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Vapor Precooling in a Pulse Tube Liquefier

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ABSTRACT

Experiments were performed to study the effects of introducing vapor into a dewar where a coaxial pulse tube refrigerator was used as a liquefier in the neck of the dewar. We were concerned about how the introduction of vapor might impact the refrigeration load as the vapor barrier in the neck of the dewar is disturbed. Three experiments were performed where the input power to the cooler was held constant and the nitrogen liquefaction rate was measured. The first test introduced the vapor at the top of the dewar neck. Another introduced the vapor directly to the cold head through a small tube, leaving the neck vapor barrier undisturbed. The third test placed a heat exchanger partway down the regenerator where the vapor was pre-cooled before being liquefied at the cold head. This experiment also left the neck vapor barrier undisturbed. Compared to the test where the vapor was introduced directly to the cold head, the heat exchanger test increased the liquefaction rate by 12.0%. The experiment where vapor was introduced at the top of the dewar increased the liquefaction rate by 17.2%. A computational fluid dynamics model was constructed of the dewar neck and liquefier to show how the regenerator outer wall acted as a pre-cooler to the incoming vapor steam, eliminating the need for the heat exchanger.

INTRODUCTION

Liquefaction plants have always used some form of recuperative cryogenic refrigerator (i.e. Joule-Thomson, Claude, or Brayton cycles) to provide the cooling. The reason for this is the higher efficiencies that can be obtained with recuperative systems over regenerative systems (i.e. Stirling, pulse tube, or GM cycles) in larger scale cryogenic refrigerators. There is now increased interest in small to medium liquefaction plants (20 W to 1 kW refrigeration capacity) for local cryogen liquefaction in the aerospace, military, and commercial sector. As refrigeration capacity is reduced, regenerative systems become comparable with and then surpass recuperative systems in efficiency, making them attractive choices for small and medium scale liquefaction plants.

One advantage of recuperative systems is the ability to continuously cool the vapor through the recuperative heat exchanger. An ideal regenerator cannot accept heat so the regenerative systems must be multi-stage or remove all the heat at the lowest temperature, reducing efficiency. It has been shown by Radebaugh et. al.[1] that non-ideal regenerators are able to accept some heat at any point. We performed three experiments to determine whether this effect could be used to improve liquefaction efficiency of regenerative systems.

EXPERIMENTAL SETUP

Figure 1 shows the experimental setup with the pulse tube in the neck of a dewar. The pulse tube was fully characterized[2] in a vacuum chamber so that refrigeration loads could be determined from the input power. It had a nominal refrigeration capacity of 18.8 W at 90 K (20% of Carnot) and produced 14.5 W at 77 K (19% of Carnot) with 223 W PV input power. Nitrogen was used as the test fluid to be liquefied. In all experiments, the input PV power was held constant at 223 W. The nitrogen mass flow rate was measured to hold the pressure in the dewar constant.

In the first experiment, the nitrogen was introduced through a 1.5 mm tube directly to the cold end. This did not allow the insulating gas in the neck of the dewar to be disturbed. The second experiment introduced the nitrogen at the top of the dewar. The final experiment introduced the nitrogen through a tube leading to a heat exchanger and then through another tube leading directly to the cold end. The heat exchanger was clamped to the 50 mm long regenerator 30 mm down from the warm end. It was a split design allowing it to be clamped anywhere along the regenerator's length. The contact thickness was 1.65 mm and the heat exchanger contained a channel 25 cm long to insure adequate heat transfer between the fluid and heat exchanger.

RESULTS

Figure 2 shows a typical cool down of the dewar with the inlet at the top of the dewar. The temperature locations are shown in Figure 1. Under steady state operation, the temperature profile in the neck of the dewar changes dramatically as the warm fluid flows passed the neck. Figure 3 shows the wall temperature profiles in the dewar neck for both the cryocooler and the dewar walls. The dewar wall temperatures were measured at the three positions shown in Figure 1. Experiments 1 and 2 show linear temperature profiles, as expected, along the wall

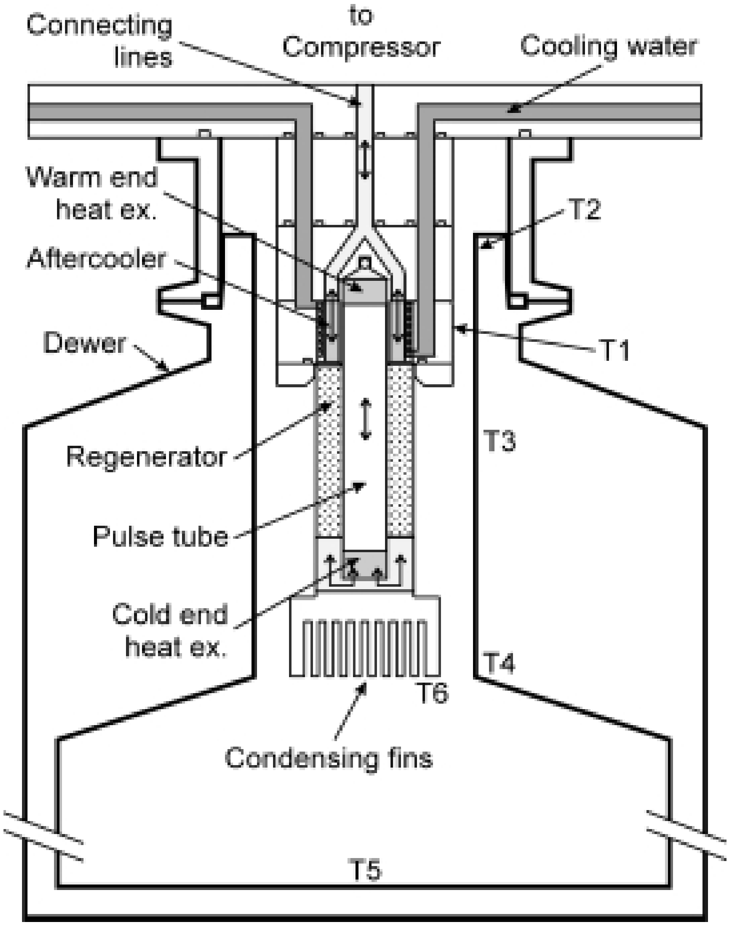

Figure 1. Experimental setup.

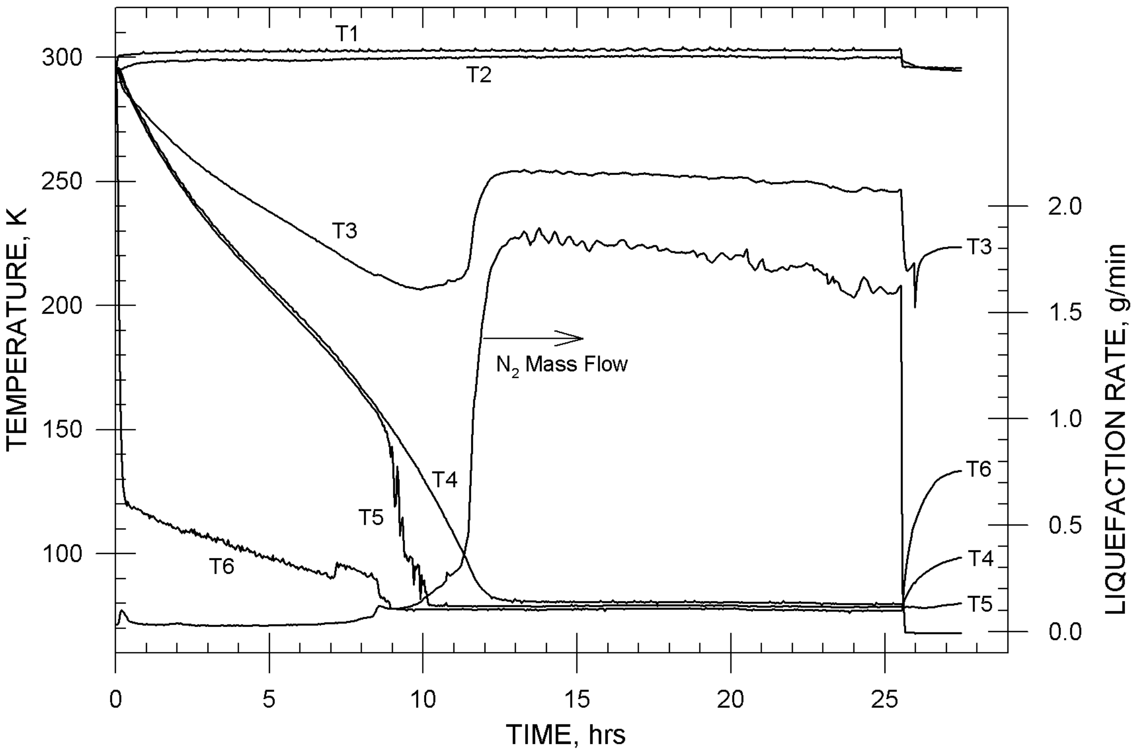

Figure 2. Typical cool down with fluid inlet at the top. Temperature locations are given in Fig 2.

within the experimental errors associated with the placement of the thermocouples. The dewar wall temperature in experiment 3, as shown in Figure 3, is interpolated from the measurements at the three locations given in Figure 1. The cryocooler wall temperatures along the regenerator for experiment 3 are derived from our theoretical model and are displayed to show the boundary conditions the gas is exposed to as it travels to the cold head.

The dewar had a measured heat leak of 1.1 W. The enthalpy required to liquefy nitrogen at 0.1 MPa from 300 K is 428 J/g. This results in 7.13 W·min/g energy required for nitrogen liquefaction from room temperature. The measured mass flow rates for the 3 experiments were 1.92, 2.25, and 2.15 g/min. Table 1 shows the refrigeration power required for the liquefaction given these mass flow rates. Q1, Q2, and Q3 represent the refrigeration load required for the three different experiments respectively.

Given the 1.1 W dewar heat leak and the 14.5 W of cooling power available, the energy required for the case where nitrogen is directly applied to the cold head, Q1, agrees well with the calculated value. The case using the mid-stage heat exchanger, Q3, shows that by accepting some energy at a mid-point, we can increase the liquefaction rate by 12%. Our theoretical model[1] predicts a 15% increase in the liquefaction rate. The case where nitrogen was introduced at the top of the dewar shows that the regenerator continuously pre-cools the fluid since we only have 14.5 W of cooling power available and with the dewar heat leak, we would require 17.15 W if heat was only absorbed at the cold head. We have increased the liquefaction rate by 17.2% without using any special heat exchangers or flow channels. The model predicts a 23% increase if the fluid is continuously pre-cooled by the regenerator.

The liquefier figure of merit, FOM, can be determined by

$$FOM = \dot{W}_{ideal} / \dot{W} = \frac{\dot{m}(T_0 \Delta s - \Delta h)}{\dot{W}}, \tag{1}$$

Table 1. Refrigeration power required for liquefaction.

Temperature (K)	Enthalpy (J/g)	Q1 (W)	Q2 (W)	Q3 (W)
300	306.0	-	-	-
165	170.4	-	-	4.86
Sat Liquid (77)	-122.0	13.70	16.05	10.48

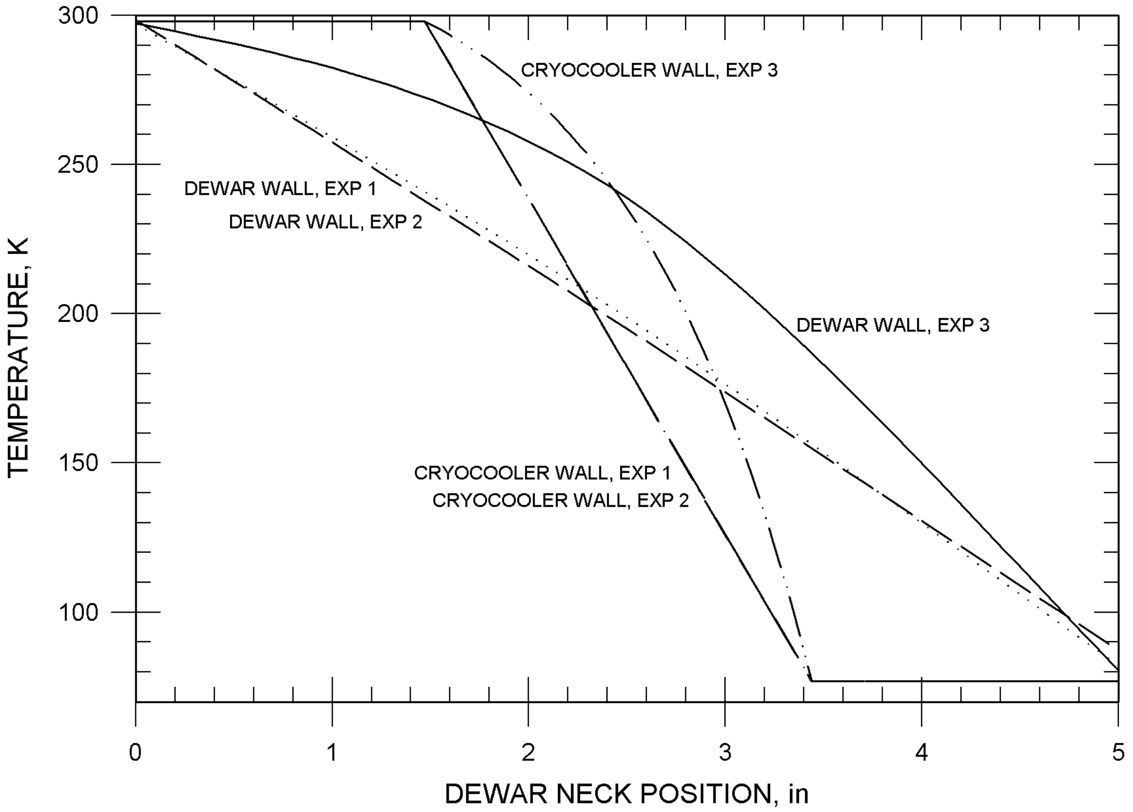

Figure 3. Temperature profile in the dewar neck.

where $\dot{W}_{ideal}$ is the ideal work required for liquefaction, $\dot{W}$ is the actual work input, $\dot{m}$ is the liquefaction rate, T_0 is the ambient temperature, Δs is the entropy difference from ambient to the saturated liquid state, and Δh is the enthalpy difference from ambient to the saturated liquid state.

Assuming the efficiency of the compressor, $\dot{W}_{PV} / \dot{W}_{elec}$, is 85%, the total electrical input power is 262 W. Table 2 summaries the experimental results.

CFD MODELING

We have numerically modeled the best case where fluid enters at the top of the dewar and the cryocooler cold head is placed within the neck of the dewar. Using a commercial CFD package, we have determined the temperature profile and streamlines within the dewar neck shown in Figure 4. These results show how the regenerator pre-cools the fluid before it reaches the cold head. The predicted fluid temperature along the regenerator closely matches the regenerator wall temperature shown in Figure 3.

To study the flow and temperature profiles inside the dewar neck, we used a finite element numerical model. We used a 2-dimensional model, discretisizing the domain into 13,350 4-node elements. Constrained temperatures were input as boundary conditions along the cryocooler walls and at the fluid entrance. Adiabatic conditions were assumed for the outside walls of the dewar. Compressible flow was modeled by assuming a Boussinesq equation of state for the density. A function for the volume expansion was input for a range of densities for vapor and liquid states. Fluid properties were taken from the NIST12 database[3] for nitrogen.

Table 2. Experimental results summary.

Experiment	Liquefaction Rate (g/min)	$\dot{W}_{elec}$ (watts)	$\dot{W}_{ideal}$ (watts)	FOM
1	1.92	262	24.61	0.094
2	2.25	262	28.84	0.110
3	2.15	262	27.56	0.105

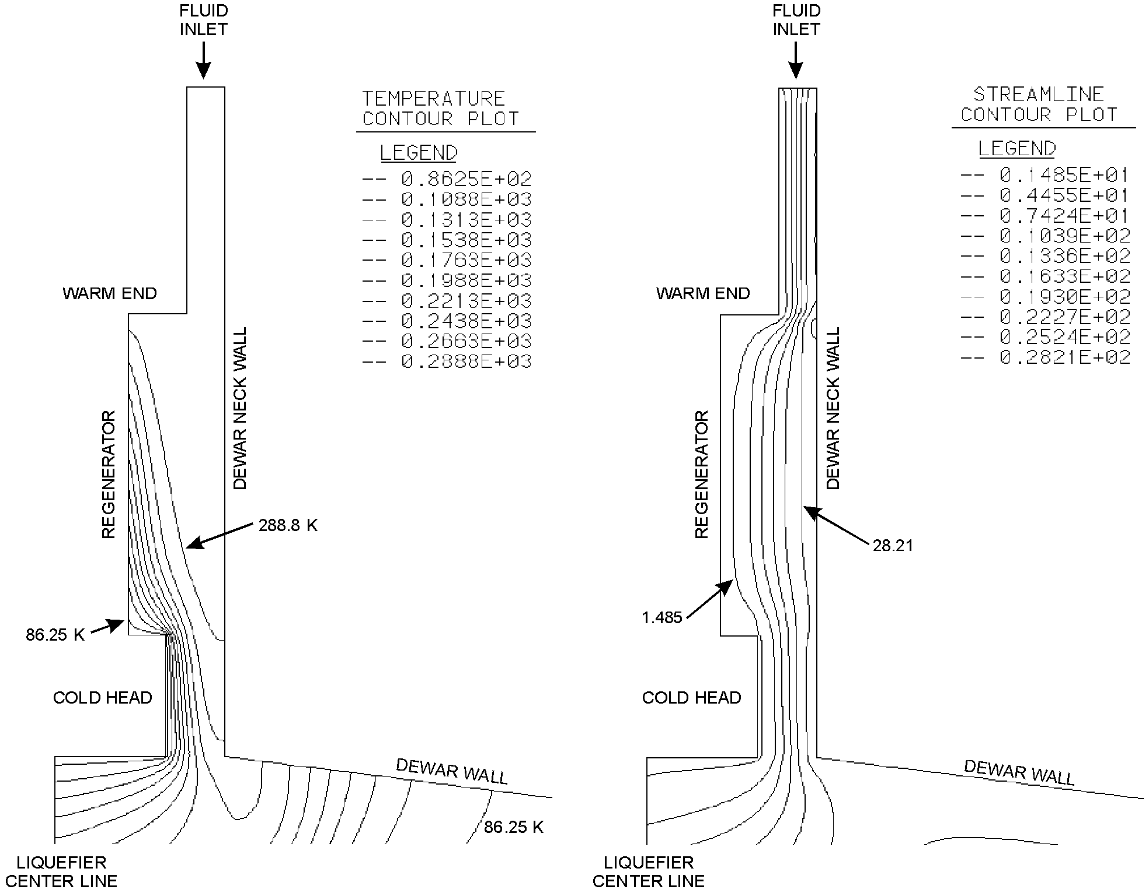

Figure 4. CFD results showing temperature contour and streamlines with in dewar neck.

CONCLUSIONS

We have shown that heat transfer to the regenerator can be used to improve liquefaction rates in regenerative cryocoolers with no special attention given to the fluid flow paths. Improvements of 17.2% were shown over then case were all the liquefaction energy is removed at the cold head. Regenerative systems do not require any complex recuperative heat exchangers where a leak could cause mixing of the working fluid and liquefaction fluid.

REFERENCES

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