Experimental Apparatus for Measuring the Performance of a Precooled Mixed Gas Joule Thomson Cryosurgical Probe

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ABSTRACT

Cryosurgery is a technique for destroying undesirable tissue such as cancers using a freezing process. A previous paper referenced here describes the development of a thermodynamic modeling tool for a precooled Mixed Gas Joule-Thomson (MGJT) cryoprobe used for cryosurgery. An experimental test facility has been constructed to capture the performance of a precooled MGJT cryoprobe; the experimental data will be used to tune and verify the model. The test facility is flexible relative to working fluid, charge pressure, pressure ratio, and flow rate. Therefore, the facility can also be used to demonstrate additional cooling capacity available with the optimal mixture compositions and operating parameters selected by the model.

A commercially available cryoprobe system has been disassembled and installed in a vacuum insulated dewar. The system has been modified in order to integrate a suite of measurement instrumentation that can completely characterize the performance of individual components as well as the overall system. Measurements include sufficient temperature and pressure sensors to resolve thermodynamic states and flow meters to calculate heat and work transfer rates. A thermal load is applied to the cycle using an electric heater to characterize the refrigeration performance. Temperature sensors are also integrated within the recuperator in order to capture the heat transfer performance of the two-phase, multi-component mixture as it flows through the recuperator. An uncertainty analysis for the experiment is presented in this paper and shows that the performance metrics can be computed from the experimental data to within 10% uncertainty under the nominal anticipated operating conditions using both a synthetic refrigerant and hydrocarbon based gas mixture. Preliminary data are reduced to demonstrate the capability of the test facility.

INTRODUCTION

Cryosurgery is a technique for destroying undesirable tissue using a freezing process. The procedure can be used to ablate prostate and liver cancer tumors and it is also used in a variety of procedures in dermatology, gynecology, and cariology.[1] Modern cryoprobes are typically energized by Joule-Thomson (J-T) cycles; the use of a gas mixture working fluid, rather than a pure working fluid such as nitrogen or argon, greatly increases the refrigeration capacity of the J-T cycle[2] and thus the freezing penetration depth of the cryoprobe. Mixture optimization techniques for J-T cycles have been described by[3,4] and applied specifically to J-T cryoprobes.[5-7] Mixed Gas

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Joule Thomson (MGJT) cycles with precooling (i.e. a system where the high pressure gas mixture is cooled prior to entering the recuperator by a second refrigeration system) provide additional cooling compared to the single stage MGJT cycle.[4] A pre-cooled MGJT cryoprobe is the focus of this paper. The cryoprobe features a Giaque-Hampson style recuperator with approximately 50 ft of 0.05 inch inner diameter, finned stainless steel tubing helically wound about a mandrel.

A model of the precooled MGJT system has been previously developed[8], and captures the fundamental thermodynamic and heat transfer processes that govern system performance. This model can be used to select optimal mixture compositions and other operating parameters that maximize cooling power given hardware size limitations. The experimental apparatus described here will be used to measure the performance of a precooled MGJT cycle. In a future study, these data will be used to tune and verify the model in order to improve its predictive capability. Finally, we hope to demonstrate the additional cooling that can be achieved when the detailed model is integrated with an optimization algorithm and used to select the mixture composition and operating parameters.

A commercially available cryosurgical probe system, shown in Figure 1, has been disassembled and installed in a thermal-vacuum test facility. The cryoprobe system has modified in order to allow the integration of sufficient measurement instrumentation to completely characterize the performance of individual components as well as the overall system. The modifications enable much more detailed measurements than those otherwise available with the cryoprobe. For example, Figure 1 highlights the tip of the cryoprobe, which encloses the expansion valve and is the active (i.e., the cold section that provides the refrigeration used to form the cryolesion) section of the probe. The thermodynamic states at locations before and after the expansion valve, as well as at a location downstream of the refrigeration load are critical in order to determine the system performance. The unmodified probe configuration is ergonomic and highly compact. Therefore, it does not allow for any measurement of the temperature and pressure at these states. The modifications that have been carried out enable direct measurements at these locations and therefore allow the resolution of these and other thermodynamic states.

Temperature and pressure measurements are used to measure the thermodynamic performance of each of the components in the cryoprobe system. It is important to empirically characterize all of the components for comparison with the corresponding component models that make up the system model. Accurately predicting the performance of a gas mixture in any of the components that make up the refrigeration cycle is challenging. The accuracy of the models used to predict the thermodynamic and transport properties of mixtures at cryogenic temperatures is not clear. There is very little information available that allows the computation of the heat transfer coefficient and pressure drop within the recuperative and precooling heat exchangers. The experimental data collected by the test facility will be useful for assessing the accuracy and limitations of the currently available property data and models and will help develop heat transfer and pressure drop models that can be applied to the MGJT system. These results will be incorporated with the MGJT cryoprobe model[8] in order to develop a physics-based empirical model that can more accurately predict the MGJT cycle performance. To our knowledge, these experimental data will capture the performance of a

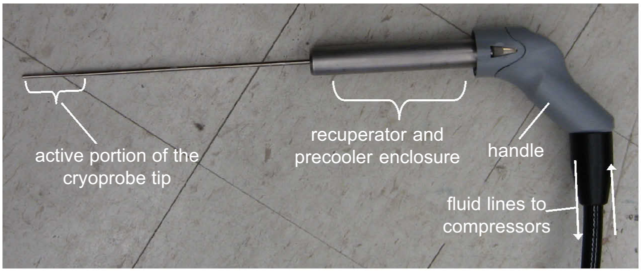


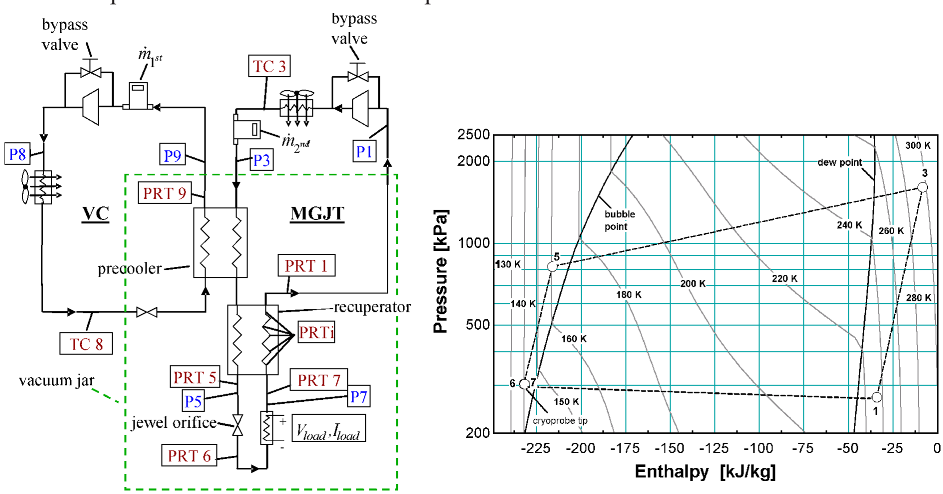
Figure 1. Picture of handheld cryoprobe showing the locations of the active (cold) portion of the tip as well as the recuperative and precooling heat exchangers.

MGJT cryoprobe with an unprecedented level of detail, and will yield valuable insight into the operation and design of these cycles.

EXPERIMENTAL APPARATUS

A schematic showing the locations of the measurement instrumentation integrated with the MGJT cycle is shown in Figure 2(a). The precooling vapor compression cycle is shown on the left side and labeled "VC" and the MGJT cycle is on the right and labeled "MGJT". Temperature and pressure measurements are used to resolve the relevant cycle thermodynamic states. Platinum Resistance Thermometers (PRTs) and thermocouples are used to measure the temperature directly in the flow stream; these measurements are denoted as "PRT#" and "TC#", respectively. Pressure measurements are labeled "P#". Additional PRTs are directly integrated into the low pressure side of the recuperator and are labeled "PRTi#". The mass flows in both cycles are measured using calorimetric flow meters and these measurements are labeled $\dot{m}_{1st}$ and $\dot{m}_{2nd}$ for the precooling and MGJT cycles, respectively. The flow measurements together with the thermodynamic states are used to quantify heat and work transfer rates within the components. An interchangeable orifice is fabricated by installing a precise jewel orifice procured from Bird Precision in a VCR gasket. The orifice is 0.01 inch thick and has an opening that varies depending on the test but nominally ranges between 0.010 inch and 0.020 inch. A bypass valve is placed between the compressor discharge and suction. The ability to change the expansion orifice and adjust the bypass valve allows independently regulation of the pressure ratio and mass flow applied to the MGJT cycle. Heat is applied to simulate a biological thermal load using a Nichrome wire heater; the heater is labeled by its voltage and current measurements, V_{load} and I_{load}. Finally, the cold components in the cycle are covered in MultiLayer radiation Insulation (MLI) and enclosed within a vacuum facility to minimize the parasitic heat leak. Figure 2(b) shows thermodynamic state points of the MGJT cycle for a nominal operating condition obtained using the original manufacturer's proprietary mixture in the J-T cycle; these data are overlaid on a pressure-enthalpy (P-h) diagram of the mixture.

Figure 3 shows the instrumentation for the temperature measurements within the low pressure side of the recuperator ("PRTi" in Figure 2(a)); eight small PRTs are embedded at diametrically opposing locations at each of four axial locations in a cryogenic grade G-10 (fiberglass-resin composite) sheath that slides over the helically wound finned-tube recuperator. The measurements provide a representation of the stream temperature distribution as the PRTs are in direct contact



(a) (b)

Figure 2. (a) Schematic of experimental test facility including measurement instrumentation integrated with the MGJT cryoprobe system. (b) Nominal JT cycle state points overlaid on a P-h diagram for the gas mixture where the #'s correspond to the thermodynamic states indicated in (a).

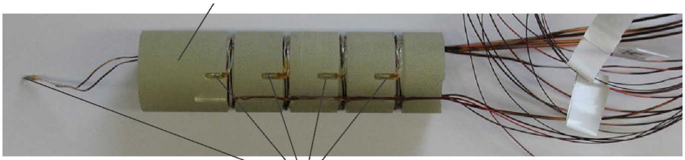


Figure 3. Picture of the G-10 sheath and embedded PRT's that measure the temperature profile in the low pressure stream of the recuperator.

with the fluid and the G-10 sheath has a very low conductivity (and therefore limits axial conduction). A ninth PRT, shown in the far left of Figure 3, measures the low pressure stream temperature before it enters recuperator. The temperature measurements within the recuperator will be used to quantify the heat transfer performance including the pinch point temperature difference (i.e., the minimum temperature difference between the hot and cold streams which is sometimes referred to as the approach temperature difference). These temperature measurements together with the measured pressure in the recuperator can be used to determine the enthalpy at the various locations. The enthalpies and temperatures allow the computation of the spatially resolved conductance. To a large degree, the performance of the recuperator governs the overall performance of the refrigeration system. Therefore, the ability of the model to predict the performance of the system depends largely on how well the performance of the recuperator can be predicted. However, as mentioned in the introduction, the heat transfer characteristics of the multi-phase, multi-component fluid flowing within the complicated recuperator geometry are not well known. It is possible to select a mixture that theoretically yields a large refrigeration power based on the thermodynamic properties[9], and yet performs poorly in a physical system due to poor heat transfer within the recuperator. The temperature profile will be useful in identifying physical explanations for the poor performance that may include: (1) temperature profiles that do not enable efficient or compact heat exchange, (2) early dry-out (i.e. two-phase flow becomes entirely vapor) causing low heat transfer coefficients, or (3) excessive pressure drop in the low pressure stream yielding higher low pressure stream temperatures, which subsequently results in less heat transfer in the recuperator. The experimentally derived conductance measurements can also be used in the development or verification of heat transfer correlations that can be integrated with the model and therefore improve its performance.

UNCERTAINTY ANALYSIS

An uncertainty analysis has been performed prior to fabrication in order to ensure that the test facility is capable of measuring the performance of the overall system with adequate fidelity. The model described in[8] was used to carry out the analysis using nominal operating parameters as well as the accuracies of the selected sensors and the uncertainty in the composition of the gas mixtures that will be generated for the project. Cryoprobe refrigeration ($\dot{Q}_{load}$), precooling and recuperative heat exchanger conductances (UA_{pc},UA_{rec}, and $UA_{total} = UA_{pc}+UA_{rec}$), and the cryoprobe compactness target ($\dot{Q}_{load}|UA_{total}$, which roughly determines the cryoprobe size[8]) are used as the measured performance metrics in order to determine sufficient instrument accuracy.

The analysis was performed for both hydrocarbon (HC) and Synthetic Refrigerant (SR) based gas mixtures; both types of mixtures will be tested in the MGJT cycle; the SR and HC mixtures used for this analysis are shown in Table 1. The precooling VC cycle working fluid is R22. Nominal operating parameters and sensor accuracies are shown in Table 2 where the measurements correspond to state points in Figure 2(a); note that some of the measurements in Figure 2(a) are not required to verify the overall system model from Skye et al.[8] and therefore are not included in Table 2. The measurements not included in the uncertainty analysis will be used for quantifying individual component performance rather than overall system performance targets. The detailed calculation of the uncertainty is not presented here due to space limitations, but will be available in a thesis document prepared for this project. The results of the uncertainty analysis are presented in

Table 1. Nominal mixture composition and accuracy used for evaluating the uncertainty in the experimental apparatus. The values for both a synthetic refrigerant and hydrocarbon mixtures are shown.

Synthetic refrigerant base mixture			Hydrocarbon based mixture		
Mixture Constituent	**Nominal Composition**	**Uncertainty**	**Mixture Constituent**	**Nominal Composition**	**Uncertainty**
R116	0.5%	4% relative	nitrogen	0.1%	4% relative
Krypton	46.2%	4% relative	methane	41.4%	4% relative
R14	5.2%	4% relative	ethane	46%	4% relative
R23	13.9%	4% relative	propane	1.7%	4% relative
R32	17.8%	4% relative	isobutane	9.5%	4% relative
Argon	2.88%	4% relative	isopentane	0.7%	4% relative
R125	13.4%	4% relative	argon	0.5%	4% relative

Table 2. Nominal operating parameters and measurement uncertainties for the cryoprobe system used in the uncertainty analysis. The uncertainties are based on readily available instrumentation.

Measurement	Nominal Value	Uncertainty	Measurement	Nominal Value	Uncertainty
1st stage mass flow ($\dot{m}_{1^{st}}$)	0.001 kg/s	5% relative	2nd stage low pressure (P1)	100 kPa	5% relative
2nd stage mass flow ($\dot{m}_{2^{nd}}$)	0.0015 kg/s	5% relative	Cryoprobe load ($\dot{Q}_{ll} = V_{load} I_{load}$)	30 W	4% relative
1st stage high pressure (P8)	1400 kPa	5% relative	Recuperator cold exit temperature (PRT 1)	210 K	1 K
2nd stage high pressure (P3)	1400 kPa	5% relative	Ambient Temperature (T_{amb})	290 K	1 K
1st stage low pressure (P9)	200 kPa	5% relative	Load temperature (PRT 7)	140 K	1 K

Table 3. Uncertainty analysis results for the synthetic refrigerant and hydrocarbon based mixtures.

Uncertainty targets for synthetic refrigerant based mixture			
Precooler conductance (UA_{pc})	**Recuperator Conductance (UA_{rec})**	**Total Conductance (UA_{total})**	**Cyroprobe compactness (Q_{load}/UA_{total})**
5.06 ± 7.9% [W/K]	19.69 ± 6.2 % [W/K]	24.7 ± 6.2% [W/K]	0.61 ± 7.2%[K]
Uncertainty targets for hydrocarbon based mixture			
Precooler conductance (UA_{pc})	**Recuperator Conductance (UA_{rec})**	**Total Conductance (UA_{total})**	**Cyroprobe compactness (Q_{load}/UA_{total})**
3.8 ± 10.5% [W/K]	9.13 ± 9.3% [W/K]	12.93 ± 7% [W/K]	2.32 ± 7%[K]

Table 3; both the heat exchanger conductances (*UA*) and the cryoprobe compactness target ($\dot{Q}_{load}/UA_{total}$) can be measured with 10% or less uncertainty.

PRELIMINARY EXPERIMENTAL RESULTS

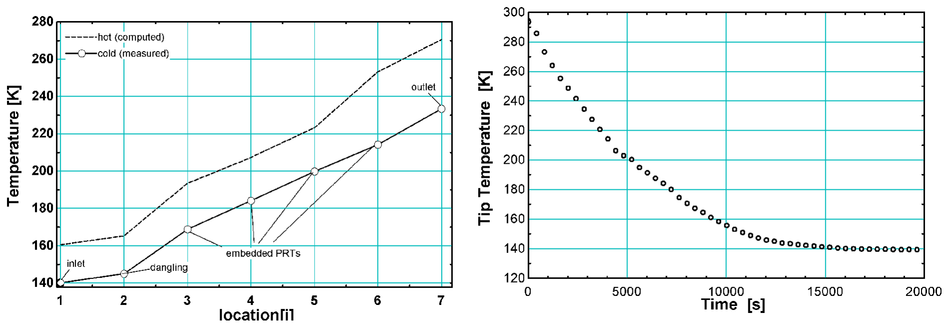
The experimental test facility was used to characterize the performance of the MGJT cryoprobe with the manufacturer's original mixture (the mixture is proprietary so the composition is not given here, future tests will include performance data using a mixtures with publically available compositions).

These preliminary data are useful to demonstrate the types of performance metrics available through data reduction. The system level performance is shown in the cycle diagram in Figure 2(b). The refrigeration capacity is computed using the Nichrome wire heater input, and is reflected in the enthalpy difference between states 6 and 7 in Figure 2. The load curve performance (not shown in this paper) quantifies the refrigeration capacity over a range of cryoprobe tip temperatures (state 7 in Figure 2). The J-T cycle nominally operates between a high and low pressure of 1800 kPa and 300 kPa, respectively.

The performance of individual components is also determined using these data. The temperature distribution measured at intermediate locations within the low pressure side of the recuperator (PRTi in Figure 2(a)) is shown Figure 4(a). The warmer, high pressure stream temperature profile shown in Figure 4(a) is computed using an energy balance at each intermediate recuperator section. The temperature distribution can be used to compute the overall, as well as the spatially resolved, recuperator conductance. The specific heat of the mixture varies significantly with temperature, so the heat exchanger conductance is computed using a numerical model that divides the heat exchanger into a number of small sections over which the temperature change is small and the effectiveness-NTU relationship can be accurately applied[8]. The recuperator conductance will be used in a future study to develop a physics-based model of the recuperator.

Figure 4(b) shows the cool down curve for experimental test facility. The ultimate tip temperature (138.5 K) matches well with the unmodified probe ultimate temperature (140 K), therefore the modifications to the cryoprobe required to integrate the measurement instrumentation have not significantly changed the cycle performance.

The test facility can also be used to quantify the accuracy of gas mixture thermodynamic property data. Specifically, the Joule-Thomson effect temperature change (ΔT_{JT}) across the jewel orifice (state 5 to 6) is measured and can be compared with the ΔT_{JT} predicted given the pressure drop and upstream temperature. The ΔT_{JT} was predicted using the NIST4 or SUPERTRAPP mixture property database[10] and compared with measured values as shown in Figure 5. Note that these data



(a) (b)

Figure 4. (a) Measured low pressure and computed high pressure temperature profiles within the recuperator. (b) Cool down curve for the experimental test facility.

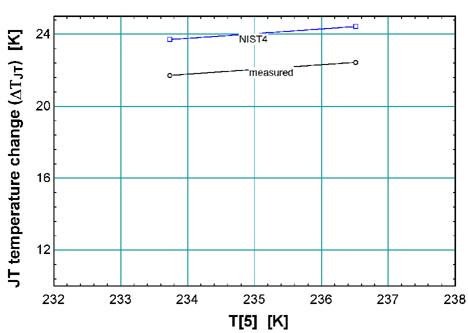


Figure 5. Measured and predicted JT-effect temperature change vs. temperature at state 5.

were collected at relatively high temperatures (~235 K); future tests will measure ΔT_{JT} at lower temperatures that more closely represent typical tip temperatures in the cryoprobe (~140-180 K). For the few data points presented here the predicted and measured values agree to within 10%.

CONCLUSION

The facility described here has been constructed and preliminary data have been acquired. The facility will be used to carry out experimental tests over a wide range of temperatures, thermal loads, pressures, and flow rates in order to ensure that the semi-empirical cryoprobe model based on these data is applicable over a broad range of operating conditions. The empirically-tuned model will be used to select optimal gas mixtures and operating parameters that maximize the performance of the cryoprobe. The test facility will be used to demonstrate the additional cooling available through optimization. A detailed comparison between the model and the data, as well as the performance with the new, optimized mixtures selected by the model will be presented in a future study.

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