Development of a 4 K Regenerator and Pulse Tube Test Facility

R. Taylor[1,2], M. Lewis[2], P. Bradley[2], and R. Radebaugh[2]

[1] Virginia Military Institute
Lexington, VA 24450 USA

[2] National Institute of Standards and Technology
Boulder, CO 80305 USA

ABSTRACT

Recent advances in superconducting electronic systems are requiring larger envelopes for cooling power, efficiency, and operational environments from commercial based cryogenic cooling systems. One such system targeted at meeting these requirements is the pulse tube cryocooler. While the pulse tube cryocooler system is a well-documented technology at moderate cryogenic temperatures (40-80 K), its behavior at 4 K is not well understood. Recent modeling results using REGEN3.3 and CFD models have shown that 4 K pulse tube cryocoolers can be successfully applied to superconducting electronic systems. To gain confidence in the modeling predictions, experimental validation is required. This paper discusses a test facility designed and constructed to allow for precise measurement of all relevant regenerator and pulse tube energy flows when operating over the temperature range of 4 - 30 K, frequency range of 10-30 Hz, and cold end phase angle range of -15° to -45°. The novel features of this test facility include independent regenerator and pulse tube characterization, modulation of the system phasing using a commercial expander operating at 4 K, precise off-axis rotation, and rapid experimental turnaround time.

INTRODUCTION

In recent years the Pulse Tube Cryocooler (PTC) has been utilized to provide reliable cryogenic cooling for many applications ranging from cooling of superconducting electronics to basic laboratory workhorse closed cycle coolers. This technology has been commercialized (GM variant) by various manufactures with nominal cold end temperatures of 4.2 K under load. Even with this significant growth, the 4 K PTC suffers from large and bulky size, significant input power, and is plagued by complex loss mechanisms. In order for the PTC to remain a viable system for future applications requiring cooling at 4 Kelvin, two areas must be improved: 1) specific cooling capacity and 2) physical size of the cooler to include the phase shifting device and pressure wave source. In order to achieve these goals there must be significant effort aimed at better understanding the complex processes which occur in the PTC over the temperature range of 4-20 K.

The design process for modern PTC's involves balancing many competing effects to attain a desired operational envelope. To aid in this design process, designers often use a combination of

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design software coupled with analytical models and accepted "rules of thumb." Specifically, there exist numerous modeling tools ranging from basic analytical models to multidimensional CFD codes for cryocooler design. In this regard, much of the system design is focused on two components: the regenerator and the pulse tube. These two components dominate the design process due to the relative magnitude of system losses that occur in these two components. The relative magnitude of these losses is shown in Figure 1 for a moderate cold end temperature of 4K.

Observation of the data shown in Figure 1 indicates the losses stemming from the regenerator and pulse tube components are significant and increase with reduction in cold end temperature. A critical step in the development of next generation 4 K PTC's is the fundamental understanding of the hydrodynamic and thermal processes that occur. Specifically, these losses manifest themselves as regenerator ineffectiveness, pressurization losses (real gas effect), asymmetric flow instabilities, shuttle heat transport, and secondary flow streaming. While some of these losses are well understood at moderate cryogenic temperatures (40-80K) their effects are less understood at temperatures ranging from 4-20 K. This lack of understanding in the range of 4-20 K is predominantly due to the effects of real gas fluid properties (viscosity, density, heat capacity, compressibility), the solid to fluid thermal capacity ratio being of unity or less, advanced rare-earth regenerator materials, and novel regenerator matrix configurations. To gain better understanding of these phenomena, and to optimize 4 K performance, various modeling programs are used. In general, these models include SAGE1 (overall system), REGEN3.32 (regenerator), and/or commercial CFD codes (overall or component based) to design these components. While these models have been extensively validated at moderate cryogenic temperatures, detailed validation is lacking in the temperature range of 4-20 K.

Based on the aforementioned discussion, there exists a critical void related to experimental measurements of 4 K regenerator and pulse tube performance required for validation of critical design models. Previous researchers such as Pfotenhauer3 and Kashani4 have detailed regenerator test facilities for operation down to 10 Kelvin with mixed success. To the author's knowledge no modern facility has been developed that is capable of providing performance data at 4 K for the regenerator and pulse tube components. As a result, the remainder of this paper details the development of a 4 K test facility capable of precise measurement of performance parameters for an isolated regenerator and regenerator pulse tube combination. Unique to the developed test facility is rapid testing turn-around time, modulation of system phasors using a cold expander, off-axis rotation capability, and a wide temperature testing envelope allowing for applicability at all temperatures of interest to designers.

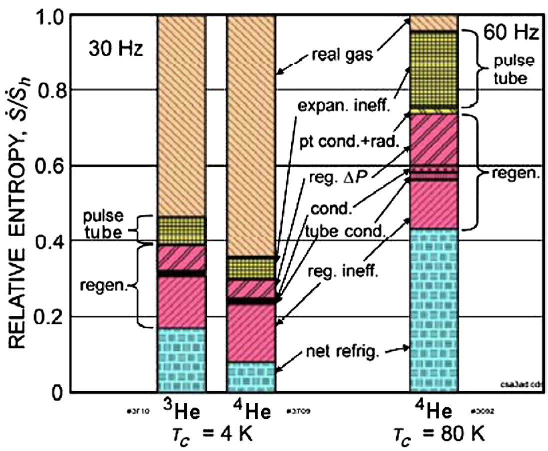

Figure 1. Illustration showing the relative magnitude of losses in a PTC with delineation of the regenerator and pulse tube losses; from Radebaugh.[5]

TEST FACILITY DESIGN

The design process for the 4 K test facility involved numerous constraints in addition to retaining utility for future areas of investigation. Specifically, it was determined the test facility design should incorporate the following characteristics/abilities:

All Configurations
1) Off-axis regenerator and pulse tube measurements from 0° → 180°,
2) Operating frequency range of 30 Hz or 60 Hz,
3) Charge pressure of 0.75 MPa → 1.5 MPa, and
4) Cold end phase angle of 0° → -45°

4 K Nominal Configuration
1) Regenerator and pulse tube cold temperatures from 3.2-7 K, and
2) Regenerator and pulse tube warm temperatures from 20-35 K

80 K Nominal Configuration
1) Regenerator and pulse tube cold temperatures from 15-35 K, and
2) Regenerator and pulse tube warm temperatures from 60-90 K

Using these criteria, the overall test facility was developed using the REGEN3.3, PHASOR [6], and ISOHX [7] design software coupled with the use of a new analytical model for cold expander performance. The results of this design process yielded a three-stage in-line PTC configuration being optimal with regard to the desired operational space. Specifically, this configuration allows for a high degree of testing flexibly via its modular nature achieved by removal or addition of cooling stages. Note that while this facility allows for measurements at moderate cryogenic temperatures, the remainder of this paper is oriented towards 4 K performance measurements. However, the measurement principles, configurations, and methods used for 4 K experimentation are essentially identical for higher temperatures.

To facilitate performance measurements for 4 K operation, the developed test facility can be operated in one of two configurations: 1) isolated regenerator characterization, and 2) combined regenerator and pulse tube characterization. These two facility configurations are shown graphically in Figure 2.

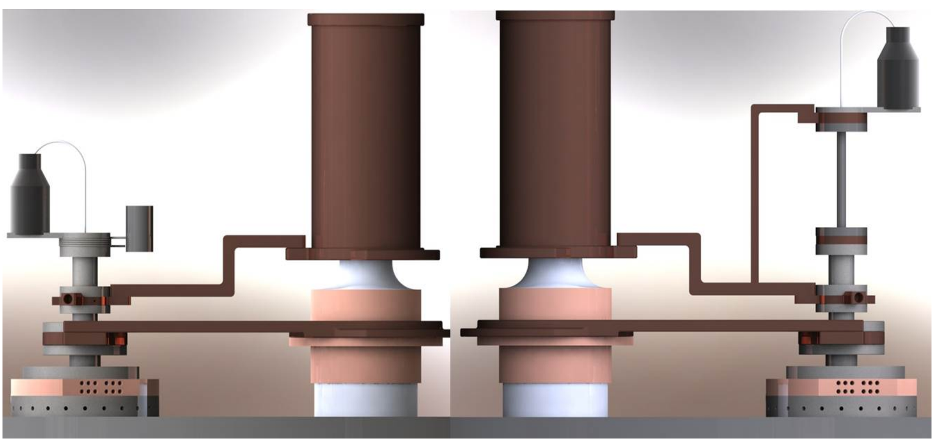

Figure 2. (left) Illustration of the test facility configured for 4 K regenerator measurements; (right) Illustration of the test facility for configured for 4 K regenerator/pulse tube measurements.

Both system configurations shown in Figure 2 contain the following components: linear compressor, aftercooler, 1st stage pre-cooling regenerator, 1st stage thermal intercept, 2nd stage pre-cooling regenerator, 2nd stage thermal intercept, 3rd stage test regenerator or test regenerator and pulse tube, 3rd stage thermal intercept, and a cold expander. A commercial GM cryocooler is used to provide precooling at the first and second stage intercepts which operate at nominal temperatures of 80 K and 20 K, respectively. The test regenerator/pulse tube cold end (3rd stage thermal intercept) is fixed at a nominal temperature of 4.2 K using a continuous flow of LHe. Cooling of the 3rd stage thermal intercept via LHe was implemented for three reasons: 1) 4 K heat flow measurement resolution, 2) variable heat loads can be accounted for via modulation of LHe flow, and 3) the large specific heat of the boil-off He gas allows for supplemental cooling of the cold expander or pulse tube warm heat exchanger. Unique to this test facility is the ability to modulate the system phasors in real time. This ability is realized through use of a small linear compressor that operates as a frequency-locked cold expander. Prior work[8] has shown this expander to be capable of sustained operation at cryogenic temperature. A summary of the test facility specifications are listed in Tables 1, 2, and 3.

Table 1. Test facility operational specifications.

Specification	Nominal Value
Frequency (Hz)	15-30
Charge Pressure (MPa)	0.5-1.5
1st Stage Temperature (K)	60-90
2nd Stage Temperature (K)	20-35
3rd Stage Temperature (K)	3.2-7
3rd Stage Cold Phase Angle (deg)	0 – (-45)

Table 2. Test facility regenerator specifications.

Specifications	Nominal Values θ_c= -15°	Nominal Values θ_c = -30°	Nominal Values θ_c = -45°
1st Stage Regenerator			
Length (cm)	2		
Diameter (cm)	2.43		
Matrix (-)	#325 diffusion bonded SS304 screen		
Cold Pressure Ratio	1.64	1.61	1.585
Warm PV Power (W)	335	261.5	206
Cold PV Power (W)	63.1	56	45.5
2nd Stage Regenerator			
Length (cm)	2		
Diameter (cm)	2		
Matrix (-)	#325 diffusion bonded SS304 screen		
Cold Pressure Ratio	1.595	1.577	1.557
Warm PV Power (W)	67.5	54	43.4
Cold PV Power (W)	22.5	19.6	15.1
3rd Stage Regenerator*			
Length (cm)	3.5		
Diameter (cm)	2		
Cold Pressure Ratio	1.5	1.5	1.5
Warm PV Power (W)	20.8	18	14.4
Cold PV Power (W)	4.71	4.2	3.36

*** Assumes the regenerator material is 100um GOS spheres.**

Table 3. Test facility thermal intercept specifications.

Specifications	Nominal Value
1st Stage Thermal Intercept	
Length (cm)	1
Diameter (cm)	2.5
Matrix (-)	#100 diffusion bonded copper
Temperature (K)	80
2nd Stage Thermal Intercept	
Length (cm)	0.8
Diameter (cm)	2
Matrix (-)	#200 diffusion bonded copper
Temperature (K)	20
3rd Stage Thermal Intercept	
Length (cm)	0.6
Diameter (cm)	2
Matrix (-)	30μm sintered silver powder
Temperature (K)	4.2

EXPERIMENTAL INSTRUMENTATION

During operation of the test facility, fundamental measurements of temperature, pressure, volumetric flow rate, and phase are required to allow for calculation of performance parameters such as the regenerator loss, pulse tube loss, acoustic power flows, mass flow rates, pressure ratios, and thermal loads. The measurement of temperature in the test facility is performed using calibrated Si diode sensors (60-300 K) or calibrated Negative Coefficient Resistance thermometers (1.4-60 K). Measurement of dynamic/mean system pressure is performed using custom calibrated piezoresistive pressure transducers with a nominal range of 1.4-3.4 MPa (200- 500 psig). Measurement of differential pressure is performed using custom calibrated piezoresistive pressure transducers that have a nominal range of 0-35 kPa (0-5 psid). Volumetric flow rate, relevant for measurement of LHe boil off, is performed using a calibrated commercial thermal mass flow sensor. Phase angles are measured using the pressure transducer signals via lock-in amplifiers. The location of temperature and pressure (gage and differential) measurements are shown schematically in Figure 3. Note that additional instrumentation is required depending on the testing configuration and is illustrated in Figures 4, 6, and 7.

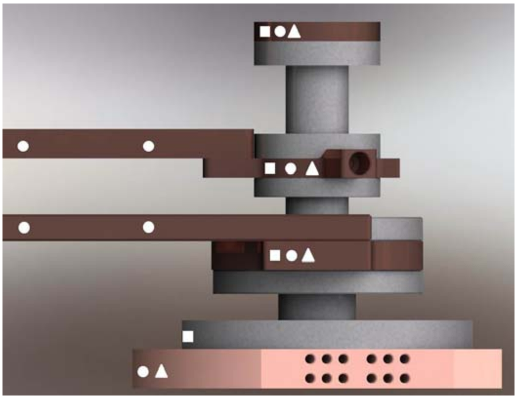

Figure 3. Schematic of the test facility noting locations of pressure and temperature measurement (squares indicate pressure, circles indicate temperature, and triangles indicate differential pressure).

Pressure Sensor Calibration

To aid in accurate measurement of pressure in the developed test facility, thorough and precise calibration of the piezoresistive transducers is required. Generally this type of transducer is rated for operation at room temperature. Past work by these authors has shown piezoresistive sensors continue to work at cryogenic temperatures provided they are calibrated for the desired operating temperature. An additional benefit of using piezoresistive sensors at cryogenic temperatures is increased sensitivity. Generally this sensitivity increases by factor of ~2 from 300-77K and ~2.5 from 300-25 K, aiding in high accuracy measurements. Calibration of the pressure sensors is a relatively simple process, even at cryogenic temperatures, that consists of setting the zero and full scale values. In practice, this process is performed by cooling the test facility to a desired testing temperature. At temperature, the system is evacuated allowing for zero scale calibration, whereas full scale is set by pressurizing the system with respect to a reference pressure standard that is NIST traceable.

Mass Flow Meter Calibration

Accurate measurement of the oscillating mass flow rate in a PTC is a non-trivial measurement as discussed by Rawlings[9] and Taylor[10]. Fortunately, a relatively simple and non-intrusive technique previously developed by the authors allows use of resistive elements already present in a PTC to serve as mass flow sensors. Specifically, the hydraulically resistive heat exchangers can serve as mass flow sensors provided the relationship between mass flow rate and pressure drop are known. This relationship is determined through generation of temperature specific calibration curves that relate the measured thermal intercept pressure difference to mass flow rate. The basic principle of this calibration is shown in Figure 4.

Knowledge of the mass flow amplitude in the thermal intercept is determined using basic thermodynamic analysis applied to the reservoir volume attached to the thermal intercept during the calibration process. Assuming adiabatic behavior in the reservoir the mass flow amplitude $|\dot{m}_{res}|$ at the reservoir can be determined from Eqn. (1),

$$|\dot{m}_{res}| = \frac{|\tilde{P}| V_{res}}{\gamma T_{res} R} Z \tag{1}$$

where V_{res} is the volume of the reservoir, T_{res} is the temperature of the reservoir gas, γ is the ratio of specific heats for the working fluid, R is the gas constant for helium, $|\tilde{P}|$ is the magnitude of dynamic pressure amplitude, and Z is the compressibility factor. It should be noted this procedure is valid for generation of mass flow calibration curves for the aftercooler, 1st stage intercept, 2nd stage intercept, and 3rd stage intercept. The compressibility term (Z) is included only for mass flow calibrations that occur where real gas effects are non-negligible (4-20 K).

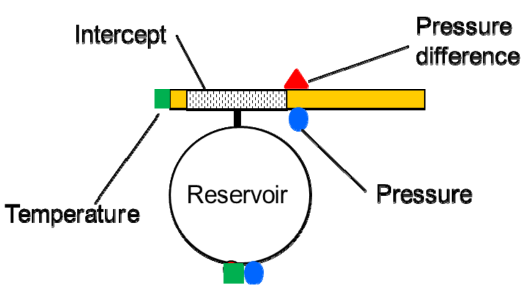

Figure 4. Schematic of the mass flow calibration test set-up.

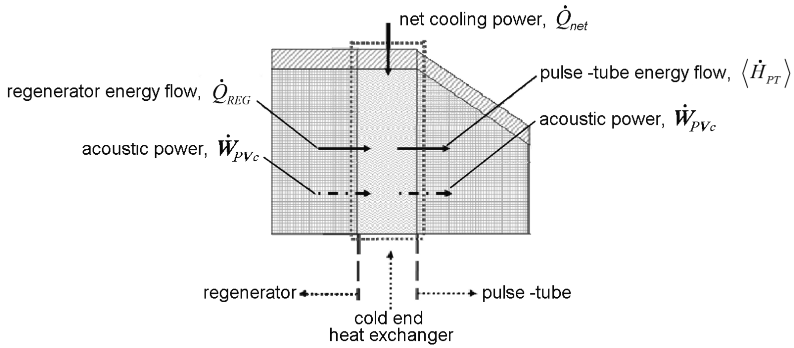

Figure 5. Illustration showing an energy balance applied to the cold end of a PTC.

PERFORMANCE MEASUREMENT METHODOLOGY

To measure 4 K PTC performance parameters of interest for system designers, care must be taken to understand the relevant energy flow terms. These pertinent energy flows can be realized via an energy balance applied to the cold end of a PTC as shown in Figure 5.
Using energy conservation, the pulse tube enthalpy flow term in Figure 5 can be represented as,

$$\left\langle \dot{H}_{PT} \right\rangle = \dot{Q}_{REG} + \dot{Q}_{net} \tag{2}$$

where $\dot{Q}_{REG,G}$ is the regenerator energy flow (gross regenerator loss), $\dot{Q}_{net}$ is the net cooling power provided by the cooler, and $\left\langle \dot{H}_{PT} \right\rangle$ is the net enthalpy flow in the pulse tube. Observation of Eqn. (2) indicates that for a fixed temperature, the cooling power (cooler performance) is directly proportional to the pulse tube enthalpy flow and the regenerator loss. For optimum performance, an ideal design minimizes the regenerator loss while maximizing the pulse tube enthalpy flow. In this context, the ability to accurately predict and understand the underpinnings of these two energy flow terms is critical for optimal 4 K performance.

The basic energy balance noted in Eqn (2) yields insight into the relevant energy flows for a 4 K PTC. However, further analysis of these energy flow terms can be realized. The gross regenerator loss noted in Eqn. (2) represents potential cooling that is irreversibly lost due to a combination of specific regenerator loss mechanisms,

$$\dot{Q}_{REG} = \left\langle \dot{H}_{RG} \right\rangle + \dot{Q}_{eff} + \dot{Q}_{Matrix} + \dot{Q}_{Wall} + \dot{Q}_{Gas} \tag{3}$$

where $\left\langle \dot{H}_{RG} \right\rangle$ is the real gas enthalpy flow (pressurization loss), $\dot{Q}_{eff}$ is the thermal load developed due to imperfect heat exchange between the matrix and working fluid (ineffectiveness), $\dot{Q}_{Matrix}$ is the conductive heat flow in the regenerator matrix, $\dot{Q}_{Wall}$ is the conductive heat flow in the regenerator wall, and $\dot{Q}_{Gas}$ is the conductive heat flow of the gas. Of these five components, the conductive terms are well understood and typically represent a minor portion of the gross regenerator loss. The remaining two terms, the ineffectiveness and pressurization losses, are of practical interest for validation of design models and must be experimentally quantified. Furthermore, a similar approach can be performed with respect to the pulse tube enthalpy flow. Per Eqn. (2), knowledge of the pulse tube enthalpy flow can be inferred from measurement of the aforementioned gross regenerator loss and the net cooling power. However, the losses present in the pulse tube component must be inferred from knowledge of the maximum available work that could be extracted if the gas exiting the regenerator were to expand against a reversible piston.

Following this logic, the pulse tube loss can be defined as,

$$\dot{Q}_{PT,Loss} = \langle \dot{P}V_C \rangle - \langle \dot{H}_{PT} \rangle \tag{4}$$

where $\langle \dot{P}V_C \rangle$ is the acoustic power delivered to the cold end of the pulse tube and $\dot{Q}_{PT,Loss}$ is the loss due to the complex thermal and hydraulic phenomena that occur in the pulse tube component (shuttle heat loss, asymmetric flow streaming, turbulence, etc.).

Based on this discussion, measurement of the regenerator and pulse tube losses require knowledge of various energy flow terms present in a PTC. The methodology required to facilitate measurement of these energy flows is non-trivial and requires specific processes and experimental test set-ups. The developed measurement methodology and experimental techniques employed to measure these quantities using the developed 4 K test facility is discussed in the following sections.

Regenerator Loss Measurement

Prior work by Taylor[10] described a methodology used to measure the gross regenerator loss in a test facility operating at nominal temperature of 60-80K. This specific technique involved a calibrated thermal bus such that a measured temperature difference corresponded to a known heat flow. This approach was considered but ultimately abandoned due to accuracy considerations. Specifically, the work by Taylor involved measurement of energy flows on the order of 10's of watts whereas the anticipated loads in this facility are on the order of 0.1-1 W. As such, temperature measurement resolution coupled with limited 4 K commercial refrigeration sources made this approach impractical. To mitigate these potential inaccuracies a test set-up unique to this facility was developed for measurement of regenerator energy flows and is shown in Figure 6.

In the test set-up shown in Figure 6, the thermal load from the test regenerator is inferred from measurement of LHe boil off rate,

$$\dot{Q}_{REG} = \langle \dot{H}_{RG} \rangle + \dot{Q}_{eff} - \dot{Q}_{cond} = \rho_{He}\dot{V}_{He}(h_{out}|_{T=Tsat} - h_{in}|_{T=Tsat}) - \dot{Q}_{cond} \tag{5}$$

where $h_{in}|_{T=Tsat}$ is the enthalpy at the inlet evaluated at T_{sat}, $h_{out}|_{T=Tsat}$ is the enthalpy at the exit evaluated at T_{sat}, ρ_{He} is the fluid density at the saturation condition, $\dot{V}_{He}$ is the LHe boil off rate measured at STD conditions. Unfortunately the use of Eqn. (5) requires precise knowledge of the inlet and exit thermodynamic states of the LHe. In an ideal scenario a LHe supply Dewar would continuously feed the thermal intercept with LHe.

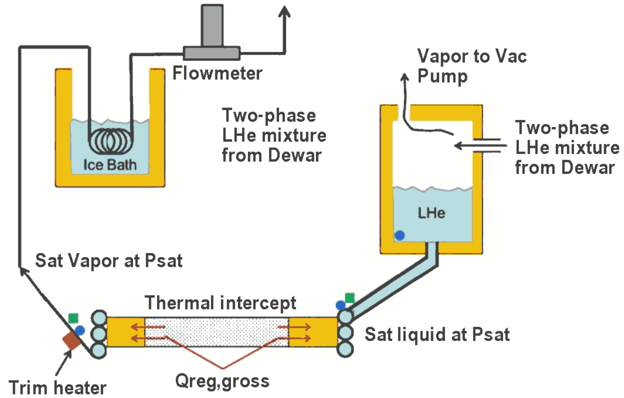

Figure 6. Illustration showing the experimental set-up for measurement of regenerator losses at a nominal cold temperature of 4 K.

However, knowledge of the inlet state is problematic due to a two phase inlet condition. To mitigate this problem, the two phase LHe mixture from the supply Dewar will enter a small LHe reservoir where phase separation occurs and liquid collects at the bottom. This liquid, at a precisely known thermodynamic state via pressure measurement, then enters the coiled tube attached to the thermal intercept. As the LHe flows through the coiled tube, thermal energy is transferred to the LHe causing the quality to approach unity. Much like the inlet condition, the exiting thermodynamic state is not readily measured due to the potential for a two-phase condition. Fortunately this issue can be readily overcome by forcing the LHe exit condition to be minimally superheated (<0.1% superheat) through use of a PID heater loop fixed to the coiled tube exit.

Use of the described LHe test set-up for measurement of the combined regenerator effectiveness and pressurization loss ($\dot{Q}_{REG}$) is relatively straightforward and consists of two steps. During experimental testing, the heat load on the 3rd stage thermal intercept represents the gross regenerator loss defined by Eqn (3). To isolate the terms of interest, the three conduction terms ($\dot{Q}_{cond}$) must be precisely known and subtracted from the experimentally determined heat load at the thermal intercept. Since the conduction term is driven solely by the time averaged temperature gradient, this term is measured under static conditions. Measurement of the actual regenerator loss during dynamic operation is achieved by subtracting the measured static conduction losses enthalpy vaporization calculation as noted in Eqn. (5).

Pulse Tube Loss Measurement

Measurement of the pulse tube loss requires knowledge of both the acoustic power flow and the enthalpy flow in the pulse tube per Eqn. (4). Calculation of the acoustic power at the cold end of the pulse tube is relatively straightforward using fundamental pressure and temperature measurements as noted below,

$$\left\langle \dot{P}V_C \right\rangle = \frac{1}{2}\left|\dot{m}_c\right| RT_c \frac{\left|\tilde{P}\right|}{\overline{P}} \cos\theta \tag{6}$$

where $\left|\tilde{P}\right|$ is the magnitude of dynamic pressure at the cold end, $\overline{P}$ is the charge pressure, $\left|\dot{m}_c\right|$ is the magnitude of the cold end mass flow rate, T_c is the cold end temperature, and θ is the phase angle between pressure and flow at the cold end. The pulse tube enthalpy flow is also readily measurable using a calibrated bus bar. The principles of this measurement technique are shown schematically in Figure 7.

During experimental testing the pulse tube enthalpy flow acts as a thermal load at the warm end heat exchanger. Rejection of this heat occurs through a calibrated pathway connected to the commercial GM cooler. Using measurement of temperature difference coupled with calibration of the bus, the pulse tube enthalpy flow can be measured.

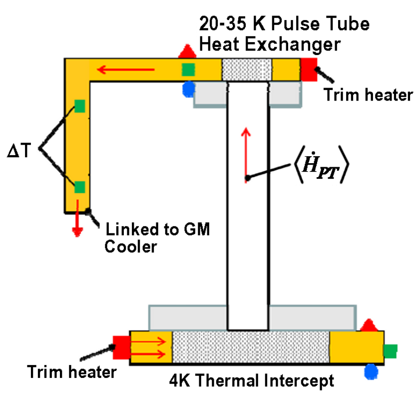

Figure 7. Schematic showing the principles of the measurement technique.

CONCLUSION

This paper has discussed the design of an experimental methodology used for precise measurement of 4K energy flows in the regenerator and pulse tube component. Use of information gained from this new test facility will allow for validation of sophisticated regenerator and pulse tube component models, allowing their application as design tools in the cryocooler industry. This new facility has many notable advantages such as rapid testing turn-around time, modulation of system phasors using a cold expander, off-axis rotation capability, a wide temperature testing envelope, and high accuracy. This new test facility, to the author's best knowledge, is the only one in the world of its type.

Current and continuing work is focused on final machining of all components. Following completion of part machining, assembly of stage components will take place. During this initial assembly, requisite mass flow calibrations will be performed. These calibrations will be focused on mapping the hydraulic resistance of the thermal intercepts with respect to mass flow rates at various operational temperatures. Upon successful calibration, the test facility will begin normal operations. Initial work is slated for measurement of regenerator performance using new ceramic magnetic based regenerator materials.

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