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PULSE TUBE OXYGEN LIQUEFIER*

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ABSTRACT

The performance of a single-stage coaxial pulse tube refrigerator used as an oxygen liquefier is discussed. The liquefier is a half-size laboratory unit for NASA/JSC to demonstrate the technology of liquefying and storing oxygen on Mars. The liquefier would be part of a plant that extracts oxygen from the Martian carbon dioxide atmosphere and stores the oxygen in liquid form. The liquid oxygen could then be used either for the oxidizer of a fuel or for breathing in a manned mission. The pulse tube and regenerator, which are arranged coaxially, provide 18.8 W of cooling at 90 K with 222 W of PV input power. The resulting coefficient of performance (COP) is 20.0% of the Carnot value based on PV input power, among the highest ever achieved. Liquid nitrogen was produced at a rate of 1.75 g/min (2.17 cm^3/min) with 215 W of PV input power. Oxygen should be produced at about 2.7 g/min (2.37 cm^3/min). While this cooler is not a flight version, it is a flight-like design similar to what would be used on a mission. This paper presents details of the liquefier geometry and results of thermal performance tests.

INTRODUCTION

Manned missions to Mars will require in situ resource production[1] (ISRP), the use of resources found on Mars. The robotic missions planned over the next decade will be used to prove some of the technology required for ISRP. One primary requirement is oxygen for both breathing and as an oxidizer for fuel. NASA is currently developing the technology to produce oxygen from the carbon dioxide atmosphere of Mars. Another requirement is the long-term storage of the oxygen in liquid form. NASA/JSC is building an environmental chamber to simulate the Martian environment to study the complete system of oxygen production and storage. This liquefier will be used within that chamber.

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LIQUEFIER DESIGN

The pulse tube liquefier is made of several components: the compressor, connecting lines, aftercooler, regenerator, cold end, cold end heat exchanger, pulse tube, warm end heat exchanger, orifice, inertance tube, reservoir volume, and condensing fins. Table 1 lists the performance goals. The design of the cold head is summarized in Table 2.

In order to be used as a liquefier, the pulse tube cold head must completely fit within the neck of a dewar. Clearly, an in-line pulse tube would not be appropriate and a U-tube geometry would require a larger dewar neck. A coaxial pulse tube makes the integration with the dewar easy. Performance will suffer compared to an in-line design by about 5-10%. Figure 1 shows a photo of the complete system. Figure 2 shows a schematic diagram.

Compressor

The compressor, designed with a swept volume of 20 cm^3 and a resonant frequency of 40 Hz, is capable of delivering 300 W of PV power. It uses a clearance seal and linear-arm flexure bearings for long life. In this system, it is being used with a swept volume of 15.5 cm^3 at 45 Hz. The compressor is not very efficient, partially because it is operating off the resonant frequency. Thus, we will report PV power in this paper. Under the liquefier operating conditions, the compressor converts AC electrical power to PV power at 62% efficiency. The most advanced linear compressors have an efficiency of 80% to 85%.

Connecting Lines

The connecting line between the cold head and compressor has a diameter of 4.62 mm and a length of 111.3 mm. Next, it splits into two lines, each with a diameter of 3.80 mm

Table 1. Liquefier design goals

Parameter	Goal
Operating temperature	90 K
Cooling load	15 W
Heat rejection temperature	300 K
Oxygen Liquefaction rate	2.2 g/min 1.93 cm^3/min
Assumed compressor efficiency (PV Power/Electrical)	85%
PV Input Power	260 W
Specific Power (load/PV Power)	17.3 W/W
% Carnot (based on PV power)	13.5 %

Table 2. Cold head design

Parameter	Value
Frequency	45 Hz
Average pressure	2.0 MPa
PV Input Power	~220 W
Compressor swept volume	~15.5 cm^3
Regenerator	28 mm OD x 12.75 mm ID (annular) x 50 mm length 400 mesh SS screen
Pulse tube	∅12.45 mm ID x 70 mm length, 8.52 cm^3 volume
Inertance tube	∅2.57 mm ID x 2.20 m length
Secondary orifice	∅0.25 mm x 1.25 mm length

Figure 1. Pulse tube liquefier system.

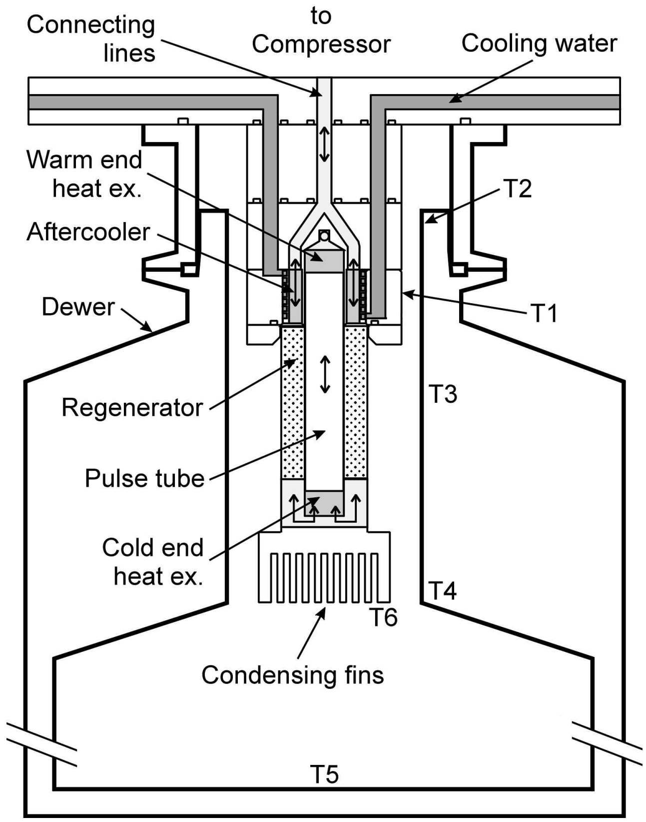

Figure 2. Schematic diagram of the liquefier. T1 through T6 show the temperature sensor placement referred to in Figure 5.

and a length of 22.5 mm. The split lines end in an annular space, for re-mixing, which has a 22.86 mm OD, 15.24 mm ID, and a 1.78 mm depth. The compressor pressure is measured here. Also connected to the annular space is a line 2.53 mm in diameter and 14.5 mm long, connected to one side of the secondary bypass orifice.

Aftercooler

The aftercooler is a radial parallel plate design. It is composed of 104 radial gas flow passages, each with a gap 150 μm by 4.11 mm, and 17.40 mm long. A radial slot heat exchanger is a very good match for a coaxial pulse tube. The pulse tube fits into the large central hole of the annular slots. Uniform slots are cut from the large central hole using a wire electro-discharge machine (EDM). This results in a heat exchanger with a low pressure drop, low void volume, and high heat transfer area.

Regenerator

The regenerator is placed in the annular space surrounding the pulse tube. The outer diameter of the regenerator tube is 28.57 mm, the wall thickness is 0.28 mm, and the length is 50.0 mm. The outer diameter of the pulse tube, which forms the inner wall of the regenerator, is 12.75 mm. The annular space is filled with 400 mesh stainless steel screen with a wire diameter of 25 μm and a porosity of 68.7%. The regenerator tube is made of 718 Inconel. Testing a coaxial pulse tube makes it difficult to independently change the size of the regenerator and pulse tube. A possible way to change the regenerator length is to insert a spacer in place of some of the screen at the warm end. The spacer must be designed to have low pressure drop, void volume, and heat transfer. We have made two spacers, 5 and 10 mm long. They were made of stainless steel with the same inner and outer diameters as the regenerator but with 16 radial slots cut from the inner diameter. Each gap was 0.44 mm by 6.35 mm.

Cold End

The cold end reverses the flow between the regenerator and the pulse tube. This is an important part of a coaxial pulse tube design as it is easy to add extra undesirable void volume; we must balance pressure drop and void volume. We have used 16 slots each with a gap 200 μm by 7.00 mm, and length of 15.50 mm. After the slots, the flow enters a small volume below the cold end heat exchanger with a volume of 18.9 mm^3. The slots also act as part of the cold end heat exchanger, providing about 25% of the required heat transfer.

Cold End Heat Exchanger

The cold end heat exchanger is made of 100 mesh, 114 μm diameter wire, copper screen. It is 12.75 mm in diameter and 8.08 mm long. This provides the bulk of the heat transfer and provides flow straightening for the pulse tube.

Pulse Tube

The pulse tube is made of stainless steel tubing with an outer diameter of 12.75 mm and a wall thickness of 0.15 mm. The length is 70 mm and the volume is 8.52 cm^3. In a coaxial design, the pulse tube volume may be changed by using a thin walled insert; G-10 composite with its low thermal conductivity, is a good choice of material. To prevent turbulence, the insert must extend the entire length of the pulse tube. It is also possible to taper the insert, allowing for the cancellation of any flow streaming[2] within the pulse tube. We did not experiment with any inserts.

Warm End Heat Exchanger

The warm end heat exchanger is made of 100 mesh, 114 μm diameter wire, copper screen. The diameter is 12.75 mm and the length is 7.32 mm. There is a volume of 0.19 cm^3 after the heat exchanger where the pulse tube pressure is measured. Between this volume and the orifice is a connecting line with a diameter of 2.53 mm and length of 18.7 mm.

Orifice

The pulse tube can be run with either a single orifice, double orifice, and/or with an inertance tube. Each of the two orifices, shown in Figure 3, is a plug into which a channel may be cut. The orifices fit together in a recess on the side of the aftercooler into which three lines enter: one each to the compressor, pulse tube warm end, and the reservoir volume. A cover plate allows access. Two orifices are required, although the secondary orifice is sometimes filled with a blank plug. When the inertance tube is used, the primary orifice is a channel 2.5 mm wide, 1.25 mm high, and 2.5 mm long. This provides only a small pressure drop and is considered ‘wide open’. The secondary orifice is more difficult to make. A symmetric pressure drop element cannot be used since it will (and did) cause a very large DC flow[3] through the pulse tube and regenerator. With a symmetric pressure drop element, such as the one used for the primary orifice, the system achieved only temperatures of around 270 K. Figure 3b and 3c show an asymmetric pressure drop element, which can eliminate the DC flow as indicated by the temperature gradient along the regenerator tube. The flow rate is controlled by the hole size connecting the top and bottom sides, typically with a diameter ranging up to 0.6 mm. Following the primary orifice

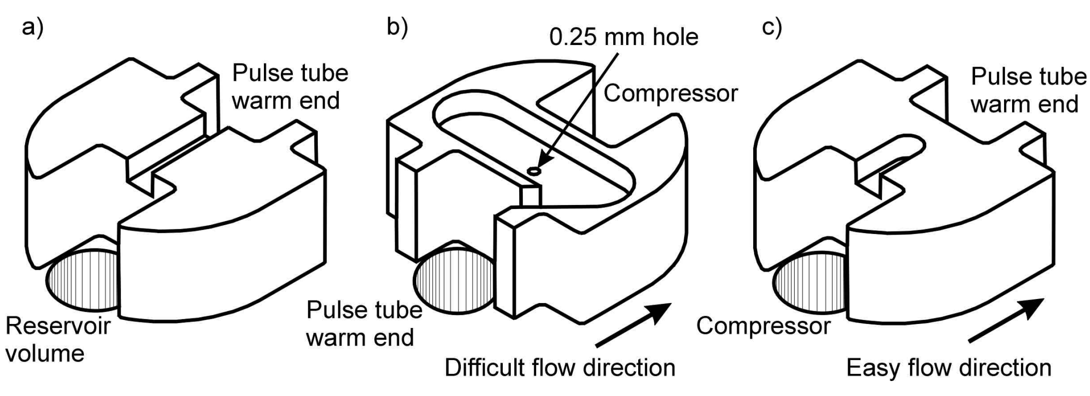

Figure 3. a) Primary orifice b) Secondary orifice top c) Secondary orifice bottom

is a connecting line with a diameter of 3.18 mm and length of 100 mm. Next follows another connecting line of 2.62 mm diameter and 52 mm length. Then comes either the inertance tube or the reservoir volume.

Inertance Tube

The best performance was achieved with an inertance tube[4,5] in place but the system was also run without the inertance tube. The best performing single diameter inertance tube had an inner diameter of 2.57 mm and a length of 2.20 m. The best overall results were obtained using a double inertance tube made with two different diameters with a smooth transition between them. These two stainless steel tubes were: 2.57 mm ID, 1.20 m long and 4.23 mm ID, 3.10 m long, with the larger tube adjacent to the reservoir volume.

Reservoir Volume

Most tests were performed with an external reservoir volume of 500 cm^3. The final configuration uses a 500 cm^3 volume internal to the compressor but with a separate pressure boundary from the backside of the compressor.

Condensing Fins

The condensing fins were of gold plated copper with a diameter of 42.5 mm and height of 18.9 mm. In this block, 9 slots 2.0 mm wide and 15.7 mm deep were cut. This allows a large surface area to be exposed to the fluid while not allowing a meniscus to form in any slot, even in the 0.38 g gravity on Mars.

EXPERIMENTAL RESULTS AND DISCUSSION

Background Heat Leak

The background heat leak was measured by observing the warm up rate of the cold end with the compressor off and with different applied heat loads. By assuming the thermal degradation factor[6] for the regenerator screens to be 0.1, we can separate the radiation and conduction terms. This method assumes that all the heat capacity is at the cold end. We have about three times as much mass in the cold head as in the regenerator. Table 3 summarizes the thermal background losses measured with a cold end temperature of 90 K.

Cryocooler Refrigeration Performance

All experiments use the same pulse tube and regenerator. We have not experimentally optimized the pulse tube or regenerator volumes. The volumes used were those optimized from our modeling, not from experimental tests. For this pulse tube and regenerator, we have found the optimized inertance tube length for a calculated diameter and for a double inertance tube. We also experimentally determined the optimized secondary orifice size.

Table 3. Thermal losses at 90 K

Parameter	with MLI	No MLI
Regenerator tube	0.95 W	0.95 W
Regenerator screen	0.76 W	0.76 W
Pulse tube	0.32 W	0.32 W
Helium	0.04 W	0.04 W
Radiation	0.17 W	0.90 W
Total measured	2.24 W	2.97 W

Table 4 summarizes the results of four experiments. The first run was done with a single diameter inertance tube. Run two was done with a double inertance tube; both lengths were optimized. Run three optimized the

Table 4. Experimental results at 90 K

Parameter	Run 1	Run 2	Run 3	Run 4
Inertance tube (ID x length)	∅2.57 mm x 2.20 m	∅2.57 mm x 1.20 m/ ∅4.23 mm x 3.10 m	∅2.57 mm x 1.20 m/ ∅4.23 mm x 3.10 m	∅2.57 mm x 1.20 m/ ∅4.23 mm x 3.10 m
Secondary orifice	closed	closed	∅0.25 mm x 1.25 mm	∅0.25 mm x 1.25 mm
MLI	none	none	none	aluminized mylar
No load temp.	45.35 K	42.49 K	42.61 K	40.38 K
Cooling power	16.18 W	17.51 W	18.07 W	18.78 W
Rejection temp.	302 K	302 K	302 K	302 K
PV input power	221.5 W	217.3 W	221.7 W	221.6 W
Specific power	13.7 W/W	12.4 W/W	12.3 W/W	11.8 W/W
% Carnot	17.2	19.0	19.2	20.0
V_{co}	15.49 cm^3	15.50 cm^3	15.47 cm^3	15.57 cm^3
P_{co}	0.303 MPa	0.317 MPa	0.320 MPa	0.320 MPa
P_{pt}	0.221 MPa	0.244 MPa	0.244 MPa	0.247 MPa
$\dot{m}_{res}$	1.184 g/s	1.741 g/s	1.710 g/s	1.712 g/s
$\dot{m}_{pt}$	1.08 g/s	1.14 g/s	1.12 g/s	1.12 g/s
$<\dot{W}_{pt}>$	36.3 W	37.3 W	30.2 W	30.2 W
Regenerator loss	9.2 W	7.0 W	5.7 W	5.7 W
FOM_{pt}	0.78	0.74	0.885	0.885
PA $\dot{m}_{res}$	-24.8 degrees	-56.2 degrees	-56.3 degrees	-56.2 degrees
PA $\dot{m}_{pt}$	-7.8 degrees	-33.9 degrees	-43.0 degrees	-43.0 degrees
PA V_{co}	148.9 degrees	148.6 degrees	148.0 degrees	148.2 degrees
PA P_{co}	13.1 degrees	12.2 degrees	12.4 degrees	12.3 degrees

V_{co}: Compressor swept volume
P_{co}: Pressure amplitude measured at the compressor
P_{pt}: Pressure amplitude measured at the pulse tube
$\dot{m}_{res}$: Mass flow rate amplitude measured at the reservoir volume
$\dot{m}_{pt}$: Mass flow rate amplitude calculated at the pulse tube warm end
PA $\dot{m}_{res}$: Phase angle by which the reservoir volume mass flow leads the pulse tube pressure
PA $\dot{m}_{pt}$: Phase angle by which the warm end pulse tube mass flow leads the pulse tube pressure
PA V_{co}: Phase angle by which the compressor swept volume leads the pulse tube pressure
PA P_{co}: Phase angle by which the compressor pressure leads the pulse tube pressure

secondary orifice with the double inertance tube. Run four repeated run three except the cold head was wrapped in about 10 layers of aluminized mylar. Figure 4 shows a performance plot of the cryocooler with the double inertance tube, a secondary orifice, and aluminized mylar (run 4). The Carnot efficiency of 20% relative to PV power is among the highest ever achieved with a pulse tube refrigerator or any other small cryocooler.

We can define a figure of merit for the pulse tube, FOM_{pt}, as the ratio of the time-averaged enthalpy flow, $<\dot{H}_{pt}>$, to the hydrodynamic work flow, $<\dot{W}_{pt}>$, through the pulse tube. The hydrodynamic work flow is the time average of the instantaneous product of the volumetric flow and pressure. The best way to measure the enthalpy flow along the pulse tube is to measure the heat rejected at the warm end heat exchanger. In our coaxial pulse tube, this is not possible since the warm end heat exchanger is built inside the aftercooler. We can also measure the enthalpy flow by adding the thermal loss terms to the net cooling power, $\dot{Q}_c$. We have measured the conduction, $\dot{Q}_{cond}$, plus radiation term, $\dot{Q}_{rad}$, but we must calculate the regenerator loss, $\dot{Q}_{reg}$, from a numeric model. We then have

$$FOM_{pt} = \frac{<\dot{H}_{pt}>}{<\dot{W}_{pt}>} = \frac{\dot{Q}_c + (\dot{Q}_{cond} + \dot{Q}_{rad}) + \dot{Q}_{reg}}{\frac{1}{\tau}\int_0^\tau P_{pt}\dot{V}_{pt}\,dt}. \tag{1}$$

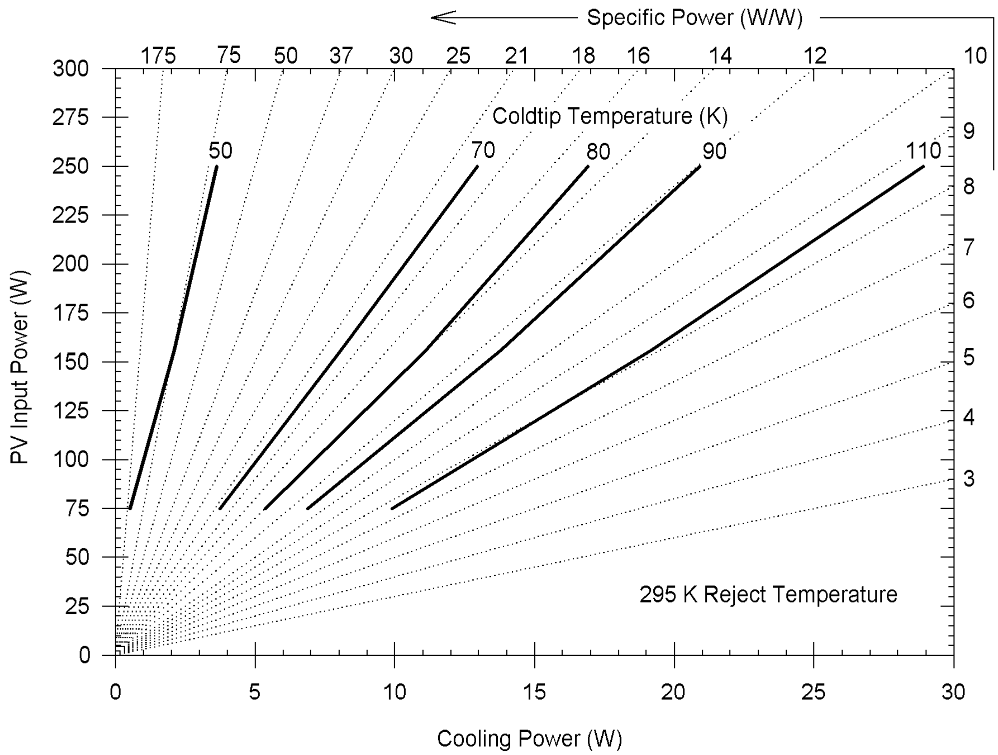

Figure 4. Measured cooler performance from run 4.

In general FOM_{pt} for a cryogenic pulse tube will be 1.0 if all losses in the pulse tube are zero. We cannot eliminate the boundary layer or non-adiabatic losses, but other pulse tube losses could be due to turbulence or acoustic flow streaming, which we can reduce. Rawlins et. al.[7] have shown that typical small pulse tubes have a FOM_{pt} of 0.60 to 0.85. Swift et. al.[8] described a large tapered pulse tube (1.5 kW cooling power) with a FOM_{pt} of 0.96. Figures of merit between 0.74 and 0.885 have been measured here.

Liquefier Performance

The condensing fins were added to the cold head and the dewar was filled with nitrogen gas at atmospheric pressure. Nitrogen has a specific enthalpy difference similar to that of oxygen from room temperature to the liquid state at atmospheric pressure, but has a lower liquefaction temperature. For safety reasons, we chose to liquefy nitrogen.

Figure 5 shows the experimental results for a period of about 27 hours. Thermocouples were placed at three locations along the neck of the dewar as well as on the cold head and at the bottom of the dewar (placement is shown in Figure 2). First, the dewar had to be cooled to the liquefaction temperature by convection. This process took about 12 hours. Liquid began to condense and drip to the bottom of the dewar after about 9 hours. After about 13 hours, the liquefaction process reached its equilibrium and liquid was produced at a rate of 1.75 g/min (2.17 cm^3/min) with 215 W of PV input power. The dewar had a measured heat leak of 0.15 g/min or 1.1 W. The liquefier should produce about 2.7 g/min (2.37 cm^3/min) of liquid oxygen.

There was a 1.4 K temperature difference between the cold head and the liquid. This shows that the condenser surface area was acceptable. The liquefaction rate decreased slightly with time. The initial reduction was probably due to a reduction in average pressure of the cryocooler caused by a small helium leak. After about 23 hours, the temperature difference between the cold head and liquid increased to 1.5 K and the liquefaction rate decreased somewhat more, due probably to contamination on the condenser.

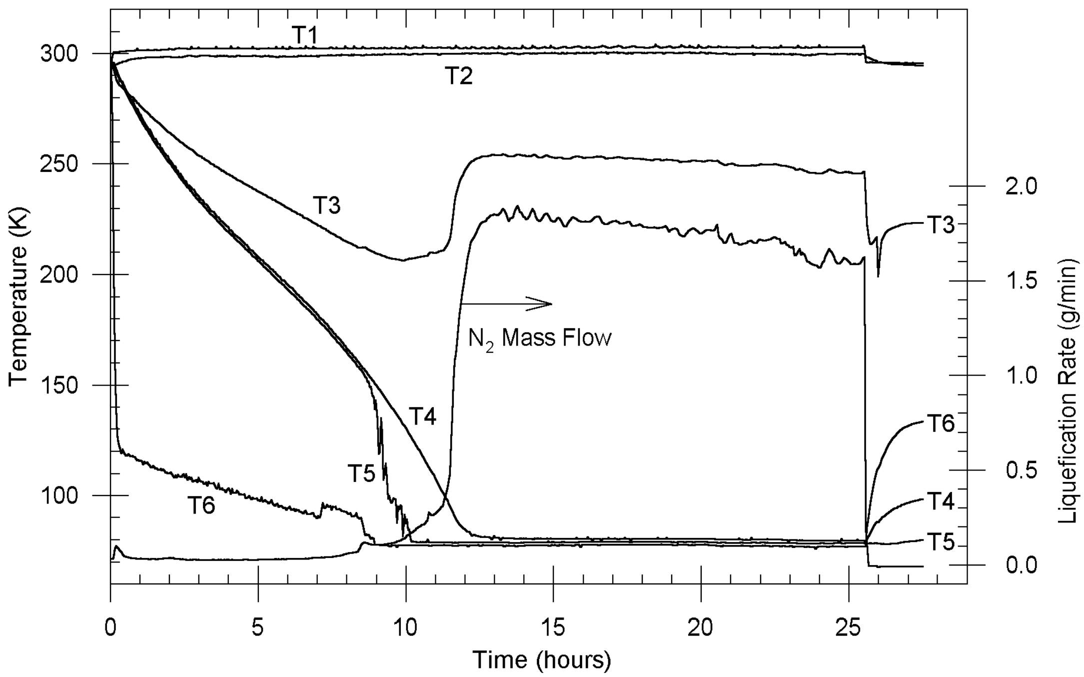

Figure 5. Liquefier performance using nitrogen. The locations of the temperature sensors T1-T6 are shown in Figure 2.

The cooler was switched off after about 25.5 hours; this would be normal operation for the liquefier running on solar energy, where it would be switched off at night. We were interested in finding the equilibrium temperature of the cooler to determine the background heat leak at night. The boil-off caused by this heat leak would have to be recondensed in the morning before the full liquefaction rate could be resumed. The cold fins remained at about 134 K with the cooler off, resulting in an additional heat leak of about 2.5 W from the cold head. This means that for every hour the cooler is off, it must run for 11.7 minutes to re-condense the boil-off from the cold head. While this cooler was designed for optimum performance, it may be possible to optimize the cold head for less off-state thermal conduction for a system design where the liquefier will run for only part of a day. A longer, smaller diameter regenerator may not perform as well but it will not have to re-liquefy as much boil-off and the liquefier may use less energy over the entire day/night cycle.

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