Dynamic Operation of a 4 K Pulse Tube Cryocooler with Inverter Compressors

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ABSTRACT

This paper introduces the concept of operating a 4 K pulse tube cryocooler using an inverter-driven compressor. The cryocooler is a Cryomech model PT410. By adjusting the power frequency of the inverter compressor from 46 to 70 Hz, the cryocooler can offer 22 W to 43 W at 45K on the first stage and 0.5 W to 1.1 W at 4.2 K on the 2nd stage; for this range, the compressor input power changes from 5.0 kW to 8.6 kW. Dynamic operation of the 4 K pulse tube cryocooler has been successfully demonstrated using a liquid helium cryostat. The compressor controller maintained the desired cryostat temperature by adjusting the power frequency to reduce the cooling capacity of the pulse tube cooler at 4 K, and resulted in less compressor input power.

INTRODUCTION

4 K pulse tube cryocoolers have been used for conductive cooling and recondensing helium in cryostats.[1,2] When this is done, the cryocooler is usually selected to have more capacity than the cryostat needs with a margin of 20-40%. In order to maintain the cryostat temperature at 4 K, a heater is used to compensate for the excess cooling capacity of the cryocooler. For an application of recondensing helium in an MRI, a heat load of 0.3 W to 0.5 W will be applied to maintain a positive vapor pressure in the cryostat. The COP of the current commercial 4 K GM and pulse tube cryocoolers is around 0.00014. Therefore, a few kilowatts of input power could be wasted during steady system operation.

Inverter technology has been used for two decades in air conditioning systems for energy efficient operation. The concept uses a variable-frequency drive to control the speed of the motor and thus the compressor. The variable-frequency drive uses a rectifier to convert the incoming AC current to DC and then uses pulse-width modulation of the DC current within the inverter to produce AC current of the desired frequency.

In this paper, we examine the use of an inverter-driven 4 K pulse tube cryocooler to regulate the cooling capacity by altering the speed of the compressor in response to the cooling demand. Thus, one can maintain a desired cryostat temperature without using a heater. Dynamic operation of the Cryomech model PT410 4 K pulse tube cryocooler has been demonstrated in conjunction with maintaining zero boil off and positive vapor pressure in a liquid helium cryostat.

SYSTEM DESIGN

A 4 K cryocoolers normally operates with 50 Hz power or 60 Hz power. An inverter driven compressor provides an adjustable compressor speed when driven by power frequencies from 30 to

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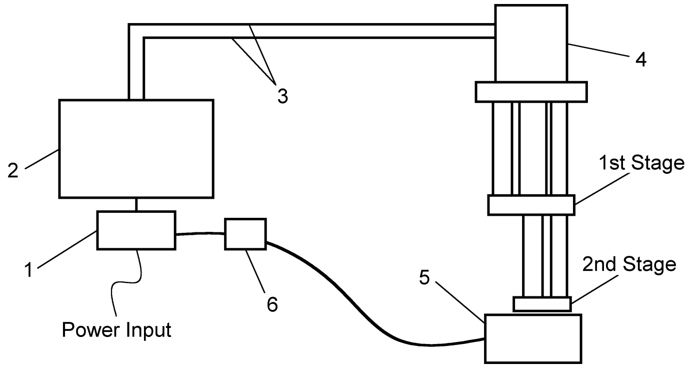

Figure 1. Schematic of the 4 K pulse tube cryocooler with an inverter compressor and the concept of its application. 1. Inverter; 2. Compressor; 3. Flexible lines; 4. Cold head; 5. Cryogenic device; 6. Controller.

78 Hz. Therefore, the system can dynamically operate with different input powers as required to meet the cooling demands of the cryostat. Figure 1 shows a schematic of a 4 K pulse tube cryocooler with an inverter driven compressor and the concept of its application. A standard 4 K pulse tube cryocooler, Cryomech Model, PT410, was selected for the testing. The specifications of it are >35 W at 45 K on the first stage and >1 W at 4.2 K on the 2nd stage, while consuming ~7.5 kW.

The PT410 pulse tube cryocooler includes a compressor package (2), two flexible lines (3), and a cold head (4). The inverter (1) is used to alternate the frequency of the input power for the compressor. The cryogenic device (5) cooled by the cold head has a temperature sensor or pressure sensor. The data from the temperature sensor or pressure sensor are sent to the controller (6). The controller controls the frequency of the inverter to maintain the desired temperature or vapor pressure of the cryogenic device.

Three compressor packages have been tested with the PT410 cold head. The standard PT410 is driven by the CP2880 compressor with a Copeland scroll compressor module, model ZC68. Two compressor models, CP2870 and CP2860F, have been installed with Hitachi compressor modules, the inverter in the present testing. The Hitachi S500DHV is an inverter model designed to operate at frequencies from 30 Hz to 78 Hz. The CP2860F is a prototype compressor package at Cryomech, Inc at this time.

EXPERIMENTAL RESULTS

Cooling Performance with Inverter Driven Compressors

The performance of the PT410 operating with three different compressor packages is illustrated in Figure 2. The performance comparisons are based on similar input powers to the system. The PT410 cold head operates very well and provides comparable performance with all three compressors allowing the cold head to perform within the specifications of the PT410 cryocooler. The system with the CP2880 compressor operates with the standard parameters of 60 Hz power and a static pressure at 1.69 MPa. It provides 40W at 42.7 K on the first stage and 1.0W at 4.05 K on the 2nd stage, simultaneously, with an input power of 7.6 kW. The system with the CP2870 inverter compressor operates with a power frequency of 62 Hz and a static pressure at 1.75 MPa. It can provide 40 W at 43.1 K and 1.0 W at 4.15 K with an input power of 7.9 kW. The system with the CP2860F inverter compressor operates with the power frequency of 66 Hz and a static pressure of 1.82 MPa. It provides 40 W at 44.9 K and 1.0 W at 4.12 K with an input power of 7.6 kW. The slightly lower efficiency with the two inverter compressors is most likely caused by: 1) Conversion losses in the inverter, which could be as high as 4-6%, and 2) the cold head being optimized for the CP2880 compressor, not for the CP2870 or CP2860F compressors.

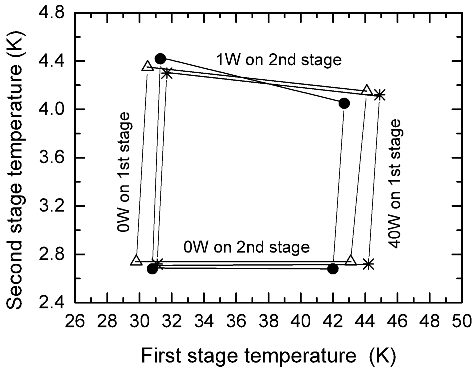

Figure 2. Cooling load map of the PT410 with three different compressors: —Δ— CP2870; —•—CP2880; —*— CP2860F.

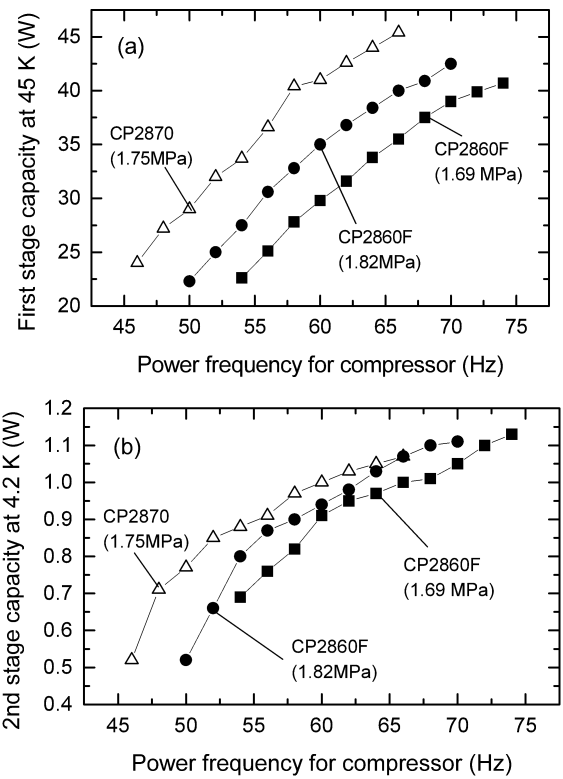

Figure 3. Variation of 1st stage cooling and 2nd stage capacity with power frequency: (a) 1st stage capacity, the 2nd stage is at 4.2 K; (b) 2nd stage capacity, the 1st stage is 45 K.

Next, we examine the performance of the PT410 pulse tube cryocooler operating with the two inverter compressors. Figure 3 shows the variation in the 1st stage and 2nd stage performance for different power frequencies. The system with the CP2860F compressor has been tested with two static pressures of 1.69 MPa and 1.82 MPa. The CP2860F has less displacement than the CP2880 and CP2870 compressor, leading it to operate with a higher frequency to meet the PT410 specifications. To obtain 25 W to 40 W at 45 K on the 1st stage and 0.5 W to 1.0 W at 4.2 K on the 2nd stage cooling capacity, the CP2870 and CP2860F systems required operation with power frequency ranges

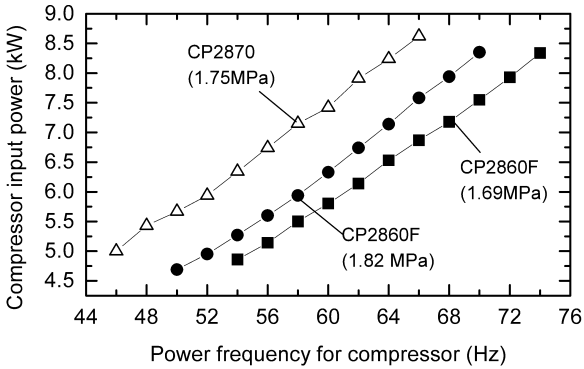

Figure 4. Variations of compressor input power with power frequency. The 1st and 2nd stages are at 45 K and 4.2 K, respectively.

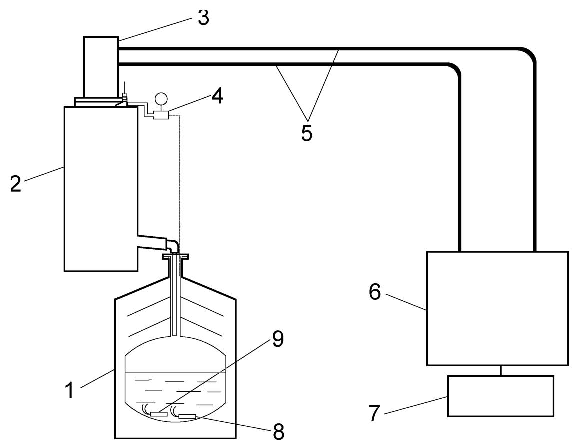

Figure 5. Schematic of the cryostat with the helium reliquefier driven by inverter compressor. 1. Liquid helium cryostat; 2. Reliquefier assembly; 3. PT410 cold head; 4. Pressure gauge; 5. Flexible lines; 6. Compressor; 7. Inverter; 8. Temperature sensor; 9. Heater.

of 46 Hz - 62 Hz and 52 Hz - 68 Hz, respectively. The static pressure of the system with the CP2860F shows a lager effect on the 1st stage performance and less effect on the 2nd stage performance.

Variation of power consumption with power frequency is shown in Figure 4. The PT410 cryocooler consumes 4.6 kW to 8.5 kW over the adjustable power frequency range.

Helium Recondensing with Inverter Cryocooler

The PT410 with the inverter compressor CP2870 was installed in a helium reliquefier to recondense helium in a cryostat. The details of the reliquefier are described by Wang [2]. Figure 5 shows a schematic of the liquid helium cryostat with the reliquefier driven by the inverter compressor. The reliquefier liquid return line is inserted into the neck of the cryostat and a vapor line connects to the top of the reliquefier assembly. Thus, the reliquefier forms a closed helium loop for the cryostat.

A temperature sensor (8) and a heater (9) are installed inside of the liquid helium bath in the cryostat. The heater applies heat loads to the liquid helium and simulates the cryostat boil off. Another temperature sensor is installed on the condenser of the reliquefier. A pressure gauge (4) monitors the vapor pressure in the cryostat.

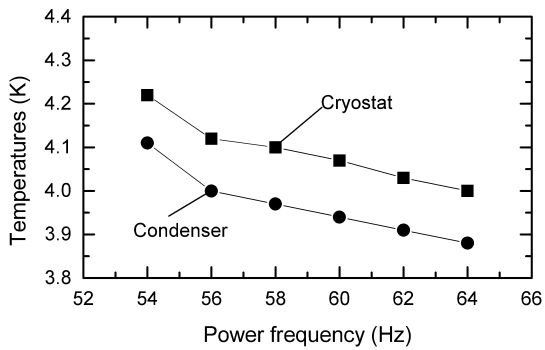

Figure 6. Temperature of cryostat and condenser as a function of the power frequency used to drive the compressor. A heat load of 0.7 W is applied into the liquid helium.

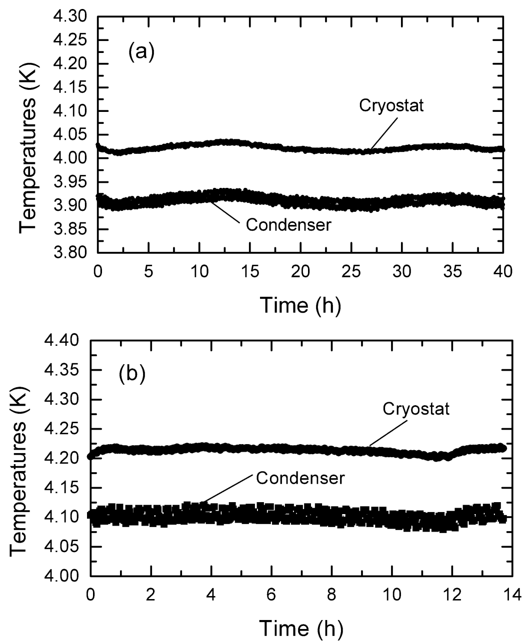

Figure 7. Stability test of the recondensing system with two different heat loads in the liquid helium. (a) 0.5 W heat loads in LHe and reliquefier with 48 Hz power frequency; (b) 0.7 W heat loads in the LHe and reliquefier with 54 Hz power frequency.

Figure 6 shows the temperature of the liquid helium and the reliquefier condenser achieved by adjusting the power frequency while applying a heat load of 0.7 W into the liquid helium bath. The reliquefier has extra capacity at most power frequencies to condense the boil off from the cryostat, and therefore a lower vapor pressure of <1 atm occurs in the cryostat. By reducing the power frequency to 54 Hz, the reliquefier can maintain the cryostat at a temperature of 4.22 K (1 atm vapor pressure). The power consumption of the system can be reduced from a full load of 7.9 kW (62 Hz) to 6.3 kW (54 Hz). Here we select the capacity with a 62 Hz power frequency as a measure of the full capacity of the PT410 with CP2870 compressor.

Figure 7 shows stability tests when applying 0.5 W and 0.7 W heat loads into the liquid helium bath of the cryostat. In Figure 7 (a), the reliquefier operates with the power frequency of 48 Hz and maintains the liquid helium temperature at 4.02 K while consuming 5.4 kW. In Figure 7 (b), the heater applies 0.7 W into the liquid helium bath, and the reliquefier operates at a power frequency of 54 Hz while consuming 6.3 kW. Both tests demonstrate steady operation of the helium recondensing by adjusting the power frequency to control the cryostat vapor pressure. Slight temperature oscillations on the condenser and in the cryostat are caused by the variations of heater power. A DC power supply provides current to the heater, which is not very stable during testing.

CONCLUSION

A 4 K pulse tube cryocooler has successfully operated with two inverter compressors. It can provide 22 to 43 W at 45 K on the 1st stage and 0.5 to 1.1 W at 4.2 K on the 2nd stage by adjusting the power frequency from 46 Hz to 70 Hz. The 4 K pulse tube cryocooler with the inverter compressor has been used to recondense helium in a cryostat and demonstrate high system efficiency by adjusting the power frequency.

ACKNOWLEDGMENT

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