Further Development of a Regenerative Flow Compressor

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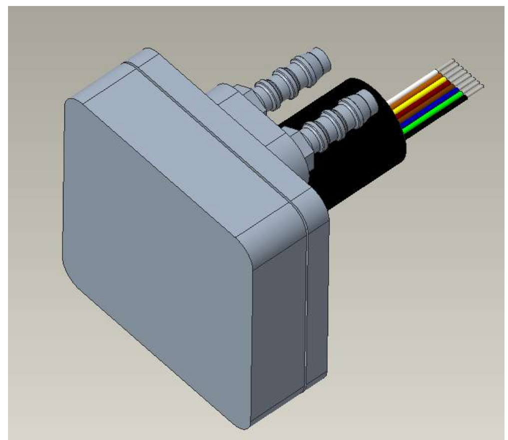
Scope/Introduction

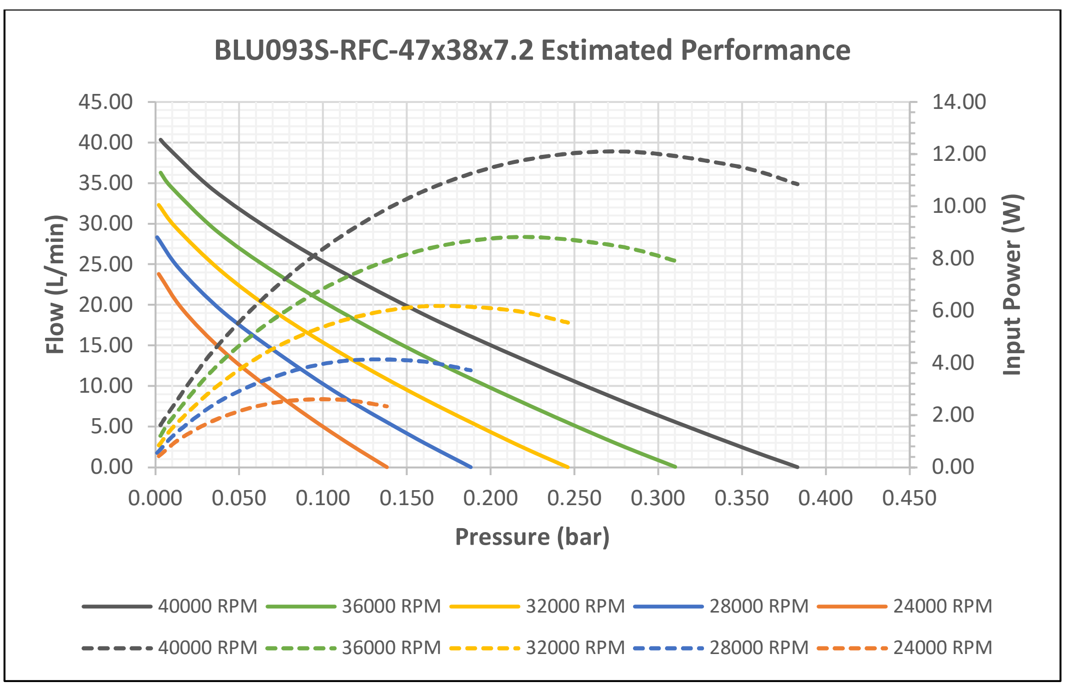
This report summarizes the continued development and testing of a prototype regenerative flow compressor (RFC). It will only focus on the development of the high-speed, machined aluminum RFC. For background information on the design theory of the RFC and prior development, the reader is advised to review the original white paper on this subject titled *Development of a Regenerative Flow Compressor*, dated 18 December 2020.

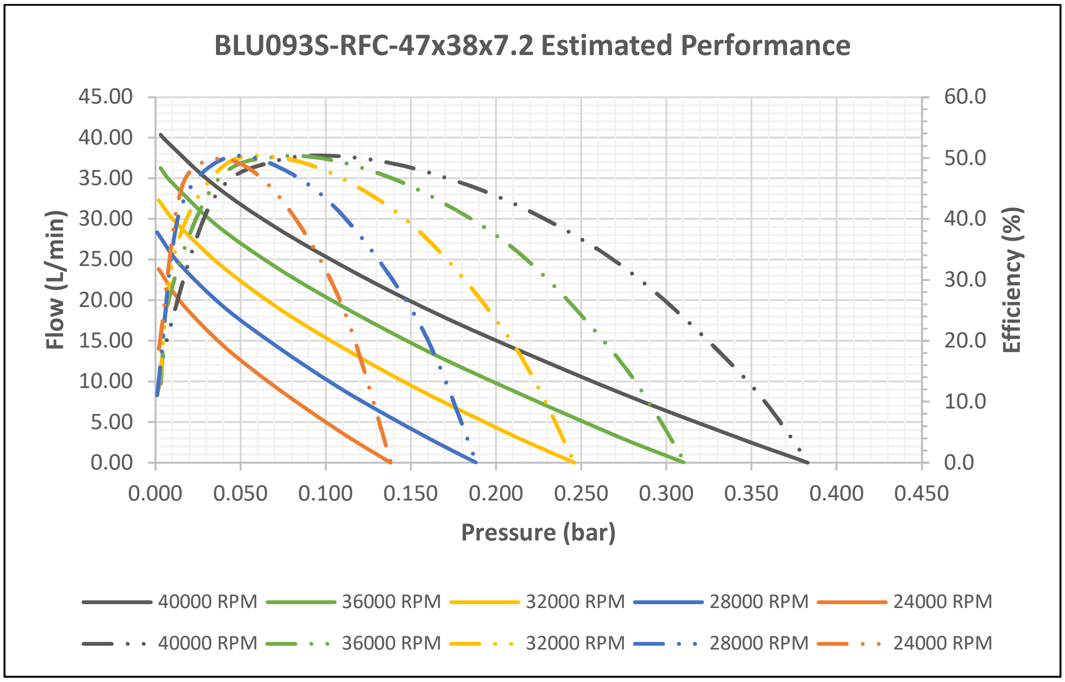
Background

The original recommendation for a high-speed, machined aluminum RFC was for a compressor with parameters and estimated performance as shown below.

Parameter	Description
R_c	25.00 mm
R_{2t}	23.50 mm
R_h	19.00 mm
t	7.20 mm
b_i	3.00 mm
b_c	1.80 mm
c_a	0.15 mm
Inlet/Outlet	G1/8 w/hose barb
Motor Type	Anaheim Automation BLU093S, 24V, 84W
Motor P/N	BLU093S-24V-34400



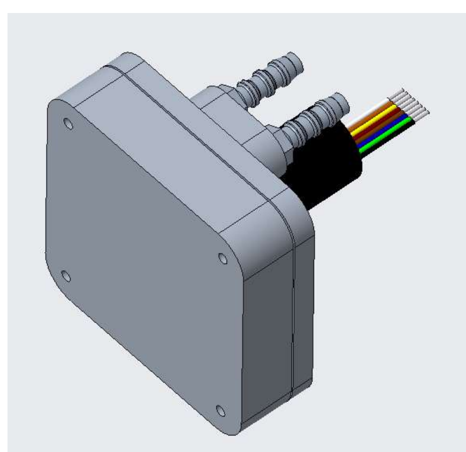




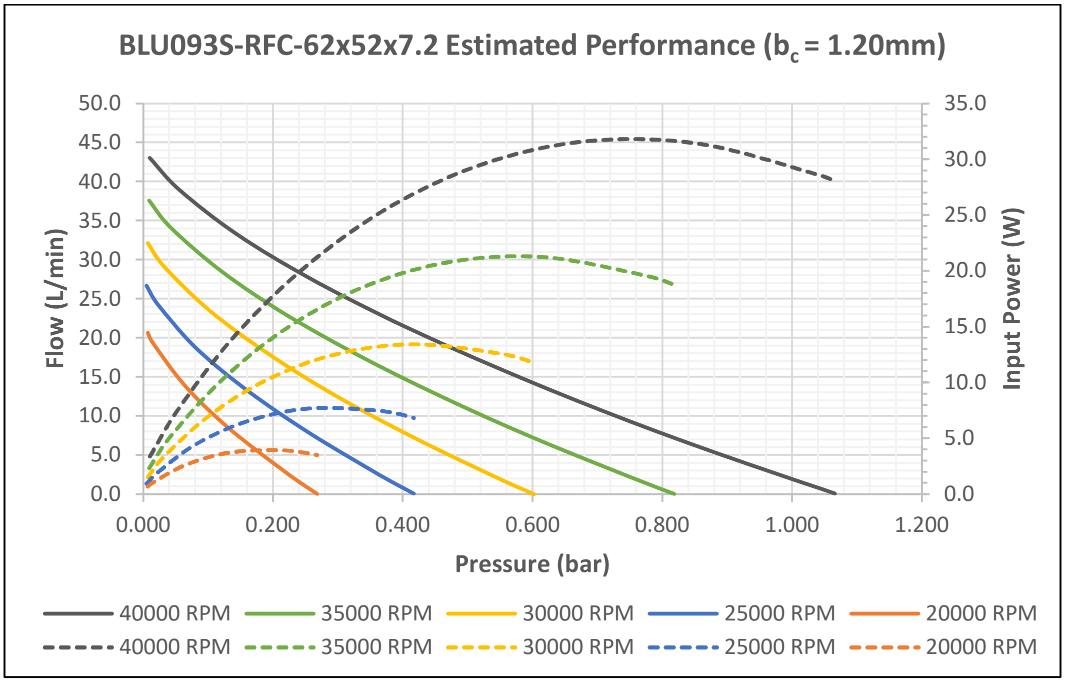
Looking at the required power of the compressor plus the impeller flywheel power (the power required just to spin the impeller at speed – see Appendix A) it was felt the compressor was undersized for the selected 84W motor and a slightly larger compressor could be developed. The decision to increase the size of the compressor was made based on the assumption that the Excel calculations were correct and that the 84W motor was rated at its nominal, 24VDC speed of 34,400 RPM.

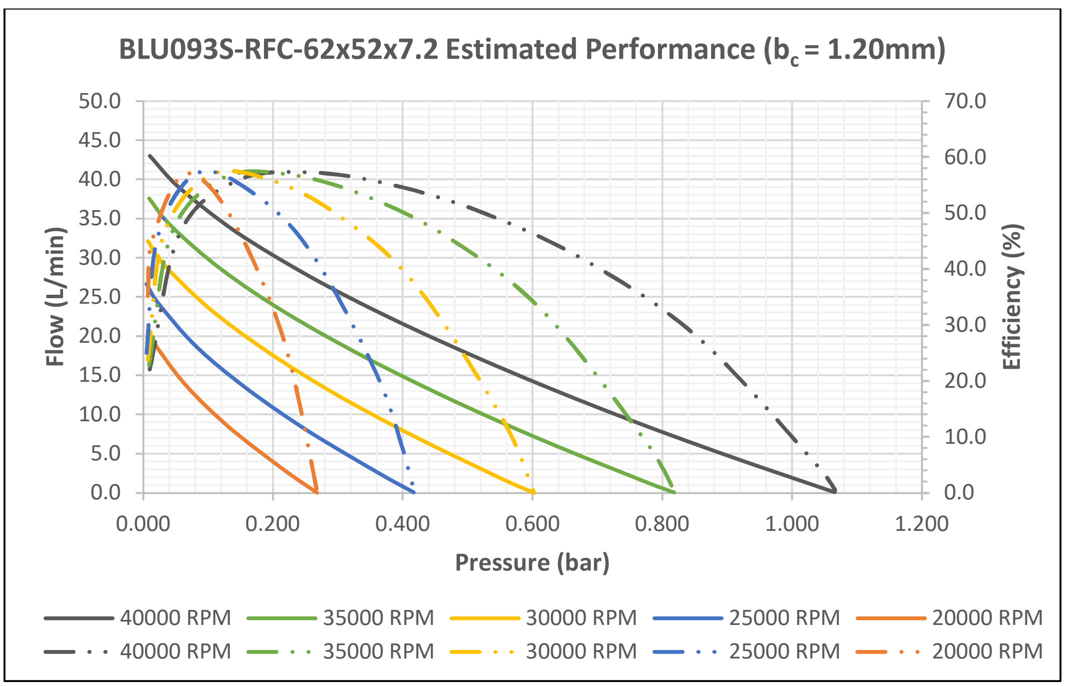
A new pneumatic set was designed with impeller dimensions of 62x52x7.2 and performance estimates calculated. The new parameters are shown in the table below. Externally the compressor is very similar to the 47x38x7.2 impeller version originally proposed, but the external length x height dimensions of 64mm x 64mm have increased in size to 76.2mm x 76.2mm to accommodate the larger diameter impeller. The channel depth, b_c, has been reduced from 1.80mm to 1.20mm to allow for testing with channel depths of 1.20mm, 1.80mm and 3.20mm via in-house machining. This will allow the shifting of the performance curve to determine the effect channel depth plays on overall performance.

Parameter	Description
R_c	32.50 mm
R_{2t}	31.00 mm
R_h	26.00 mm
t	7.20 mm
b_i	3.00 mm
b_c	1.20 mm
c_a	0.15 mm
Inlet/Outlet	G1/8 w/hose barb
Motor Type	Anaheim Automation BLU093S, 24V, 84W
Motor P/N	BLU093S-24V-34400

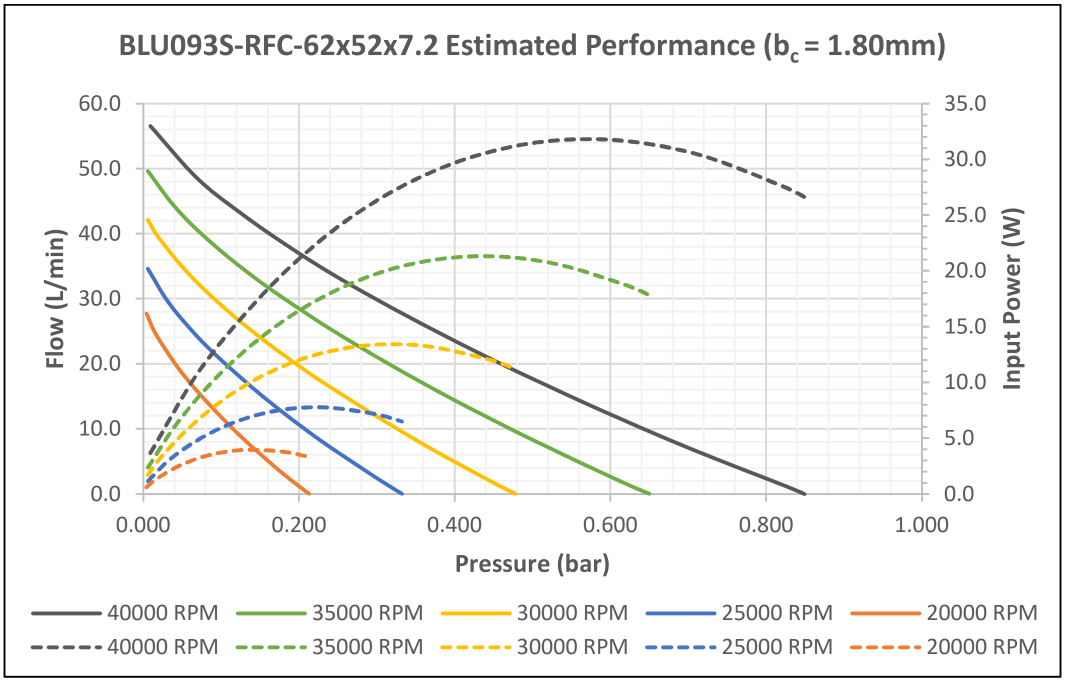


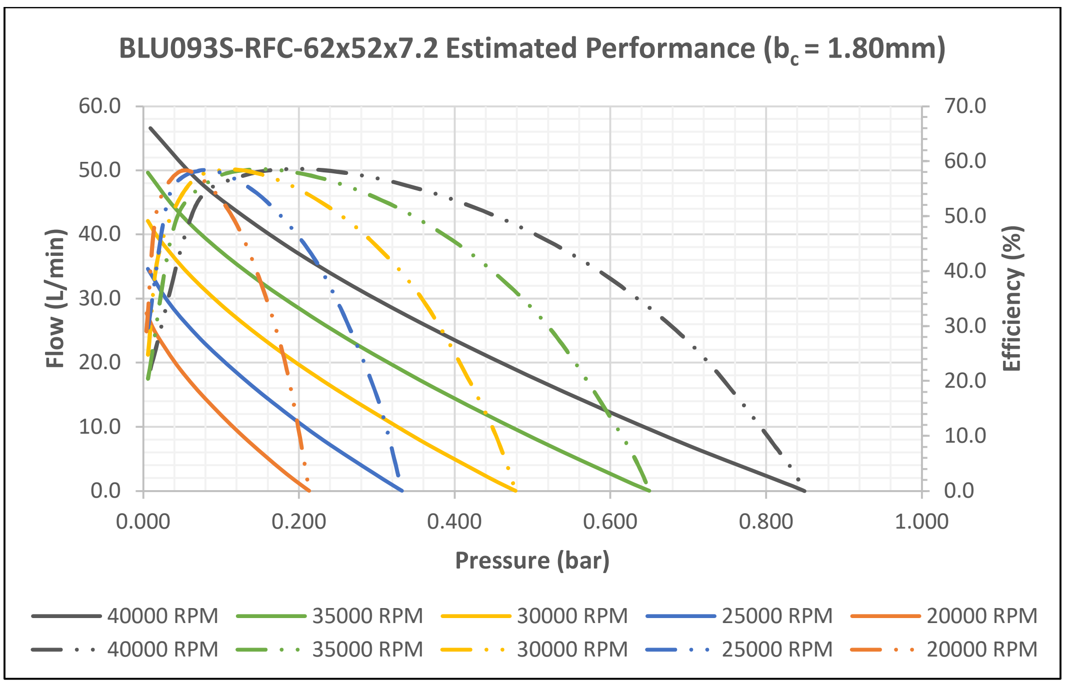
The performance estimates for each channel depth are shown on the following pages, starting with b_c = 1.20mm. Note that the compressor speeds were changed to 5000 RPM increments versus 4000 RPM from the original calculations.



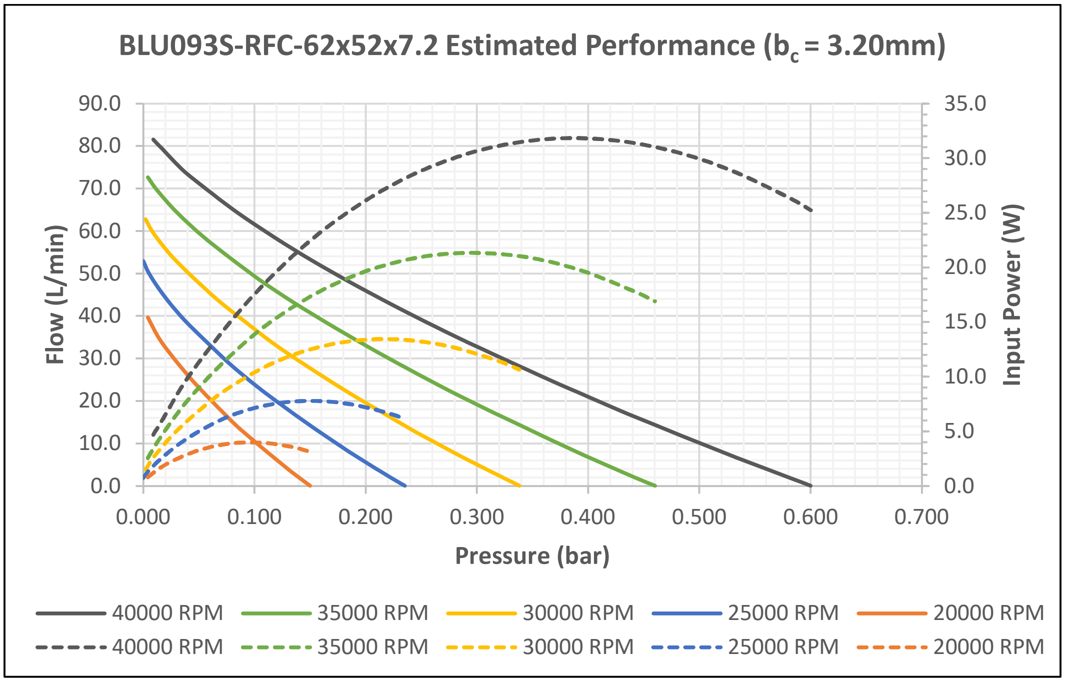


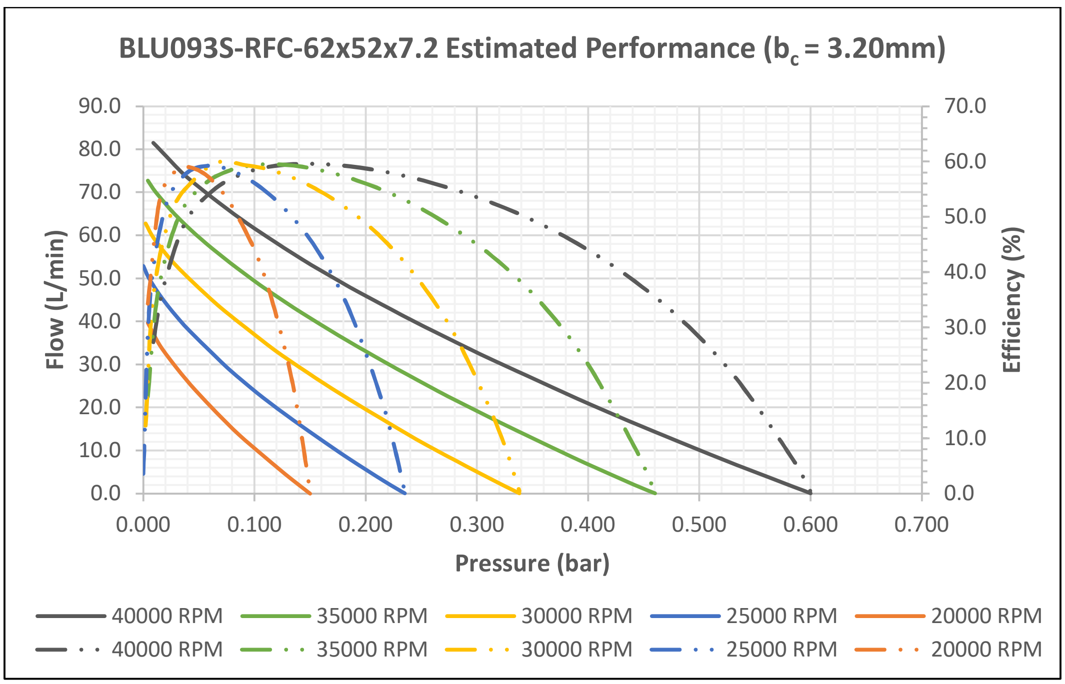
An impeller diameter of 62mm versus the original 47mm allows for an estimated increase in flow and pressure at the same compressor speeds when combined with a b_c = 1.20mm channel depth. The output pressure estimate is approximately 3x that of the original 47mm design.





Increasing channel depth to 1.80mm allows for an estimated increase in flow of approximately 32% while still delivering an estimated output pressure of more than 2x that of the original 47mm design. Note how the performance curve has shifted, allowing for increased flow with decreased pressure by simply changing the depth of the side channel while utilizing the same impeller.





Increasing channel depth even further to 3.20mm we see that the flow estimate is now approximately double the original 47mm design. Maximum output pressure has dropped significantly compared to the 62mm impeller with the 1.20mm side channel depth, but the overall compressor performance envelope is still significantly broader than the originally proposed design.

Equipment Used

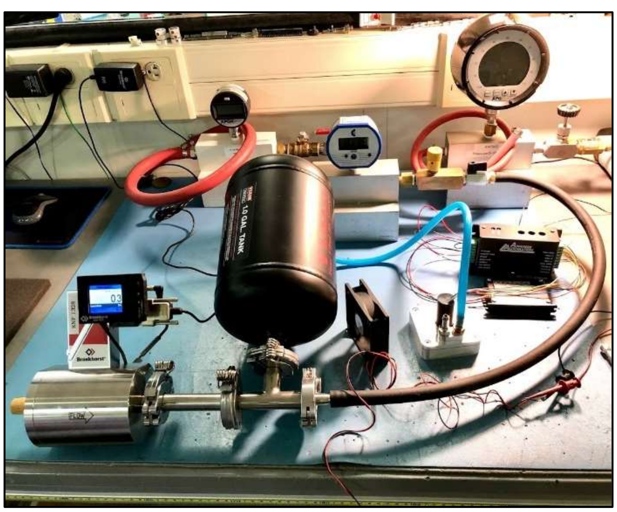
The following equipment was used during RFC prototype testing.

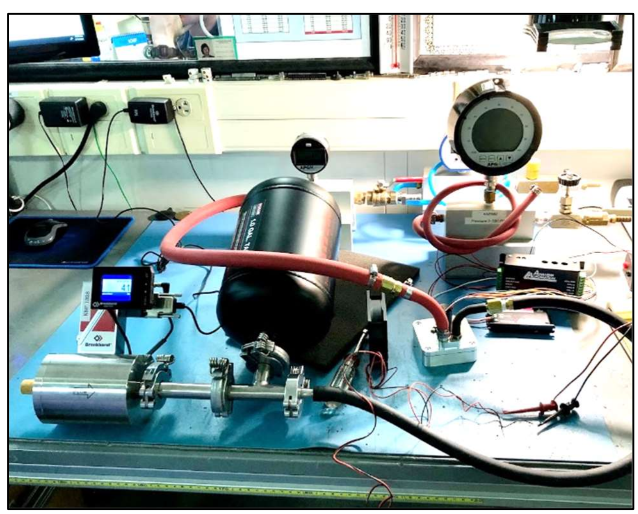
Equipment Type	Manufacturer	Model Number	Range	Gauge No.
Mass Flow Meter	Bronkhorst	-	4 – 200 L/min	1328
BLDC Controller	RioRand	B087M3GVYX	380 W, 6.5 – 50 VDC	-
BLDC Controller	Anaheim Automation	MDC151-050101	250 W, 20 – 50 VDC	-
Digital Readout	Anaheim Automation	SPDRO-4	0 – 9,999 RPM	-
Multimeter	Fluke	23 III Series	0 – 600 V	145
Multimeter	Fluke	23 II Series	0 – 10 A	146
Pressure Gauge	APG	PG10-100.00-PSIG-N2	0 – 100 PSIG	882
Vacuum Gauge	Cecomp	DPG1000B15PSIA-10	0 – 15 PSIA	827

Test Set Up

The new RFC was tested using the equipment listed in the ***Equipment Used*** section shown above. A Bronkhorst mass flow meter was used instead of rotameters to allow for easier testing without having to switch between devices as flow increased/decreased. For testing with the BLU093S-24V-34400 motor, an Anaheim Automation BLDC controller and digital readout for monitoring speed were used. For later testing with a Maxon ECX22L-150W motor, a RioRand sensor-less BLDC controller was used due to the increased compressor speed and continuous duty current requirement.

The 4-digit Anaheim digital readout allowed for a programmable gear ratio of 1:10 such that 25k-40k RPM speeds could be monitored with a low-cost display ($39) versus a much more expensive high-speed stroboscope. Images of the test set ups (vacuum on the left, pressure on the right) are shown below.





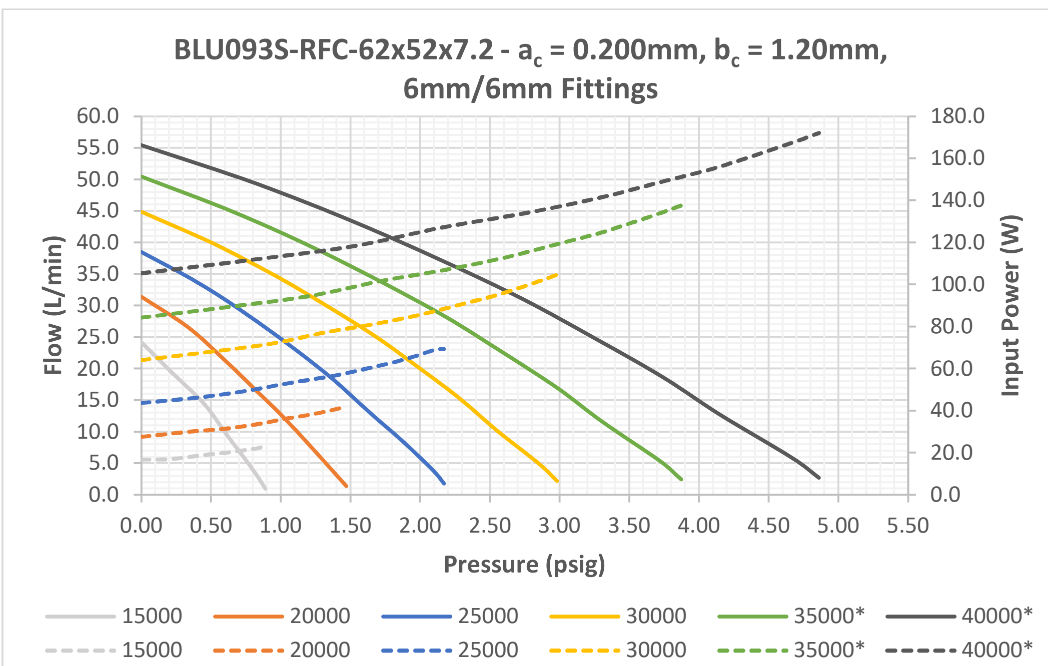
Results and Discussion

BLU093S-RFC-62x52x7.2

Multiple configurations of the BLU093S-RFC-62x52x7.2 were tested while attempting to validate the design calculations. The original configuration was designed to be assembled with an axial clearance a_c = 0.100mm and shimmed in 0.050mm increments to test the real-world effects of increasing axial clearance. Unfortunately, the shaft bore for the impeller was machined slightly oversized, causing a wobble and associated rub between the impeller and compressor head/volute, forcing the original assembly to utilize a 0.200mm axial clearance.

Using 6mm inlet/outlet fittings, the compressor was tested from 15,000 RPM to 30,000 RPM in 5,000 RPM increments under both pressure and vacuum conditions. The original calculations do not provide a method for determining vacuum performance, so it was excluded from the simulations and instead the compressor efficiency calculations were included to help determine how realistic the projections were. With real-world testing, determining the compressor efficiency is not completely straightforward since we do not have motor efficiency ratings at various speeds under load. Therefore, the test results shown henceforth will simply show flow vs. pressure and flow vs. vacuum.

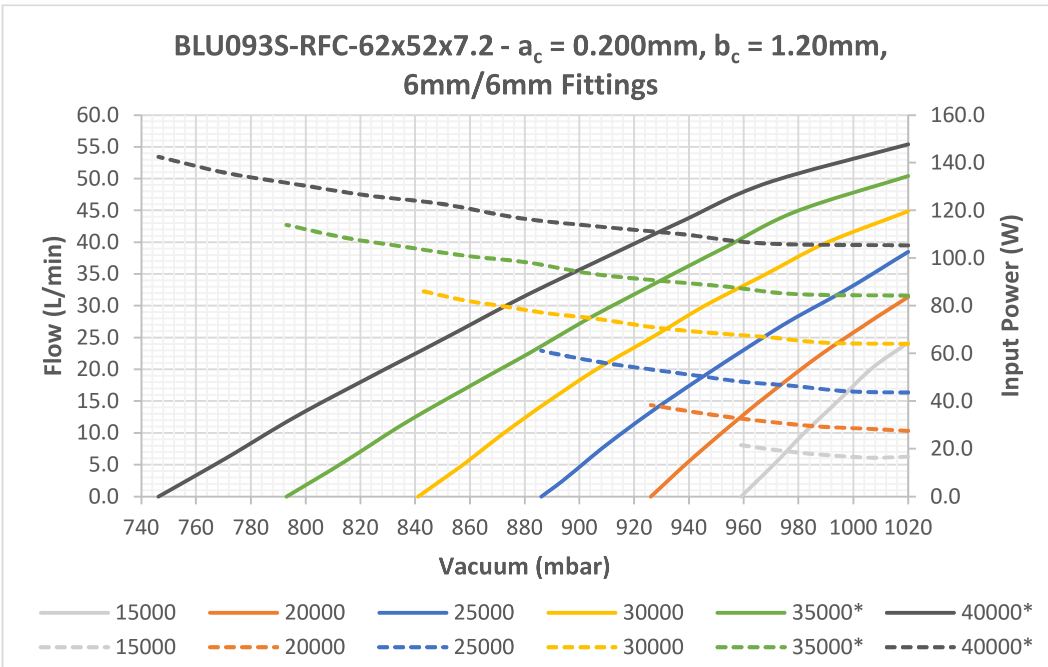
It should be noted that the units for pressure on the X-axis have been changed from bar in the performance estimates to PSIG in the test results. This was done simply to eliminate the need to convert to bar from the PSIG measurements recorded in R&D during testing.



What is immediately apparent from the above pressure curve is how low the output pressures are and how high the input power requirements are compared to the estimated values. Granted, input power shown is the RMS power of the whole system calculated by multiplying input current by input voltage and not just of the compressor end, but these values are still significantly higher than expected.

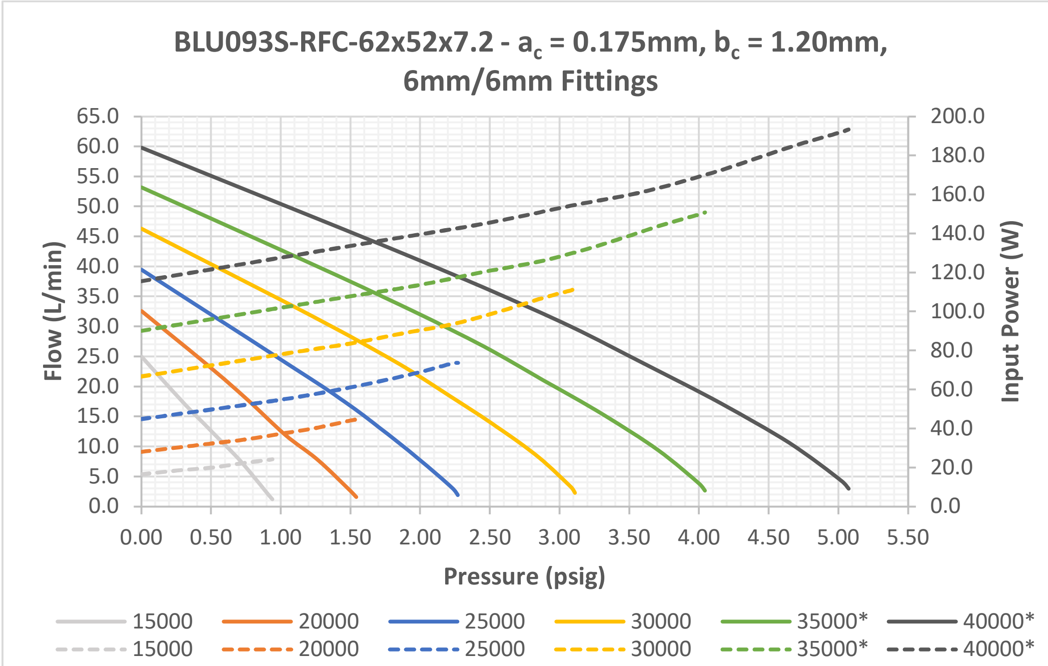
Free flow is approximately 25-40% greater than estimated, depending on speed and the characteristic shape of the individual flow vs. pressure curves are more of a downward convex shape versus the downward concave shape of the estimates. The power curves are an upward convex shape continuing to trend upward as speed increases compared to the estimated concave shape.

It is also worth pointing out that only speeds of 15,000, 20,000, 25,000 and 30,000 RPM were tested; 35,000 and 40,000 RPM were extrapolated based on the previous test results at lower speed. Unfortunately, the BLU093S motor did not have the power to run speeds above 30,000 RPM at anything above free flow without the risk of overheating the motor.

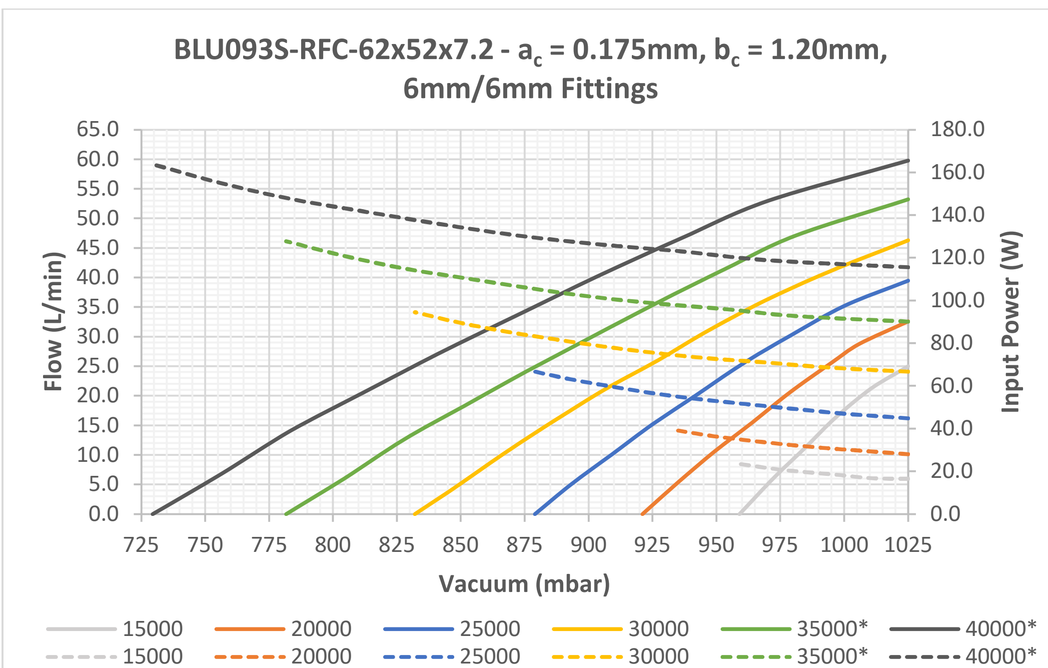


Vacuum performance closely tracked pressure performance in terms of characteristic curve shape with the main difference being lower input power required at maximum vacuum per speed compared to maximum pressure. This is the same trend that was seen when testing the 3D printed plastic prototypes in 2020. Once again, 35,000 and 40,000 RPM were extrapolated from the lower speeds where the motor was able to run without overheating.

Since the compressor did not perform as anticipated, additional tests were carried out to try and find some of the missing performance. To start, the axial clearance was reduced from 0.200mm down to 0.175mm to reduce the leakage losses. In order to do this, the impeller had to be manually ground in a few locations to reduce high spots that were the cause of rubbing previously mentioned. Although an axial clearance of 0.100mm to 0.150mm was desired, 0.175mm was the lowest possible for the compressor to reliably start without rubbing. The results from the reduced clearance test are shown below, once again performed with 6mm inlet/outlet fittings.



Free flow and maximum pressure increased at each speed but not without corresponding increase in input power, providing a negligible efficiency improvement by reducing the axial clearance at this point. The shape of the curves did flatten out somewhat with a concave shape not seen until the compressor is closer to maximum pressure and low flow.

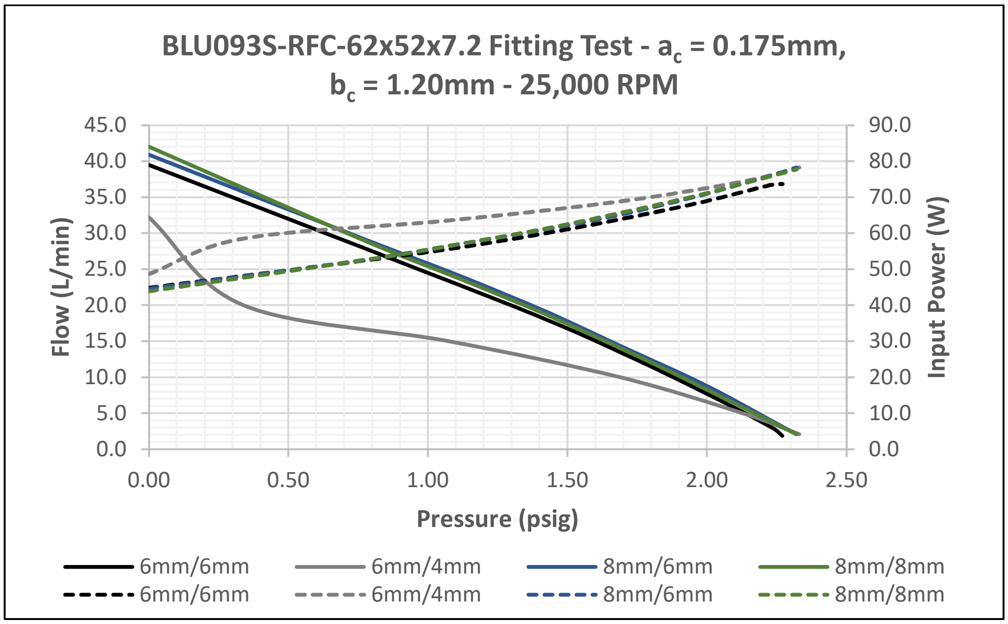


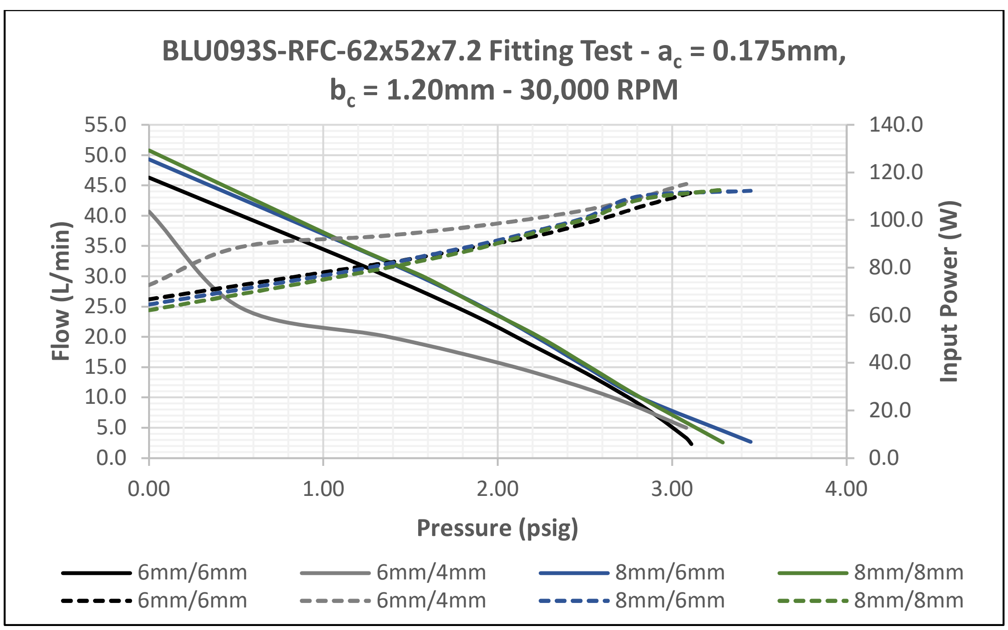
Vacuum performance followed the same trend as pressure performance with measured improvements only possible with increased input power. Unlike the pressure curve, the vacuum curves didn't flatten out as much with the 0.175mm axial clearance compared to the 0.200mm clearance.

The internal ports of the compressor were originally designed with a diameter of 5.5mm to match the internal size of the standard G1/8 x 6.0mm HID fittings typically used for testing pumps of similar flow capacities. A series of tests were performed to determine if any losses are present due to fitting restrictions. The following additional configurations were tested:

1. 6.0mm HID inlet, 4.0mm HID outlet
2. 8.0mm HID inlet, 6.0mm HID outlet
3. 8.0mm HID inlet, 8.0mm HID outlet

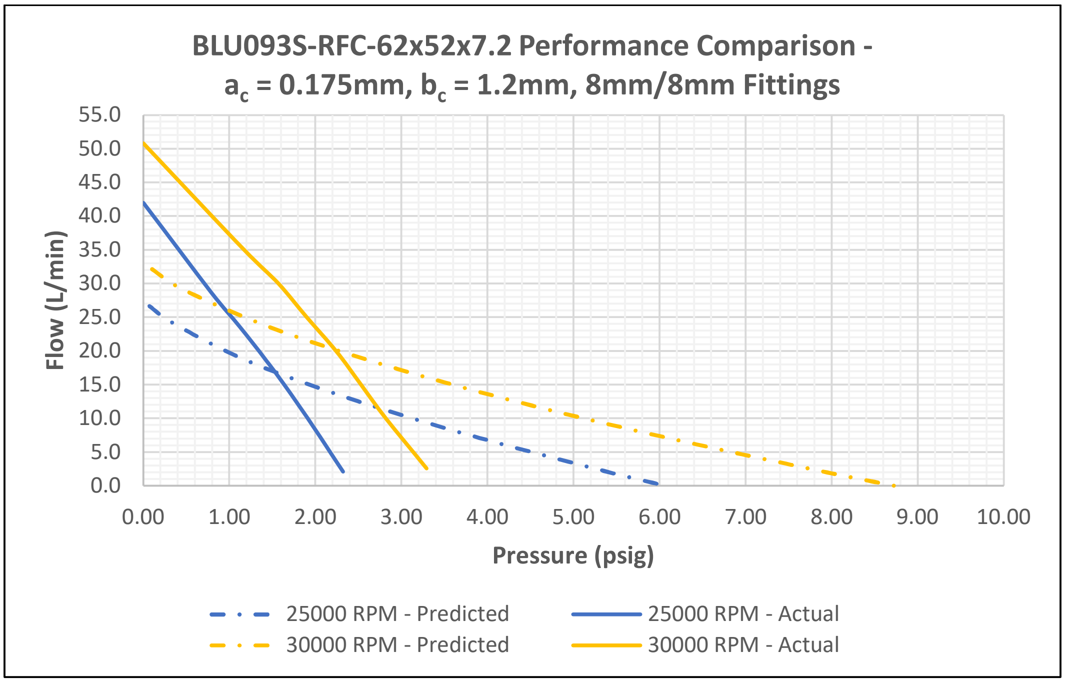
These tests were only performed at 25,000 and 30,000 RPM since this provided the most useful information and the results are shown below for pressure performance only.





The testing clearly proves a 4.0mm HID outlet fitting is very restrictive and causes decreased performance and increased power consumption. The testing also shows that when speed is increased, even the standard 6.0mm fittings become restrictive on the inlet side and performance is improved across the board when both are converted to 8.0mm HID fittings. It is assumed that at speeds of 35,000 and 40,000 RPM the 8.0mm HID inlet fitting will be even more critical to achieve maximum flow.

At this point in the testing it seemed relevant to compare the actual performance data at 25,000 and 30,000 RPM to the predicted performance at those same speeds. The comparisons are shown below.



It is evident that a major disconnect exists between the performance estimates generated by the calculations and the real-world performance – free flow is significantly higher while pressure is significantly lower. Multiple attempts were made to develop calculations that more closely matched the real compressor performance by changing loss coefficients and testing the sensitivity of removing various terms from the equations. Although some points in the calculations would agree relatively well with the real performance, it was not possible to generate a full calculated curve that agreed even within a margin of error. The calculations continued to generate deadhead output pressures much higher and free flows much lower than the tested performance.

During the testing it was discovered that the Anaheim BLU093S-24V-34400 motor was not as powerful as initially expected. The motor has a maximum power output of 84W and a speed of 34,400 RPM at 24V. However, the maximum power does not occur at the 34,400 RPM rated speed. The maximum power occurs at only 22,500 RPM and by 34,400 RPM the motor output drops to approximately 20W – not a very useful output for this compressor. The full performance curve for the motor, unfortunately not available as part of the standard specifications sheet, is available in Appendix B.

ECX22L-RFC-62x52x7.2

With the Anaheim motor underperforming and limiting speed to 30,000 RPM and below, it was decided to purchase and test a Maxon ECX22L motor rated for 153W and 47,800 RPM at 24V and a maximum speed of 60,000 RPM. This performance came at a cost of roughly 3x the Anaheim motor, which is why the lower cost option was initially tested. Even though the compressor was not performing to the predicted calculations, it was deemed beneficial to determine its functionality at higher speeds.

The RFC components were modified to accommodate the larger shaft and pilot bearing diameter of the Maxon motor and initial testing was performed using the Anaheim MDC151-050101 controller. The MDC151-050101 is rated for 5A continuous and 10A intermittent, so it was assumed this would be acceptable for lower loads using the Maxon motor. However, it was immediately apparent that the controller was limiting the speed of the ECX22L motor when coupled to the compressor as it would not spin above 20,000 RPM. Due to the nature of the high-speed, 2-pole motor, while the RMS current with low load only measured 1.0A, the individual phase current spikes were on the order of 12-13A, above the limit of the controller, which caused it to trigger a fault and limit speed to avoid controller damage.

Next an Allied Motion DPFlex Gen I sensor-less controller was used since these were readily in stock at our facility. This controller had the power and current capability needed but was limited to 40,000 RPM for a 2-pole motor. The goal was to run the motor at 40,000, 45,000 and maybe even 50,000 RPM, so the use of this controller was abandoned. A Maxon ESCON 72/10 4-Q controller, programmable with a user-friendly GUI and high power, current and speed capability was available via Maxon but carried a steep price tag for testing of a compressor that wasn't meeting the performance expectations. Instead, a low-cost Rio-Rand sensor-less controller from Amazon was procured for $17 and proved to work very well for controlling the motor between speeds of 15,000 RPM and 50,000 RPM.

Unfortunately, testing of the Maxon ECX22L motor did not last very long before the motor burned up. The low-cost sensor-less controller does not have any kind of current over-protection, so it is up to the user to monitor the input RMS current during testing. The compressor speed was increased to 40,000 RPM and free flow measurements of 65 L/min were observed (far in excess of the original 44 L/min that was estimated). At this capacity, the RMS current was in the 7.3-7.5A range (far in excess of what was expected) and an input power of approximately 175-180W. This motor has an efficiency of 92% at 40,000 RPM, so an input power of 175-180W translates to an output of 161-166W, which exceeds the motor's continuous duty rating of 153W. Needless to say, the motor was only able to run for a few minutes before the windings overheated causing an electrical short and ultimate failure.

Conclusion

The goal of this project was to develop a compact, regenerative flow compressor that could provide a good balance between flow and pressure for applications outside the performance envelope of a diaphragm or piston pump of similar size. Unfortunately, that goal was not met due to the inability of the compact RFC to deliver efficient, usable pressure capability. The free flow capability of the compact RFC is quite impressive for its size, but with the overall performance envelope being so small, it is mostly a high flow, ultra-low-pressure device. Reviewing the designs of competitors, it appears the usable size for the RFC utilizes an impeller diameter in the 100mm and larger range. Designs smaller than this don't justify their high power consumption with their flow and pressure capabilities compared to a diaphragm or piston pump design.

Producing meaningful calculations that provided good agreement with the physical test results proved to be largely impossible during this development project. Upon further research, it was determined that this is because the calculations are one-dimensional and only applicable at specific points when used with static loss coefficients due to the compressibility effects of air, and thus the changing internal volume due to the compression process. The calculations derived by T. Meakhail and S.O. Park and used in the original white paper *Development of a Regenerative Flow Compressor – 18-Dec-2020*, were developed around an incompressible fluid, and while valid are not capable of predicting full performance curves for air compressors. This explains why individual performance points could be matched with the one-dimensional calculations by modifying the loss coefficients, but it was not possible to develop a full performance curve that provided good agreement with the physical results. Utilizing computational fluid dynamics (CFD) or a more complex formulae to model the air movement is required in order to fully understand what goes on inside the compressor at high speeds.

Overall, the project was a very useful learning experience completed through an iterative design approach. It is unfortunate that the target results were not achieved, but such is the nature of research development work. Currently, there are no recommendations for future work on a compact RFC due to its inability to perform as desired. A larger RFC with high flow capabilities in the 100-250+ L/min range and low output pressure could be considered in the future if deemed appropriate at that time, as we do see requests for these high flow applications that we are unable to meet.

Appendix A – Impeller Flywheel Power

BLU093S-RFC-47x38x7.2

RPM	Power (W)
40000	15.93
36000	14.34
32000	12.75
28000	11.15
24000	9.56

BLU093S-RFC-62x52x7.2

RPM	Power (W)
40000	41.40
35000	36.23
30000	31.05
25000	25.88
20000	20.70

Appendix B - Anaheim Automation BLU093S-24V-34400 Performance Curve

Appendix C – Final Configuration – ECX22L-RFC-62x52x7.2