0-15” H_2O range. The largest pressure differential measured by the static tap was 0.74 inches H_2O, corresponding to a wide-open throttle and 12,000 RPM fan speed. This was calculated to be approximately 220 CFM of air. The downstream static tap location initially selected was found to be too close to the fan outlet. Presumably it was influenced by a flow irregularity instead of experiencing steady pipe flow. The static tap was moved far downstream, and a consistent set of data was then acquired. The largest pressure differential measured by the fan pressure rise static taps was 4.0 inches H_2O, at 12,000 RPM and 120 CFM.

2.5 Safety Instrumentation

The motor temperature was monitored with a thermocouple, bonded to the motor casing before the fan was assembled. A pair of accelerometers were mounted to the exterior of the fan casing and used to monitor motion of the fan during operation. Current to the motor controller to drive the fan was measured by a current transducer with the positive 48-volt wire passing through it. Rig data was recorded with a National Instruments Compact DAQ ethernet chassis (NI cDAQ-9188) and a computer running LabVIEW 2020 software with a customized virtual instrument developed by the authors.

2.6 Test Procedure

The test procedure used for making a fan map was to set the throttle to be wide open and then set the fan to the desired speed. The airflow reaches steady-state in a matter of seconds. This condition is nearly unloaded. A small amount of pressure rise is measurable and causes airflow, but the fan is very far from the design point. The throttle can then be closed to achieve either the desired flow rate or pressure rise corresponding to the test plan. For test reported here, the throttle was closed until the airflow reached a multiple of 10 CFM. This measurement was taken, and the throttle was closed again until the next multiple of 10 CFM. The test was repeated until the fan was in a deep stall. Using this method, the pressure rise becomes a dependent parameter.

3. RESULTS

In total, approximately 150 GB of data was acquired during the test. This includes both steady-state data such as pressures and temperatures, along with unsteady data like microphones and hot wires. Post-processed data from the microphone mode array measurement and unsteady hot wire data sets are part of companion papers in this conference. The majority of the steady-state data is presented in the following subsections.

3.1. Fan Map

Operating the SQF under throttle was one of the main objectives of the present task. The fan design was based on achieving a significant pressure rise. Without a throttle, the flow lines through the system differ significantly from the design intent. Without a throttle, the fan operates on the far right side of the fan map in a wide-open condition with minimal airflow resistance. This is the point where the fan moves the most air, but at minimal pressure rise. In a complicated ventilation system, with filters and baffles and such, the system restrictions require significant pressure rise from the fan. On the other hand, with too much restriction the fan stalls and moves less flow with smaller pressure rise. The noise increases and the efficiency decreases with no more air or pressure rise than was available at lower restriction values. The specific fan design affects the shape of the fan speed line, including slope, maximum pressure rise point and effect of stall. The QSF was designed to produce 3.64 inches of water pressure rise at 150 CFM of airflow at 12,000 RPM. The measured performance was quite close to this, with 3.48 inches of water at 150.6 CFM. With the throttle wide open, the observed pressure rise was 0.52 inches of water and the airflow was 220.4 CFM. Peak pressure rise at was measured as 4.0 inches of water at 120.7 CFM. Lower fan speed conditions were also measured. A fan map for three fan speeds is shown in Figure 5. A map was made from the COTS fan operating at similar design points and this is shown in Figure 6. The corresponding radiated sound pressure level (SPL) as a function of flow rate is given in the companion paper (Figure 7 of [4]).

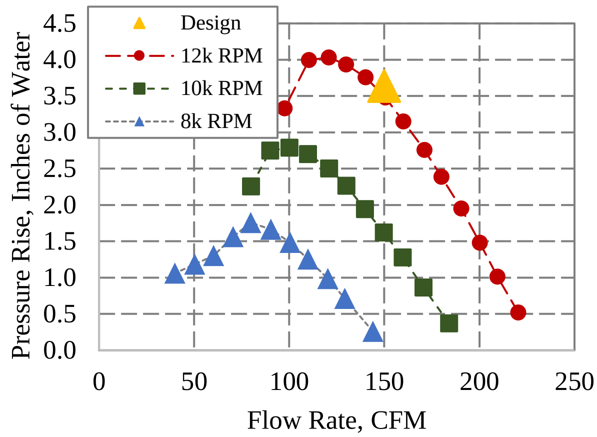

Figure 5: Fan map of QSF S/N 2

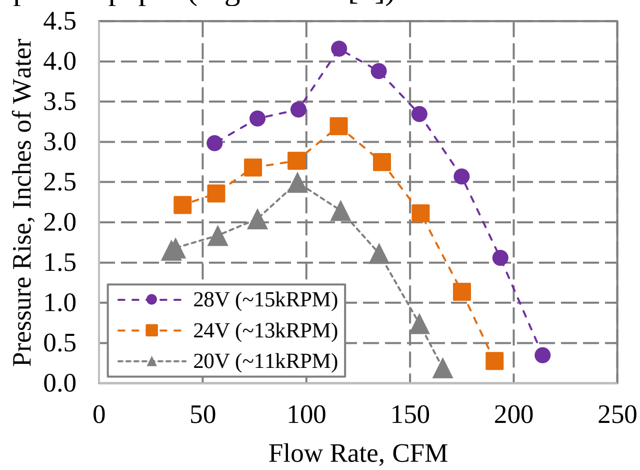

Figure 6: Fan map of COTS fan

3.2. Electrical Performance

The DC current to the motor controller was measured. Current was at a maximum of 1.73 Amps when the fan was at the design point of 150 CFM at 12k RPM. Compared to this value, the free air current was about 75%, or 1.25 Amps. This trend of peak power consumption occurring between wide open and fully closed throttle was consistent for the other speeds measured. As shown in Figure 7, this is approximately where pressure rise stops being linear with flow rate. At flow rates lower than those for peak pressure rise, the current demand by the controller drops off sharply, especially at 12k RPM. At 8k RPM, the current does not drop off as dramatically and does not fall below 0.2 Amps. This is likely because a certain amount of current is required to run the controller.

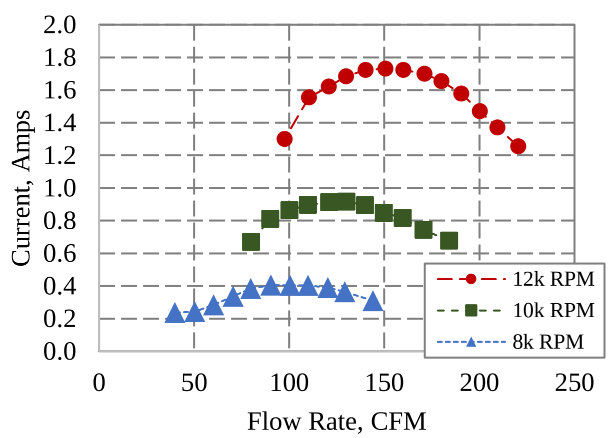

Figure 7: QSF current draw into controller

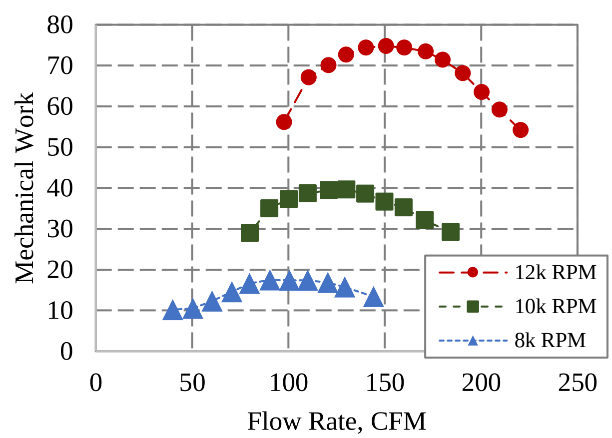

Figure 8: Motor work based on power supplied and assumed 90% efficiency

Power to the motor controller is calculated from the current provided to the controller times the voltage, which was 48 Volts for the QSF and varied for the COTS fan. The mechanical work was estimated given 90% efficiency and the power to the motor controller. The result in Watts is given in Figure 8.

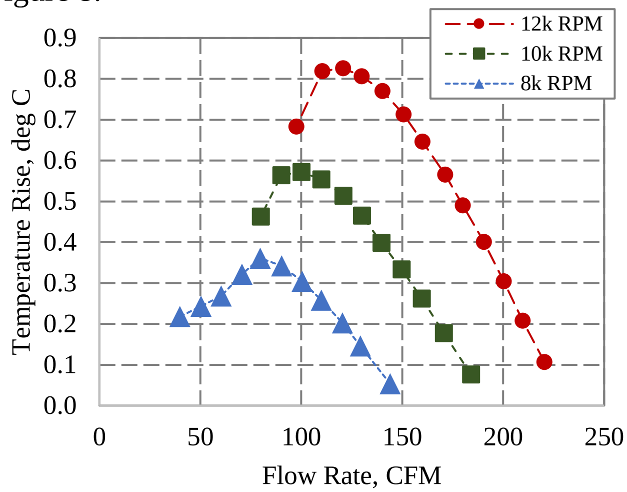

Figure 9: Calculated isentropic temperature rise to achieve measured pressure rise.

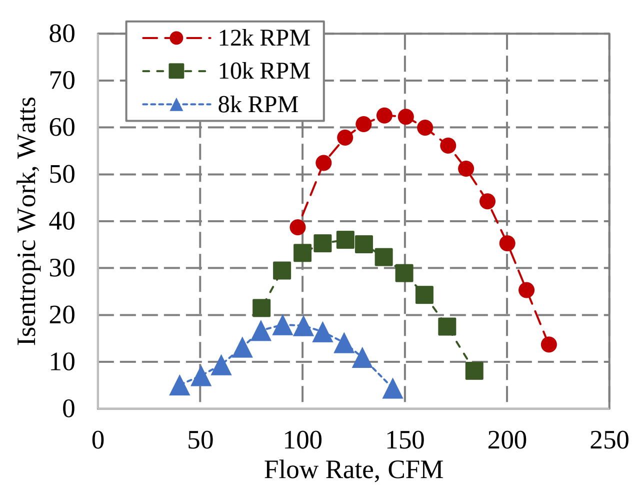

Figure 10: Calculated work to achieve measured pressure rise.

3.3. Aerodynamic Performance

The temperature rise generated by a fan is needed to properly calculate its efficiency. For fans generating a small pressure rise, the corresponding temperature rise is very small and therefore hard to measure. Measuring temperature rise in increments of less than 0.1°C was considered beyond the scope of the present project. One alternative to measuring the temperature is to assume the process occurs at constant entropy and calculate the isentropic temperature rise using the pressure rise,

$$dT = T_1\left(\frac{p_2}{p_1}^{\left(\frac{\lambda-1}{\lambda}\right)} - 1\right)$$

Where:

p_2 is the pressure in the duct downstream of the fan
p_1 is the pressure upstream of the fan,
T_1 is the upstream temperature, and
γ is the ratio of specific heats for air, 1.4 for the present calculation.

Approximate values of 25°C and 101.325 kPa were used for ambient conditions in this calculation, which have a very small impact on the result. The isentropic temperature rise is given in Figure 9. An isentropic work calculation is given as the temperature rise times the mass flow. The mass flow is estimated by the duct velocity, cross sectional area and density of air at standard day conditions. The work required if the fan were isentropic is given in Figure 10. One measure of efficiency is thus the ratio of electrical power over isentropic power. This is given in Figure 11 for the QSF and Figure 12 for the COTS fan. Efficiency for the QSF at design point is 75% compared to the COTS fan at 42%. The QSF has a number of advantages, including an aerodynamic spinner and long diffuser. The large form factor external motor controller may be more efficient also, although its power consumption is included in the measurement. Finally, the QSF was designed specifically to have a high efficiency at 150 CFM and 12k RPM.

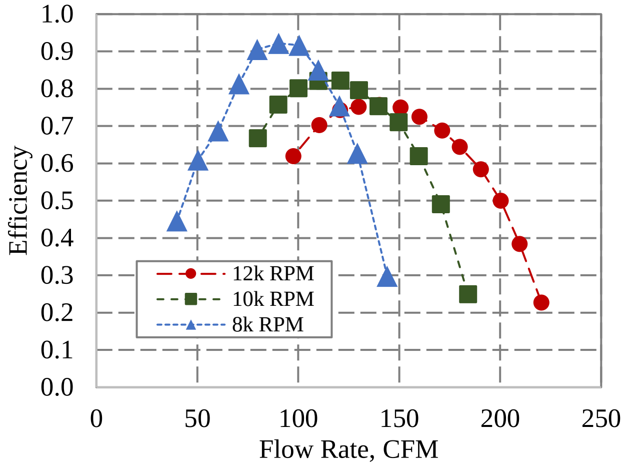

Figure 11: QSF efficiency calculated as ratio of isentropic to electrical work

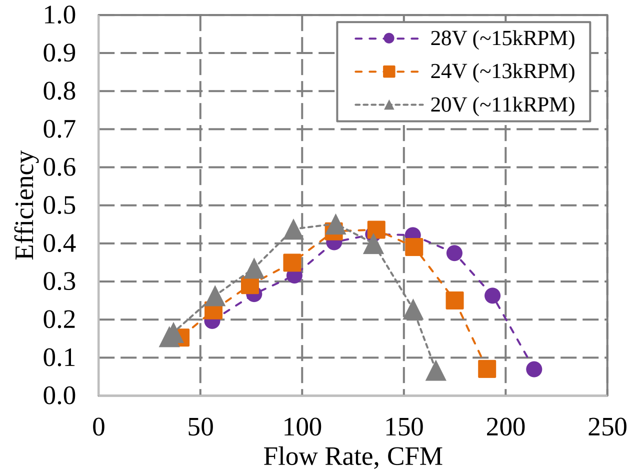

Figure 12: COTS fan efficiency calculated as ratio of isentropic to electrical work

4. CONCLUSIONS

The GRC Quiet Space Fan design developed in 2010 was adapted for manufacturing in metal using modern 3-D printing methods. Two fan assemblies were built and tested for aerodynamic and acoustic performance. Results from post-processing of the mode array measurement and hot wire data sets is given in companion papers to this report. The aerodynamic performance was measured to essentially match design intent, making 96% of the expected pressure rise at design flow rate. This performance discrepancy could be related to measurement uncertainty, design assumptions, secondary losses or the relatively rough surface finish on the printed parts. For the purposes of a ventilation fan, the workflow is shown to produce a customized fan that satisfactorily meets the design intent. The preliminary conclusion is affirmative, advanced turbomachinery design methods can be used to produce a satisfactory custom ventilation fan.

5. ACKNOWLEDGEMENTS

This work is funded under NASA Advanced Exploration Systems, ISS Habitation, Environmental Control and Life Support System. We gratefully acknowledge GRC’s Dan Sutliff, Jonathan Goodman, Rebecca Buehrle, and Tony Shook contributions in design and analysis support. Johnson Space Center’s Christopher Allen and Christopher Matty provided overall guidance and integration.

6. REFERENCES

[1] D. L. Tweedt, "Aerodynamic Design and Computational Analysis of a Spacecraft Cabin Ventilation Fan NASA TM-2010-216329," December 2010.

[2] L. D. Koch, C. A. Brown, T. D. Shook, J. Winkel and J. S. Kolacz, "Acoustic Measurements of an Uninstalled Spacecraft Cabin Ventilation Fan Prototype NASA TM-2012-217692," September 2012.

[3] D. B. Stephens, J. M. Goodman, R. A. Buehrle, A. Mirhashemi, L. D. Koch, T. D. Shook, D. L. Sutliff, C. S. Allen and C. M. Matty, "Highlights of Aeroacoustic Tests of a Metal Spacecraft Cabin Ventilation Fan Prototype," in *NOISE-CON*, Lexington, Kentucky, USA, 2022.

[4] D. L. Sutliff, "Quiet Spacecraft Cabin Ventilation Fan: Acoustic Measurements Results," in *NOISE-CON 2023*, Grand Rapids, Michigan, USA, May 15-18, 2023.

[5] L. D. Koch, "A Study of Preliminary Design Methods for Low Noise Fans," in *NOISE-CON 2023*, Grand Rapids, Michigan, USA, May 15-18, 2023.

[6] A. Mirhashemi, "Quiet Spacecraft Cabin Ventilation Fan: Wake Measurements Results," in *NOISE-CON 2023*, Grand Rapids, Michigan, USA, May 15-18, 2023.

[7] D. B. Stephens, J. M. Goodman, T. D. Shook and L. D. Koch, "Quiet Spacecraft Cabin Ventilation Fan: Vibration Measurements Results," in *NOISE-CON 2023*, Grand Rapids, Michigan, USA, May 15-18, 2023.

[8] C. S. Allen, "Quiet Spacecraft Cabin Ventilation Fan: Motivation and Context," in *NOISE-CON 2023*, Grand Rapids, Michigan, USA, May 15-18, 2023.

[9] B. A. Cooper, "NASA Glenn Research Center Acoustical Testing Laboratory," *The Journal of the Acoustical Society of America*, vol. 109, no. 5, pp. 2328-2328, 2001.

[10] D. M. Podboy, J. H. Mirecki, B. E. Walker and D. L. Sutliff, "Recent improvements to the acoustical testing laboratory at the NASA Glenn Research Center (NASA/TM-2014-218110)," NASA, 2014.

[11] ISO 5801, "Fans - Performance testing using standardized airways," International Organization for Standardization, 2017.

[12] ASHRAE Standard Project Committee 68, "Laboratory Method of Testing to Determine the Sound Power in a Duct," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, Atlanta, GA, 1997.

[13] ISO 5136, "Acoustics - Determination of sound power radiated into a duct by fans and other air-moving devices - In-duct method," International Organization for Standardization, 2003.

[14] D. L. Sutliff, "Metal Spacecraft Cabin Ventilation Fan: Acoustic Measurements Results," in *NOISE-CON 2023*, Grand Rapids, Michigan, USA, May 15-18, 2023.