Efficient Small-Scale Helium Liquefaction: From Super-Critical Gas to Super-Cooled Single-phase He I

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Abstract – **Every year hundreds of tons of helium evaporated in medical or scientific instruments are wasted into the atmosphere. Researchers and helium users have long sought, especially during the last two decades, a practical small-scale helium recycling solution. In recent publications we revealed a new, simple, and very energy-efficient helium liquefaction method that, in conjunction with associated recovery components, helps many researchers realize the dream of recovering and producing liquid helium very efficiently by their own. The method uses elevated pressure to obtain super-cooled single-phase He I from super-critical gas.**

Keywords – **small-scale helium liquefaction, super-critical gas, single-phase He I, closed cycle refrigerators, helium recovery plant.**

I. INTRODUCTION

During the last two decades, following the development and gradual improvement of 4 K Gifford-MacMahon (GM) and Pulse-Tube (PT) cryocoolers, researchers have been applying these machines also for small-scale helium liquefaction. Initial liquefaction rates (LR) were very small (0.01-0.2 l/h) [1-4], and it took almost a decade to reach values of the order of 1 l/h with a single cryocooler coldhead [5, 6].

Table I summarizes LR data available in the literature, obtained using different coldhead types and heat exchanger configurations.

Table I. Coldhead type and reference. Exchange type and LR values. HE-Vacuum: Heat-Exchanger tube for input gas around coldhead in vacuum. Condenser: Cooling stations attached to the coldhead stages and a Condenser (coldhead in contact with the vapor). Direct: Naked coldhead in direct contact with the vapor.

Coldhead Type[ref]	EXCHANGE	LR (l/h)
GM[1]	HE-Vacuum	0.010
GM[2]	HE-Vacuum	0.050
PT[3]	HE-Vacuum	0.127
PT [4]	HE-Vacuum	0.200
GM[5]	HE-Vacuum	0.542
PT[6]	Condenser	0.750
GM[8]	Direct	1.450

In two recent papers [7, 8] we have demonstrated that both energy efficiency and liquefaction rates of small-scale liquefiers can be dramatically enhanced and improved over any previous data using smart-energy compressors [7], and a new liquefaction approach [8] explained below (Section II).

The simplicity and modularity of this new technology makes it easy to interface with most cryogenic equipment. It is particularly well suited for helium recovery from magnetoencephalography (MEG) or magnetocardiograph (MCG) systems and from experimental cryostats incorporating low-noise instrumentation such as SQUIDs. Any mechanical or electromagnetic noise transmitted from cryocoolers directly incorporated can affect the measurements. To avoid interference with instrumentation, helium is captured and liquefied with external recovery and liquefaction components conveniently located in a different room.

The main components needed for different helium recovery configurations based on this new liquefaction approach are described in Section (III).

II. NEW APPROACH TO LIQUEFACTION

Rather than using heat exchangers or condensers, we take advantage of favorable helium properties and cryocooler power versus temperature characteristics, working at elevated pressure (near and above the critical pressure), to extract the coldhead power more efficiently and condense vapor into liquid with a higher LR. Those properties and characteristic are:

1) High thermal conductivity of helium permits its liquefaction without the use of any heat exchanger or condenser. Room temperature helium gas enters the top of the liquefier Dewar neck, where the coldhead is placed, and flows naturally around the coldhead cooling surface. For flows up to 20 l/min, temperature stratification occurs from 300 K at the top of the neck, down to the condensation temperature (< 5.2 K) at the second stage cold finger, about 40 cm down.

2) The cryocooler power is higher at higher temperatures; hence the helium thermal energy extraction is more efficient [8].

Combining the above two ingredients we have been able to enhance liquefaction rates by up to 80% attaining record LR values above 1.45 l/h (Figure 1) and the daily yield of liquid of nearly 35 l/day.
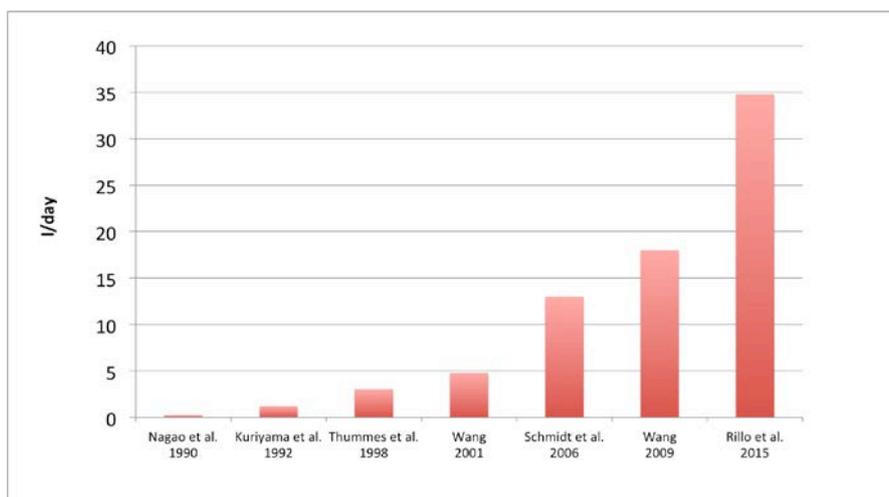
Fig. 1. Published daily yields of liquid He (l/day) using 4 K GM and PT coldhead cryocoolers**.**

We enhance liquefaction by condensing supercritical vapor in a continuous way and producing, directly, single phase super-cooled liquid He I, without undergoing a phase transition [8], illustrated here with the help of Figure 2. The desired final state of a liquefier Dewar, full of saturated liquid at atmospheric pressure (*A*), with density 125 g/l, can be obtained following different constant pressure paths in the P-T phase diagram [8]. Two of those possible paths (107 kPa and 251 kPa) are drawn in the helium density versus temperature graph of Figure 2.
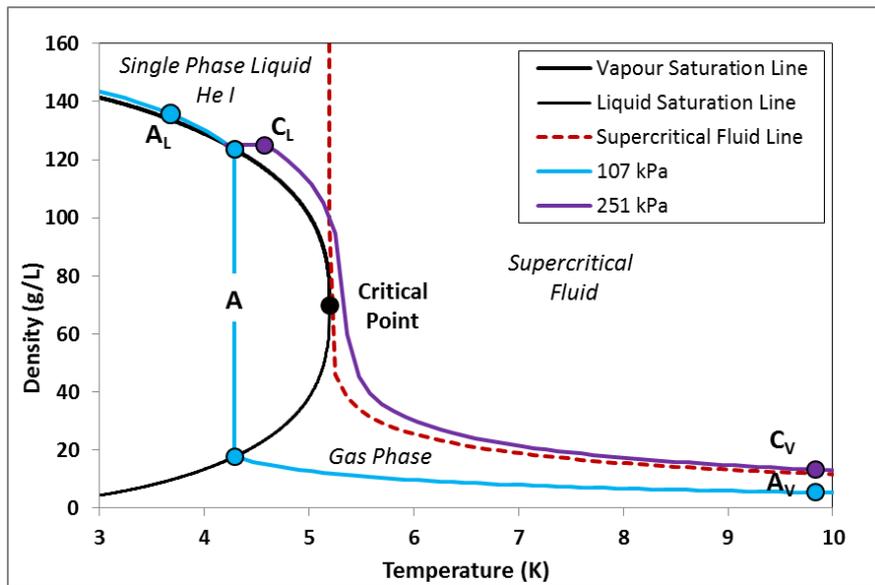
Fig. 2. Helium Density versus Temperature. Two constant pressure liquefaction paths are shown: i) slightly above atmospheric pressure (107 kPa) path $A_V{\to}A{\to}A_L$, and ii) Supercritical (251 kPa) to supercooled single phase (107 kPa) path $C_V{\to}C_L{\to}A{\to}A_L$.

The path near atmospheric pressure, 107 kPa, ($A_V{\to}$ $A{\to}$ A_L) starts with room temperature gas, passes through A_V, and halts cool-down at A where saturated liquid is produced. Once the Dewar is full of saturated liquid, cool-down continues and produces single-phase super-cooled liquid A_L down to 2.5 K for very efficient helium transfers [8]. The path at 251 kPa, also starts at room temperature, condenses the helium fluid continuously and much faster than the path at 107 kPa, profiting from the increased cryocooler power at higher temperatures and the faster enthalpy decrease when approaching the critical point ($C_V{\to}$ $C_L{\to}$ $A{\to}$ A_L) [8].

As a result of the new liquefaction approach, the time to fill, for example, a 160 liters Dewar with liquid at 4.2 K and at atmospheric pressure, is dramatically reduced from 8 days to around 4.5 days, experimentally demonstrated in [8].

III. HELIUM RECOVERY CONFIGURATIONS.

Advanced Technology Liquefiers (ATL) based on the above principles are now commercially available in two versions [9] (Figure 3) and constitute the heart unit of new very simple recovery configurations [10]. Prior to liquefaction, recovered gas from user instruments needs to be purified. Advanced Technology Purifier (ATP) [11], based on GM cryocoolers, reduces the partial pressure of contaminants down to values on the order of 10^{-11} bar, thus reducing the concentration of the impurities to trace values in the sub-ppm level.

Fig. 3. Quantum Design ATL test room.

Figure 4 shows a medium pressure (100 psi) recovery plant with virtually no losses [10], in which both the ATP [11] and the ATL [9] are based on GM cryocoolers,
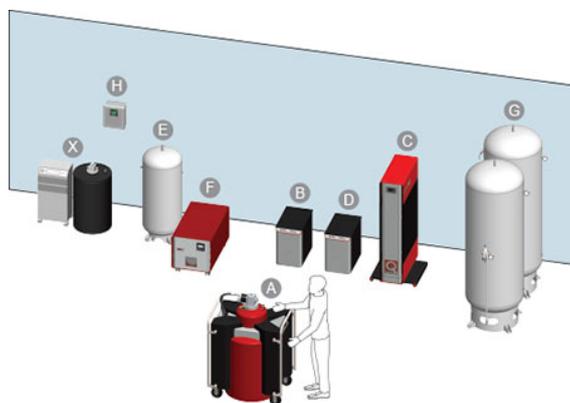
Fig. 4. Medium Pressure Helium Recovery plant. A – ATL; B – Compressor for ATL; C – ATP; D – Compressor for ATP; E – Low-Pressure Buffer Tank; F – Recovery Booster Pump-Compressor; G – Medium pressure Storage Tank; H – Back pressure Controller; X – Customer Instrument.

Instruments cooled by liquid helium (X), which may be located in different rooms, connect the helium boil-off to metallic pipes. A Back Pressure Controller (H) can be employed between an instrument and recovery piping to guarantee stable positive pressure in the instrument Dewar. The output of (H) is connected to a low-pressure buffer tank (E). Finally helium is pumped from the buffer tank (E) and compressed by a booster pump (F) in the medium pressure storage tanks (G).

In medium pressure configurations, like that schematically drawn in Figure 4, the absence of plastic pipes and gas bag storage minimizes helium contamination [12]. Even when several instruments (X) are connected by recovery pipes of tens of meters long, the final purity of gas in the storage tanks (H) is always higher than 99.99 %, thus increasing time between ATP regenerations from weeks up to several months.

In high-pressure configurations [10] with many different instruments located in different places and connected to a gas bag for recovery, by means of non-metallic pipes, the purity of the recovered gas varies typically in the range from 99 % up to 99.9 %. Even in this case the time between ATP regenerations can be of the order of several weeks, depending on the exact input gas purity.

The superior gas purity (99.9995 %) provided by the ATP [10] is independent of the input gas purity and allows continuous operation of an ATL unit for the lifetime of the cryocooler bearings and seals (>10,000 hours). Utilizing a Quantum Design smart

compressor [7] in low power mode empirically reduces wear on these components thus further extending continuous operation.

Finally, for laboratories and hospitals where space is scarce and electromagnetic interferences must be avoided, direct recovery offers a very simple configuration [10]. Only element (H) is needed to interconnect the instrument (X) and the ATL (A), the later being in a room contiguous to the instrument's shielded room. This is especially suitable for recovering gas from MEG, MCG and Nuclear Magnetic Resonance equipment (NMR). Examples in the field can be found in [10]. In this case, using relatively short metallic pipes, the gas purity can be maintained around 99.999 % and ATL long-term operation is possible without a purifier.

ACKNOWLEDGEMENTS

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Editorial note of June 25, 2015: After Preview publication on June 22, this reference list was amended per authors' request by removing part of patent references.