Testing of a 1 kW-Class Cryogenic Turboalternator

D. Deserranno, A. Niblick, M. Zagarola

Creare
Hanover, NH 03755, USA

ABSTRACT

Future NASA missions will require hydrogen liquefaction systems for spaceport, planetary, and lunar surface operations. Cryogenic expansion turbines are critical components of many liquefaction systems. Recently Creare designed, built, and tested several turboalternators suitable for hydrogen liquefaction systems producing 5000 gallons/day. The turboalternator designs were scaled from Creare's space-borne turboalternators, which were developed for sensor cooling applications with refrigeration from watts to tens of watts. The hydrogen turboalternators were optimized for operation between 77 and 20 K and produce up to 1.5 kW of refrigeration, depending on the expansion stage and operating conditions. Testing was performed in cryogenic nitrogen at 140 K and at dynamically equivalent operating conditions as hydrogen design conditions. Net efficiencies were demonstrated up to 80%, closely matching our performance predictions. The design and testing of the turboalternator, and the extension of the technology to high-capacity turbo-Brayton cryocoolers are the subjects of this paper.

INTRODUCTION

Future NASA missions will require hydrogen liquefaction systems for spaceport, planetary, and lunar surface operations. A critical part of these systems is the cryogenic turbines. While turboexpanders utilizing a brake wheel are common in industry, turboalternators offer a clear benefit due to the simplicity of their design. Indeed, the difference between the turboexpanders and turboalternators is in how the expansion work is removed from the shaft. Turboexpanders utilize a brake wheel, a simple centrifugal compressor, to circulate the process gas in an auxiliary flow loop. The auxiliary flow loop typically consists of a heat exchanger, an adjustable valve, and plumbing. The turboexpander speed control is provided by adjusting the valve, which sets the flow impedance in the auxiliary flow loop. Conversely, turboalternators convert the shaft work to electrical power in an alternator. Here, the speed control is provided by varying the electrical impedance or the back voltage in the control electronics. Turboalternators have several advantages, including (1) the increased reliability associated with the elimination of the adjustable valve, (2) the reduction in system mass associated with the elimination of an auxiliary flow loop and heat exchanger, and (3) the reduction in system input power offered by recovering the electrical power generated by the turbine. Additionally, by utilizing hydrodynamic gas bearings at cryogenic temperatures, the complexity of operation and mass is further reduced due to the lack of pneumatic (hydrostatic) or electrical (magnetic) bearing support infrastructure.

On a recent NASA project, we sized, built, and tested several turboalternators for a liquefaction system that produces 5000 gallons/day of liquid hydrogen for spaceport operations.

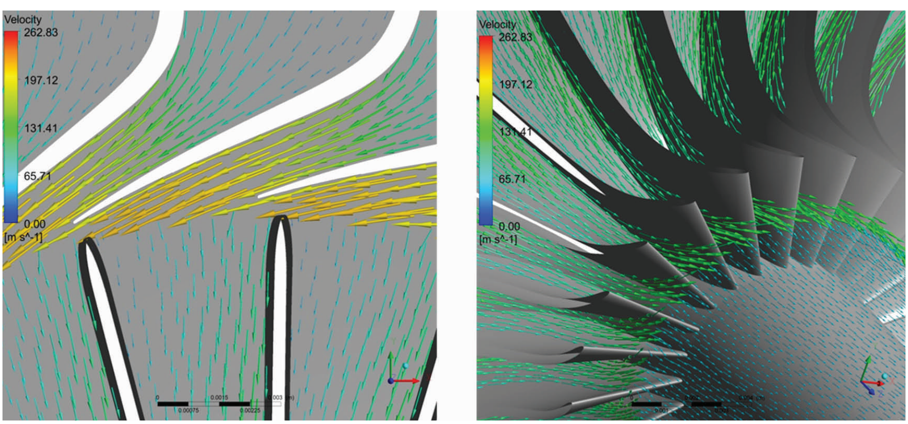
Cryocoolers 18, edited by S.D. Miller and R.G. Ross, Jr.

We quantified the benefits of using turboalternators in the product stream relative to a Joule-Thomson throttle. Five expansion stages are required to efficiently expand the hydrogen over a pressure ratio of 20:1. The turbines are designed to operate between 77 and 20 K and produce up to 1.5 kW of refrigeration, depending on operating conditions. The turbine impeller has a 1.4 inch diameter and is capable of operating with tip speeds as high as 330 m/s. Testing under dynamically equivalent operating conditions was performed using an open-loop test facility capable of producing 50 gm/s of gaseous nitrogen at about 140 K. Net efficiencies were demonstrated up to 80%, closely matching our performance predictions. In addition, spin testing was performed at temperatures down to 24 K to verify operation of the hydrodynamic gas bearings at low temperatures. This paper presents the results of our turboalternator design and testing efforts, and its use in turbo-Brayton cryocoolers.

TURBOALTERNATOR DESIGN AND PERFORMANCE

To design the aerodynamic features of the turbines, we utilized TurbAero® empirical design software and ANSYS CFX® computational fluid dynamics (CFD) software. The components to be optimized for each turbine are the nozzles and turbine rotor. First, we specified a target aerodynamic efficiency, along with parameter limits and constraints such as rotor inner and outer diameter, blade thickness, blade height, inlet and exit angles, number of blades, number of nozzles, length of diffuser, etc. Within the constraints specified, an initial aerodynamic design is determined based on empirical correlations in TurbAero design software. The design is then imported into ANSYS CFX software for a full CFD simulation. We iterated the design in ANSYS CFX to improve aerodynamic efficiency (Fig. 1). Using undesirable entropy generation as a guide, the design was optimized by varying blade nozzle and impeller blade angles, hub and shroud contours, and the diffuser area ratio. This process continues until a satisfactory aerodynamic design is produced. Table 1 illustrates the performance predictions for the various turbine stages, including isentropic work, aerodynamic efficiency, net efficiency, net alternator power, and various losses.

Upon designing the turbine blade geometries, we fabricated and assembled a turboalternator for testing. The assembled turboalternator and rotor shaft are shown in Fig. 2. To achieve high overall cycle efficiency and low development and production costs, we developed designs for the five turbine stages that have over 90% common parts. The turboalternator components are identical for all five stages with the exception of the aerodynamic parts shown in Fig. 3, which are optimized for each stage. Despite the significantly different operation conditions (20 bar to 1 bar, 77 K to 20 K), only two components must be replaced inside the turbomachine to obtain optimal performance for each stage.



Turbine Inlet Turbine Exit

Figure 1. Aerodynamic analysis used to maximize performance.

Table 1. Summary of Performance Predictions for Hydrogen Liquefaction Turboalternators.

Description	Units	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Mass flow rate	g/s	15.5	15.5	15.5	15.5	15.5
Inlet temperature	K	77.0	67.7	57.6	30.0	22.5
Inlet pressure	bar	20.0	12.2	7.2	4.0	1.7
Pressure ratio	-	1.64	1.70	1.80	2.42	1.66
Isentropic work	W	2,131	1,989	1,845	1,216	593
Rotor speed	rev/s	2940	2960	2830	1870	1600
Specific speed	-	0.146	0.187	0.232	0.223	0.387
Specific diameter	-	12.2	9.8	7.9	7.0	4.7
U/C0	-	0.63	0.65	0.65	0.53	0.65
Aerodynamic efficiency	%	79.4	88.6	89.5	81.1	89.2
Effective Area	mm^2	4.56	6.77	10.13	10.33	27.36
Total rotor drag	W	168.2	127.7	84.2	23.2	10.2
Seal leakage	gm/s	1.44	0.93	0.60	0.53	0.22
Total alternator losses	W	30.3	30.9	28.9	14.1	10.7
Net efficiency	%	63.0	75.7	80.3	75.5	84.6
Output power	W	1,343	1,506	1,482	919	502

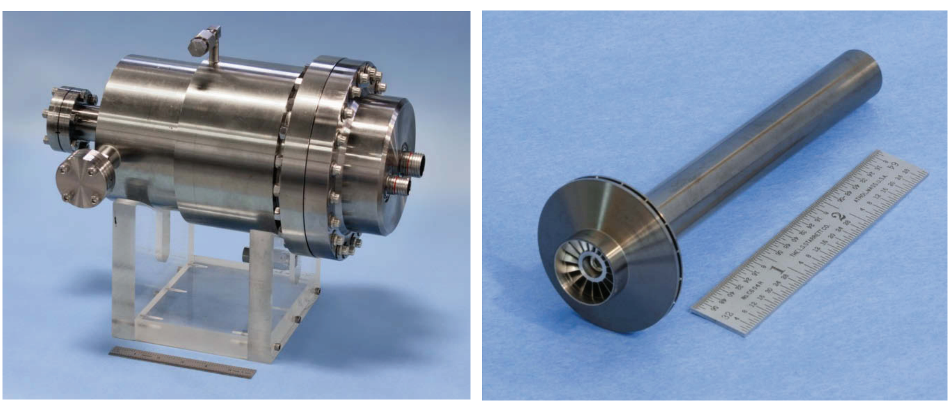
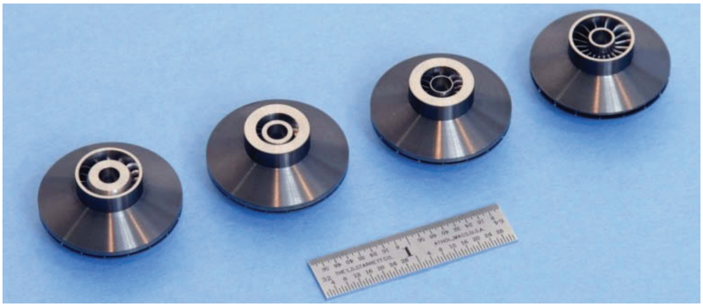


Figure 2. Fully assembled turboalternator (left) and rotor assembly (right).



a. Turbine Impellers

b. Turbine Nozzles

Figure 3. Aerodynamic components optimized for five different operating conditions.

TEST APPROACH AND FACILITY

Testing the turbines in a liquefaction system producing 5000 gallons/day of hydrogen would be an ideal demonstration of the benefits of our technology, but unfortunately, we did not have access to a prototypical hydrogen liquefaction system. The test approach that we selected was to utilize cryogenic nitrogen as the working fluid and test the turboalternator at dynamically equivalent operating conditions. The equivalent conditions were determined using the similarity concept (dimensionless scaling). Based on the similarity concept, six independent similarity parameters can be formulated that completely define the operating condition:

1. Efficiency
2. Reynolds number
3. Specific speed
4. Specific diameter
5. Laval number
6. Ratio of specific heats

Any other dimensionless parameter can be expressed as a function of the six variables listed above. For example, a common parameter U/Co, being the ratio of the tip speed to the spouting velocity, can be expressed as the product of the specific speed and the specific diameter. An optimization routine was employed to obtain the best possible agreement between key dimensionless parameters: specific speed, specific diameter, Laval number, and Reynolds number. The ratio of specific heats is a function of the test gas and could not be exactly matched when testing in nitrogen.

The performance test facility is shown in Fig. 4. To achieve the required high flow rates (~50 g/s of cryogenic nitrogen), we vaporized liquid nitrogen from liquid nitrogen dewars. This approach also has the advantage that the gas flowing into the turbine has very low concentrations of condensable contaminants (i.e., water vapor, CO_2) that can potentially freeze in the turbine nozzles. It also eliminates the need for large heat exchangers to precool the turbine inlet gas. We controlled the turbine inlet pressure by regulating the pressure of gaseous helium that is used to pressurize the liquid nitrogen dewar. We controlled the turbine inlet temperature using the heaters on the evaporator. The exhaust pressure of the turbine was controlled by an exit valve. The turbine speed was regulated by the impedance of a programmable load bank that is connected to the alternator. The key measurements were the mass flow rate, inlet and exit pressure, inlet and exit temperature, output power, and speed. The instrumentation was selected to achieve an uncertainty of better than ±2% for the effective area and the net efficiency, the primary performance parameters for a turboalternator. The mass flow rate was determined using electronic mass flow meters. The pressures were measured using strain-gauge type pressure transducers. The inlet and outlet temperatures were measured using redundant platinum resistance thermometers. The output power and speed were recorded using a three-phase power meter. All instrumentation was calibrated.

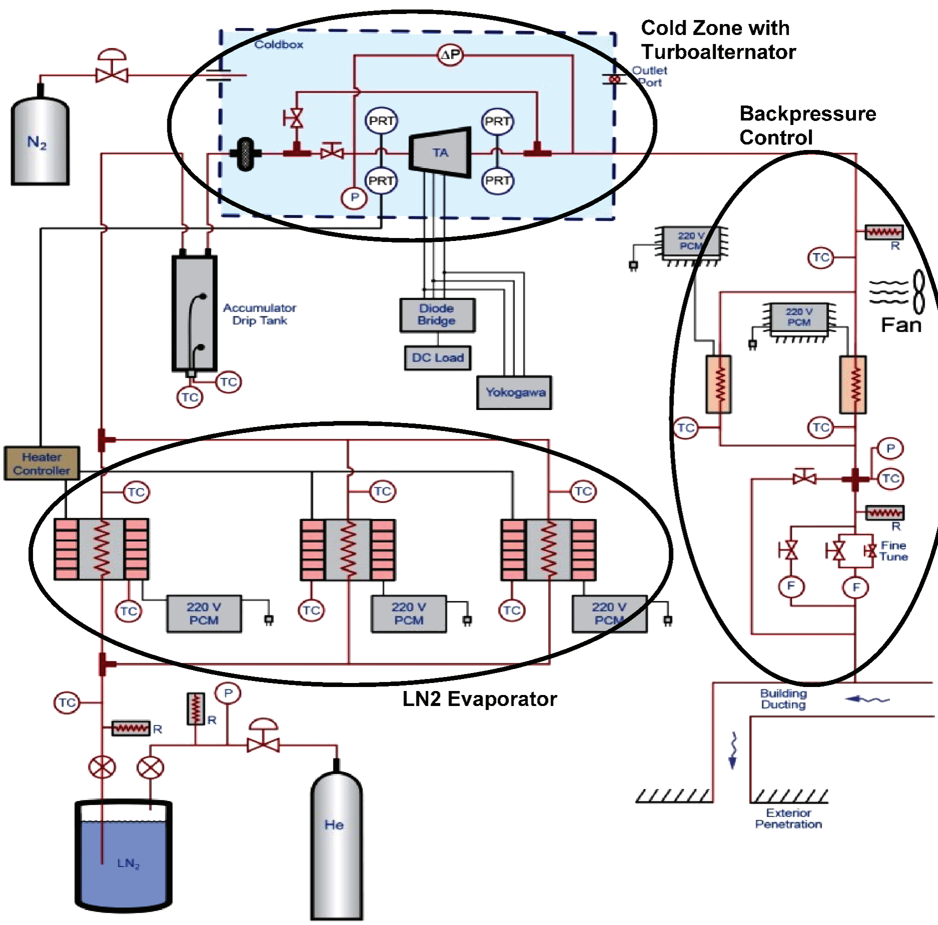


Figure 4. Schematic of turboalternator performance test with boil-off nitrogen.

TEST RESULTS

At the time of writing this paper, performance testing has been completed on the Stage 3 and Stage 4 turboalternator configurations. During each test, data were collected at dynamically equivalent conditions. Raw data (such as mass flow rate, alternator power, pressure, and temperature) were processed to compute net efficiency and effective area. The net efficiency is defined as the ratio of net refrigeration to isentropic refrigeration, where the net refrigeration is equal to the output power from the turboalternator. The effective area is defined as the ratio of the mass flow rate to the product of the inlet density and spouting velocity, and is a measure of the flow resistance of the turbine.

The test results are shown in Fig. 5 and Fig. 6. Our predictions are in good agreement with the test data. Indeed, Stage 3 and 4 net efficiency measurements agreed very well with our estimates, as shown in Fig. 5. While the Stage 3 effective area agrees well with predictions (Fig. 6), the Stage 4 effective area measured somewhat higher than predictions due to an inability to match the design pressure ratio during testing which impacts the reaction of the turbine and the flow resistance. Despite not matching the design pressure ratio exactly, we maintained the dimensionless specific speed and specific diameter to within 4%, explaining the good agreement on efficiency. In summary, both Stage 3 and Stage 4 turboalternators performed well, demonstrating peak efficiencies of 80% and 77%, respectively.

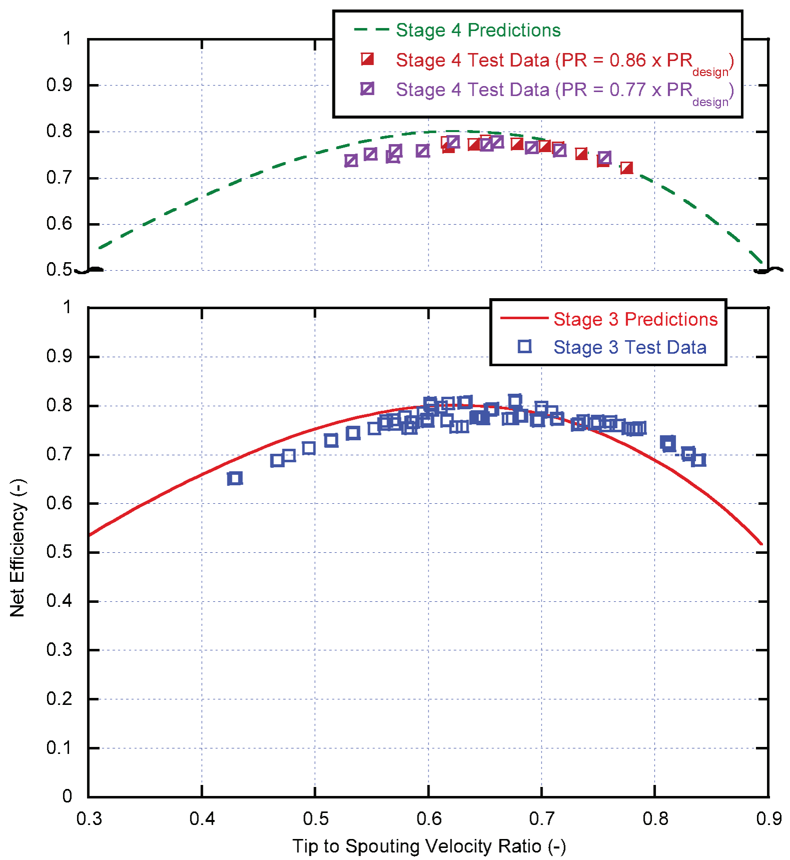


Figure 5. Measured and predicted turboalternator net efficiency for stage 3 and 4 turboalternators.

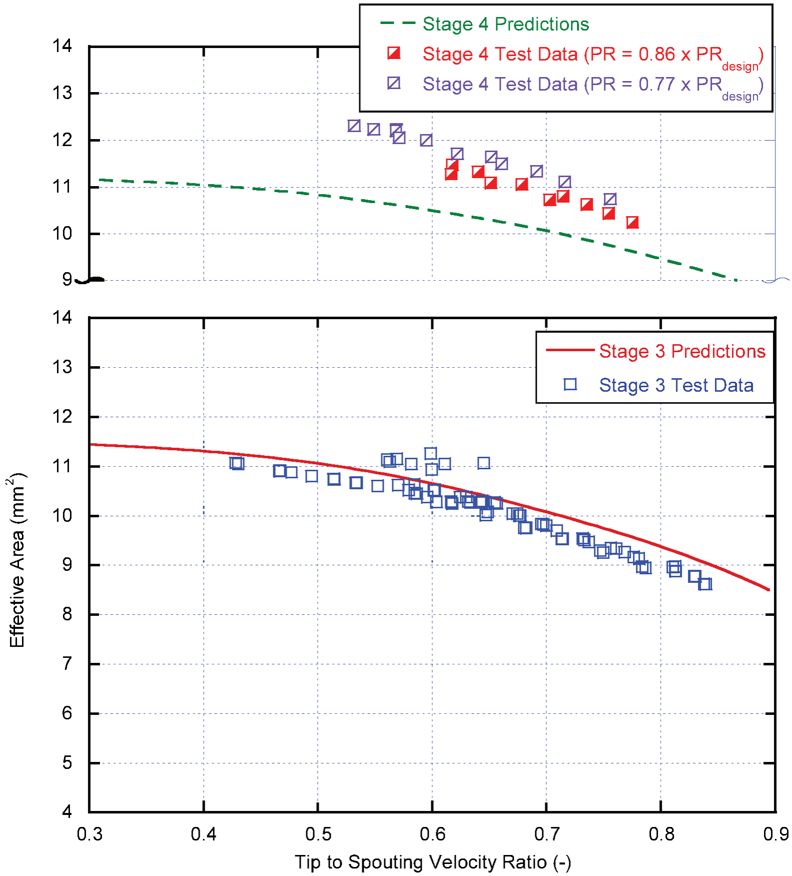


Figure 6. Measured and predicted turboalternator effective area for stage 3 and 4 turboalternators.

In addition to performance testing, we assessed the operation of the hydrodynamic gas bearings at prototypical operating conditions. During the performance testing in nitrogen, the gas bearings were being operated at non-prototypical conditions due to the difference in viscosity between 20 K hydrogen and 140 K nitrogen. To verify that the bearings could operate at prototypical operating conditions in hydrogen, the turboalternator was tested at equivalent conditions in cryogenic gaseous helium. The stability of journal bearings is typically characterized by a Stability Factor, which is the ratio of the inertial forces to the viscous forces:

$$SF \equiv \frac{m \cdot c^3 \cdot \Omega}{6 \cdot \mu \cdot r^3 \cdot b} \tag{1}$$

where m is the supported mass by the bearing, c is the characteristic dimension of the gas film thickness, Ω is the angular velocity, μ is the viscosity, r is the bearing radius, and b is the bearing width.

For bearing stability testing, the turboalternator was cooled to 88 K, 44 K, and 24 K, and the speed was increased up to the maximum operating speed at each temperature, which was governed by bearing stability or test facility limitations. Rotational speeds in excess of 2000 rev/s were demonstrated with no abnormalities. Our test conditions are equivalent to bearing stability factors around 0.3, consistent with operating conditions at 20 K in hydrogen.

USE IN BRAYTON CRYOCOOLER

In addition to expanders for liquefaction systems, these turboalternators can be used in high-capacity turbo-Brayton cryocoolers for cooling high-temperature superconducting motors, generators, transmission lines, fault-current limiters, and magnets. The advantage of these superconducting systems is reduced size, weight, and losses compared with conventional copper systems. Operating temperatures are expected to be between 15 K and 70 K depending on the superconductor, and cooling capacities are expected to range from 100's of watts to several kilowatts. Brayton cryocoolers scale well to high capacities where the cooling power per unit mass and the coefficient of performance increase due to favorable scaling of turbomachines.[1] Near-term applications include ship superconducting degaussing system. Creare is currently developing a cryocooler for the Navy that provides up to 1.5 kW of refrigeration at 50 K. Longer-term applications include cryocoolers for superconducting generators for ship power generation; superconducting motors, generators, and power transmission lines for turbo-electric aircraft; superconducting generators for wind turbines; and superconducting transmission lines for data centers and directed-energy weapons.

SUMMARY

Future NASA missions and facilities will require hydrogen liquefaction systems for spaceport, planetary, and lunar surface operations. Cryogenic expansion turbines are critical components of many liquefaction systems. Recently Creare designed, built, and tested several turboalternators suitable for hydrogen liquefaction systems producing 5000 gallons/day. The turboalternator designs were scaled from Creare's space-borne turboalternators, which were developed for sensor cooling applications with low to modest refrigeration needs. The hydrogen turboalternators were optimized for operation between 77 K and 20 K and produce up to 1.5 kW of refrigeration, depending on the expansion stage and operating conditions. Performance testing was performed in cryogenic nitrogen at 140 K and at dynamically equivalent operating conditions as hydrogen. Net efficiencies were demonstrated up to 80%, closely matching our performance predictions. Bearing stability testing was performed at temperatures as low as 24 K and at operating conditions consistent with operating at 20 K in hydrogen.

ACKNOWLEDGMENT

We gratefully acknowledge the support and guidance from NASA/Kennedy Space Center (Contract NNX12CA68C).

REFERENCES

1. Zagarola, M., and McCormick, J., "High-Capacity Turbo-Brayton Cryocoolers for Space Applications," *Cryogenics*, vol. 46, no. 2-3 (2005), pp. 169-175.