Smart Energy Compressors for Helium Liquefiers

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ABSTRACT

The high degree of control and optimization that is needed in interfacing a cryocooler to a cryogenic instrument requires a careful budgeting of the available cooling power while making the best use of energy. The operational specifications of interest for a cryocooled system include cooling time, cooling power, operating temperature, vibration, and operating time between service cycles.

In this paper, we describe a system where the individual power frequency control of the compressor capsule and the cold head motor provide for intelligent oversight and budgeting of the cooling power delivered in small-scale helium liquefiers. This system provides a new capability for a commercial 4 K Gifford-McMahon (G-M) cryocooler system to dynamically control the cooling power delivered to the first and second stages based upon the compressor capsule and displacer stroke speeds.

The combination of highest cooling power, provided at full power frequency, typically required in an "initial cool down" and "fast liquefaction" modes of operation of a helium liquefier, and very low cooling power in "standby" mode, to allow operation with minimal power consumption, is described.

INTRODUCTION

As the helium supply tightens around the world, the demand for helium liquefiers is increasing rapidly. However, while abating the need for liquid helium, these systems are not known for being energy efficient. Compounding this problem are skyrocketing electricity prices that could make the operation of cryocooled based instrumentation unaffordable in the near future. Thus the need for "smart energy" small scale helium liquefiers with lower power consumption and operating costs has been created. In this paper we report on one such liquefier, the ATL 160[1], that employs Quantum Design's smart energy inverter driven compressors.[2-3]

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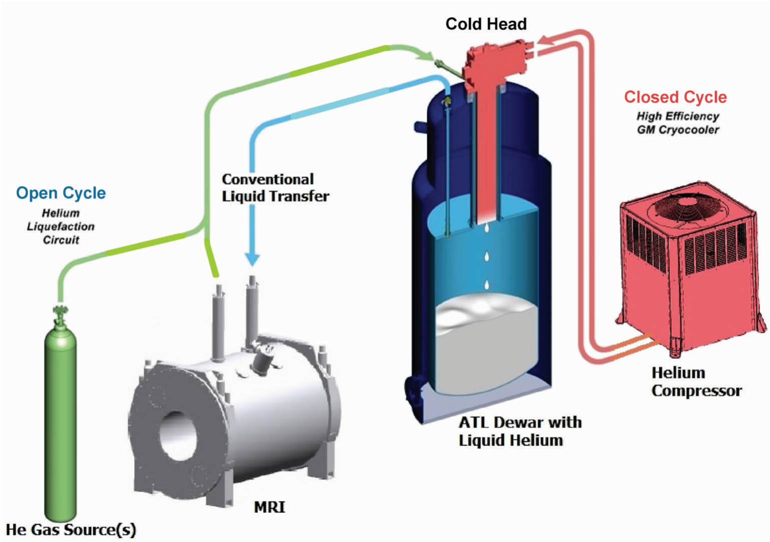

Figure 1. Schematic of a Magnetic Resonance Imaging (MRI) scanner direct recovery helium plant employing the ATL 160 (for illustration purposes only: not to scale).

SMART ENERGY DESIGN

Figure 1 is a schematic of a direct recovery helium plant employing the ATL 160 driven by the HAC 4500-LV split air cooled compressor that will be used to describe the "smart energy" design. The HAC 4500-LV is designed around an inverter rated 3-phase 5 horsepower Hitachi Scroll Capsule S500DHV. Two independent Hitachi WJ series inverters are used for driving the cold head and scroll capsule. The ATL160 is a versatile small scale helium liquefier[4], comprised of a simple Dewar equipped with a commercial two-stage G-M cold head[5] with a nominal cooling power of 1.5 W at 4.2 K used to liquefy the helium gas stream. In general, room temperature helium boil-off gas from the MRI scanner and other external sources is introduced into the liquefier Dewar, where it is precooled and liquefied. This liquefier has the ability to liquefy anywhere from 16 to 30 plus liters of liquid helium per day depending upon its mode of operation and the cooling power delivered to the cold head by the variable frequency compressor.[6]

EXPERIMENTAL RESULTS

Load Maps

Prior to the helium liquefaction experiments, the performance of the two stage G-M cold head driven by the HAC 4500-LV compressor was characterized by a number of conventional load maps with heat loads of up to 30 W applied to the first stage and loads up to 3.0 W applied to the second stage. Figure 2 reveals the rich load map landscape obtained using different compressor

and cold head input power frequencies. Of interest in this data is the exquisite control of the first and second stage cooling capacities at the temperatures of the cold stages. The load maps also indicate that during high capacity helium liquefaction the compressor and cold head power frequency should be maximized to maximize the first stage cooling power. In contrast, during periods of standby mode it might be advantageous to match the cooling power of the second stage with the low thermal heat load of this mode, something which is easily achieved by slowing the cold head and compressor power frequency to its minimum.

Variation of the power draw versus input frequency is shown in Figure 3. Using the HAC 4500-LV the two stage G-M cold head consumes between 3.1 kW to 7.6 kW (~ 0.55-0.7 P.F.) over the adjustable energy range. This data is compared with the commercially available constant frequency compressors that draw power between 8.0-10.7 kW.[7-8] This data clearly shows the HAC

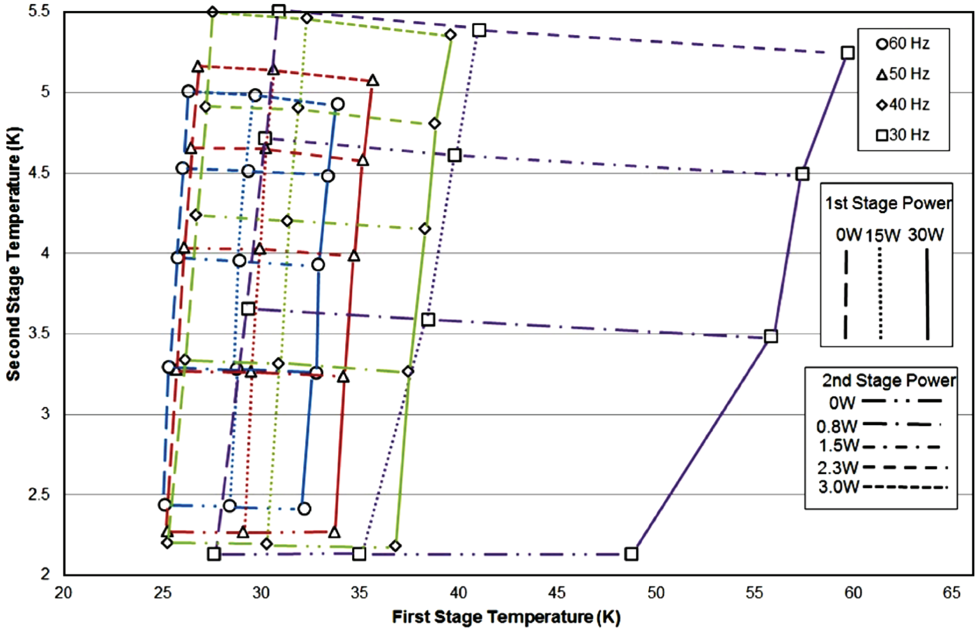

Figure 2. Cooling load maps of the two-stage cold head with the HAC 4500-LV compressor

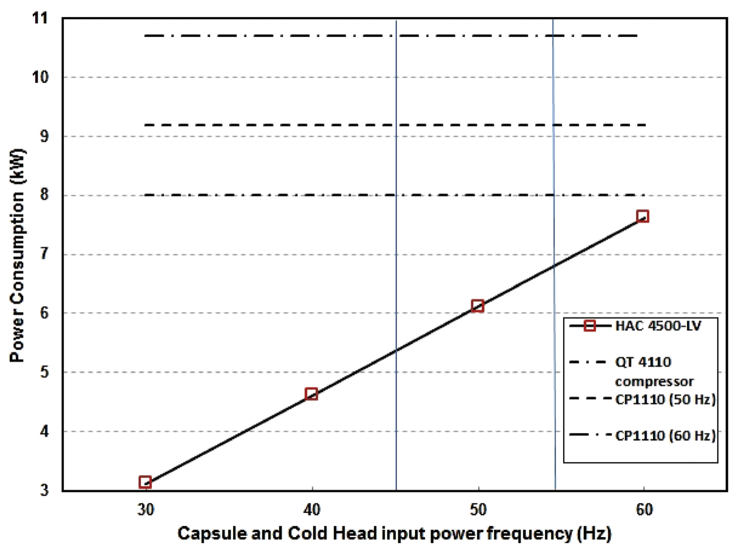

Figure 3. Comparison of power consumption between the HAC 4500-LV and constant speed compressors.

4500-LV to offer substantial operational cost reduction for the ATL160 users over systems that use constant power frequency compressors. In general three distinct regions of power consumption can be identified in the graph: 1) low power with input frequency up to 45 Hz, this range will be typically employed in the “quiescent” or “standby” mode that require minimal amount of cooling power delivered to the cold head, 2) medium power with input frequencies between 45 and 55 Hz for intermediate thermal heat loads and, 3) high power mode with frequency above 55 Hz for initial system cool down and fast liquefaction modes.

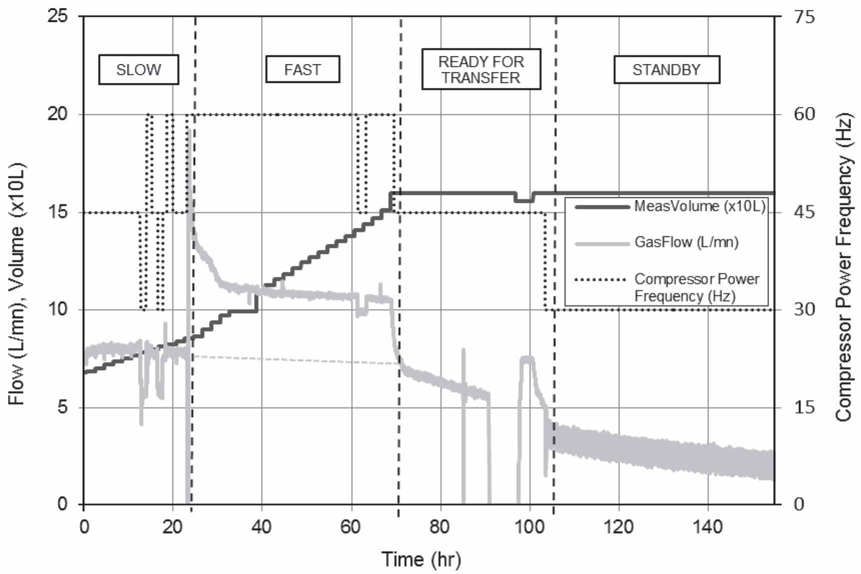

Figure 4. Smart energy operation of the ATL 160 small scale helium liquefier. Interval t = 0 -22.5 hr shows "Slow" mode at different frequencies (45-30-60-45-30-45-60-45 Hz). Interval t = 22.5 – 68 hr shows "Fast" liquefaction mode at different frequencies (60-45-60 Hz). Interval t = 68 – 105 hr shows "Ready for Transfer" at frequency of 45 Hz. Interval t=105-160 hr shows "Standby" status at frequency of 30 Hz.

Smart Energy Liquefier Operation

The data in Figure 4 show how the dynamic control of the compressor power frequency is used for ATL 160 helium liquefier smart energy operation. In general, in a helium liquefier it is important to operate at the highest cooling capacity during initial cool down of the system and in the "Fast" liquefaction mode in which liquid helium is liquefied as rapidly as possible. ATLs can operate at different liquefaction modes between "Slow" (20 L/Day) and "Fast" (>30 L/Day).[1,4]

The interval t = 0 - 22.5 hr is an example of "Slow" liquefaction mode at different compressor frequencies (30-45-60 Hz). A frequency change sequence (45-30-60-45-30-45-60-45 Hz) has been performed to find the optimum value for this mode as well as to check reproducibility. The maximum input helium gas flow is around 8-9 sL/min, that corresponds to a liquefaction rate of 19.5-22 L/Day. Clearly this is an intermediate heat load liquefaction mode since the maximum flow is obtained at around 45 Hz. The interval t = 22.5 - 68 hr is an example of "Fast" liquefaction mode. In this mode the liquefier is subject to a large thermal load from the incoming room temperature helium gas at a rate as high as 12 sL/min or more. Thus, as illustrated in Figure 4, in Fast liquefaction mode, the optimum compressor frequency value is that corresponding to the high power (60Hz) compressor mode. Liquefaction rates achieved in this mode are in excess of 30 L/Day while consuming 7.6 kW. The integral of gas flow rate above the extrapolated dashed line of the "Slow" mode is directly related with the gain in liquefaction rate when using "Fast" mode, a unique feature of ATL liquefaction technology.[1,4] At t = 72 hr, the ATL, full of liquid, reduces automatically the compressor power frequency to 45 Hz, since the "Ready for Transfer" status is also an intermediate heat load process.

Once the ATL helium liquefier is full it will keep the helium liquid inventory indefinitely until it has to be transferred into the MRI or any other cryostat. While in this "quiescent" or "standby" mode, the thermal load to which the liquefier is subject to, is minimal, and, the HAC 4500-LV reduces the power frequency of the system (30 Hz), thus, reducing the power draw to about 3.1 kW. Example of this mode is from about t~105 hr.

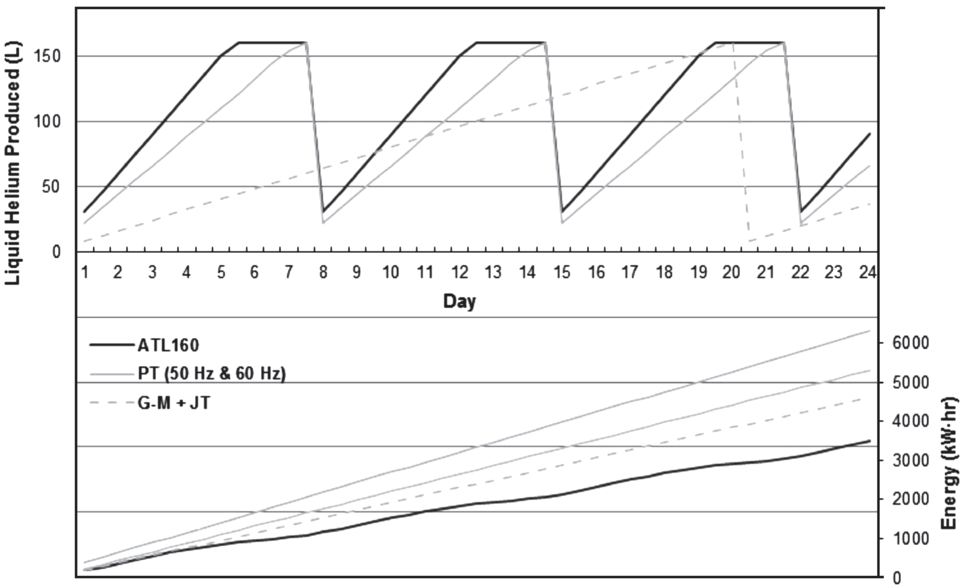

Figure 5. Comparison of liquid helium production and energy consumption.

Table 1. Summary of performance of liquefaction plants classified by their size and technology (XL= eXtra Large, L= Large, M= Medium, S=Small, XS= Extra Small).

Class	Technology	Liquefaction Rate (L/hr)	Power (kW)	Performance (L/hr)/kW
XL	Collins	>1000	>1000	>1.0
L	Collins	>100	>100	0.5-1.2
M	Collins	>10	>30	0.3-1.2
S	Variable frequency cryo-refrigerator [this work]	0.83-1.25	5.3-7.6 kW	0.15-0.16
S	Constant frequency cryo-refrigerator[7]	0.92	9.2 kW	0.10
S	Constant frequency cryo-refrigerator + JT[8]	0.33	8 kW	0.04
XS	Constant frequency cryo-refrigerator	> 0.1	> 3 kW	0.03

In practice, higher liquefaction rates and smart energy operation allow the ATL 160 liquefier to exceed by at least 60 liters/week the liquid helium production of other commercial liquefiers based on Pulse Tube (PT)[7] or G-M with Joule-Thompson cooling (G-M+JT)[8] technologies and with as much as 45% less energy consumption. Figure 5 shows that in a 24 day period, the ATL 160 is able to produce 160 liters of liquid helium every five days, with the first four days of each week operating in "Fast" mode, the next day going to "Slow (Ready for Transfer)" mode and the remaining hours before a weekly helium transfer in "standby". At the end of a hypothetical 24 day period the ATL 160 consumes 3,431 (kW·hr) compared to 6,163 (kW·hr) from a liquefier based upon a single frequency cryo-refrigerator-compressor combination.

Performance Comparison of Small Scale Helium Liquefiers

Table 1 provides a comparison of various classes of liquefiers. The performance, R, of the liquefaction system can be defined by the liquefaction rate (L/hr) divided by the electrical power (kW) of the refrigerator. To our knowledge the best prior value of helium liquefaction performance obtained with a G-M cooler was reported to be approximately 0.08 (L/hr)/kW by Schmidt-Wellenburg et al.[9] in 2006. Here we have reported on a system that not only is more efficient at peak operation but which can also dynamically reduce the power draw during periods of "idle" operation. Its performance can be dynamically varied between 0.15 to 0.16 (L/hr)/kW. The ATL160 exhibits higher liquefaction efficiency than the best liquefier commercially available based upon a pulse tube cold head[7], exploiting solely the cooling power of the cold head. This design is also more efficient than more complex devices that use Joule-Thomson (JT) cooling.[8] In the future, it is expected that the performance, R, of small scale helium liquefiers, will continue to improve and potentially be equal or even higher than those obtained with medium liquefaction plants (class M), based on the Collins liquefaction technology.

CONCLUSION

We have described a smart energy helium compressor for use in conjunction with a new versatile small scale helium liquefier. This system allows for intelligent oversight and budgeting of the cooling power delivered to a two stage G-M cold head in the helium liquefier. This novel design allows for substantial reduction in operational cost of the helium liquefier when compared to other technologies that use single speed compressors.

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