Experimental investigation of a dual flow transfer system for liquid helium

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Abstract. In transfer stations for liquid helium, single-flow transfer lines are often used to transfer the liquid into a smaller mobile dewar. During this process, a considerable amount of the liquid evaporates due to heat leak and especially due to pressure losses in the transfer line. Regardless of the liquefier's efficiency, this evaporation loss contributes to a significantly higher running time of the cold box and a higher primary energy input to generate the net liquid volume. To overcome this, a laboratory setup was realized by a combination of a flexible double-flow transfer line and a cold liquid pump, which can reduce these losses drastically. In this article, the authors report on their current test results on filling performance, operating losses and practicability.

1. Introduction

Helium liquefaction is an energy-intensive process that requires a high specific energy input of up to $4\ \mathrm{kWh/l_{Lhe}}$ to operate the helium liquefier. In the last decades, most optimization efforts have been made in the design of the expansion turbines, reducing the specific energy input down to $2\ \mathrm{kWh/l_{Lhe}}$. However, the optimization of the liquid transfer into mobile dewars offers the greatest potential for increasing the overall efficiency of the plant. Conventional single-flow transfer line use an overpressure (typically 250…500 mbar) in the primary storage dewar to transfer the liquid into a mobil dewar. During this process, up to 30% of the initial liquid volume evaporates. In detail, this is due to

a) the initial cool-down losses
b) the heat leak into the transfer line in cold state
c) the fluid expansion during transfer from $1.25 \ldots 1.5\ \mathrm{bar_{abs}}$ to $1.02\ \mathrm{bar_{abs}}$
d) cold gas displacement from target dewar.

This cumulated flash gas needs to undergo recovery, purification and in the end energy intense re-liquefaction. By improving the thermal and hydraulic design of these lines, Dittmar et al. were able to reduce these losses already down to 19% (including cool-down losses) [1].

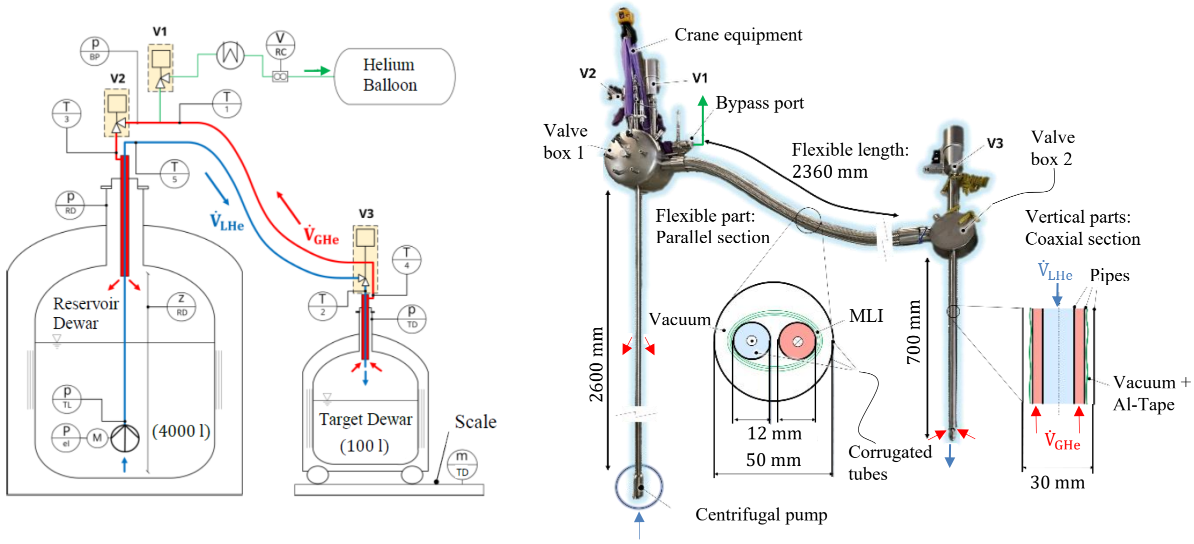
Another technical solution for decanting was established by Berndt et al. at the Walter Meissner Institute (Garching, Germany) [2], [3]. They used a rigid dual flow transfer line and a cold submersible centrifugal pump to transfer the liquid helium into mobile dewar, while the cold gas was guided back to the reservoir by means of cold counter flow line. The authors claimed to achieve transfer losses of < 2%. An identical system at IFW Dresden (Germany) operates with 6% flash losses at transfer rates of $11\ \mathrm{l_{LHe}/min}$. Main obstacles of this setup is the rigid and bulky design of the transfer line, including the necessary constructional adaptions for a mobile dewar lift. For this reason, only a small number of such pumps and even fewer transfer systems had been built.

In the face of energy crisis and the common will to reduce carbon dioxide emissions, the authors of this article present a high-performance dual flow transfer system with a flexible section that can easily be coupled to mobile dewars. In combination with a previously developed and tested submersible single-stage centrifugal pump equipped with hybrid ball bearings [4], very low transfer losses at high decanting speeds are possible.

IOP Conf. Series: Materials Science and Engineering **1327** (2025) 012171 doi:10.1088/1757-899X/1327/1/012171

2. Overview – Transfer system

Figure 1 (a) shows the P&ID of the transfer system. A cold single-stage centrifugal pump inside the reservoir dewar (Wessington CH4000) transfer the liquid helium through the liquid line (blue) into the target dewar. Simultaneously, the rejected cold gas flows in counter flow back through the gas line (red) into the reservoir dewar. During cool-down the gas will be bypassed to the recovery (green).



(a) Piping and instrumentation diagram (b) Design of the dual flow transfer line

Figure 1. Overview of TU Dresden transfer system

Figure 1 (b) illustrates the design features of the transfer line manufactured by Cryovac, applying an improved thermal design compared to usual single flow transfer lines [1]. In the horizontal section the liquid and gas line are realized as two parallel corrugated lines to ensure flexibility. A coaxial design was chosen in the vertical parts. The transfer line is coupled to the reservoir dewar with an O-ring fitting. Valve box 1 is mechanically supported by a clamp at the fitting to avoid high bending stress on the riser line. The present prototype systems is equipped with various sensors to allow in depth analysis of all transfer parameters (see table 1).

Table 1. Sensors and Accuracies

Variable	Sensor [Range]	Accuracy
pressures	Keller PAA-23SX [0 ... 2.5 bar_{abs}]	$\pm$0.25% FS ($\pm$0.63 mbar)
temperatures	Scientific Instruments Si-415, Group A [0 ... 450 K]	$\pm$0.3 K [1.5 ... 25 K] $\pm$0.5 K [25 ... 450 K]
volume flow	Höntzsch TA Di 35,9 [0 ... 200 m^3/h] (Normal condition at 1014 mbar and 294.2 K)	2% of reading + 0.073 m^3/h
mass	Dini Argeo DGT1AN [0 ... 300 kg]	$\pm$2.2 g (calibrated)

The reservoir dewar is connected to a L140 liquefier with a cold ejector made by Linde Kryotechnik AG. This allows low pressures inside the storage vessel, which is advantageous regarding depressurization losses in the target dewar (see section 3.5). However, the presented system can also be operated without an ejector, which would slightly increase the flash losses at the same transfer rates.

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Decanting procedure At the beginning of the decanting, the target dewar is coupled using a standard O-ring fitting. Due to the flexible horizontal section, neither a dewar lift nor other provisions are required for coupling. After purging of the lines, the precooling of the liquid and the gas line starts (V3 and V1 opened). As soon as reaching 20 K at T_1 and T_3, the decanting process is then initiated at full pump speed (16,000 rpm, V3 and V2 opened, V1 closed). When the target dewar is completely filled, liquid enters the gas line, causing an increased pressure difference in the line due to higher fluid friction. Together with change in the pump's power input, this can be used as stop criterion. Decoupling can be carried out after depressurization of the target dewar. Cold parts only occur at the lower tip of the transfer line, reducing the additional effort for the time-consuming warm-up procedure of the bottleneck fittings, as known from single flow transfer lines.

3. Experimental investigation

3.1. Calculus of transport parameters

The calculation of the liquid helium flow rate is a simplification by assuming that the entering and the exiting volume of the target dewar are the same ($\dot{V}_{LHe} = \dot{V}_{GHe}$). Thus, the flow rate can be determined by measuring the change in mass (see equation 1).

$$\dot{V}_{LHe} = \frac{dm_{TD}}{dt} \cdot \frac{1}{\rho' - \rho''} \tag{1}$$

The pressure loss of each line and the entire transfer system are computed according to equation 2, 3 and 4.

$$\Delta p_{LHe} = p_{TL} - p_{TD} \tag{2}$$

$$\Delta p_{GHe} = p_{TD} - p_{RD} \tag{3}$$

$$\Delta p_A = \Delta p_{LHe} + \Delta p_{GHe} \tag{4}$$

$$\dot{Q}_{s,LHe} = \dot{V}_{RC} \cdot \rho_N \cdot \left(h''(p_{TD}) - h'(p_{RD})\right) \tag{5}$$

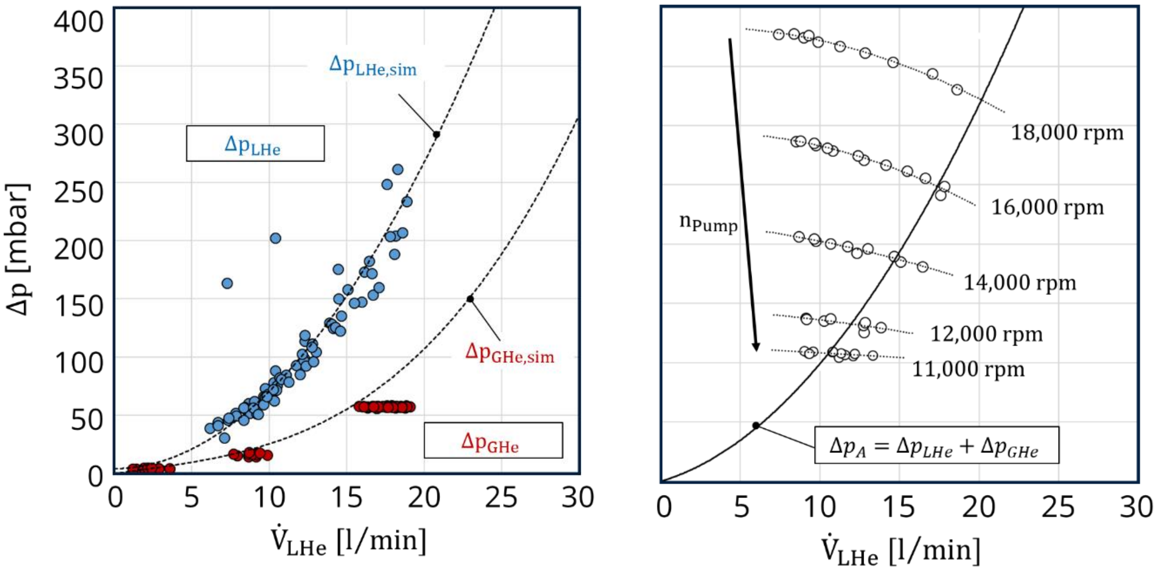
The static heat leak of the liquid line is calculated by the difference of the specific enthalpy at the entry and exit of the line (see equation 5). The gas flow rate at the recovery system is used to determine the mass flow.

REFPROP is used to calculate the fluid properties [6].

3.2 Transfer rates

Figure 2 (a) shows the pressure loss of the liquid (blue) and the gas (red) line versus the liquid helium transfer rate. The data was collected using two different approaches: the pressure loss in the liquid line was measured during the acceleration of the pump in the start-up sequence, while the pressure loss in the gas line is recordered in three different steady state conditions. Due to the uncertainty of the scale and the dynamic system behavior, the data points for Δp_{GHe} occur to a large extend independently of $\dot{V}_{LHe}$ in the range of 15-20 l/min. In this case, the mean value must be used. In general, the experimental data for both lines are in good agreement with the prior simulation results (see $\Delta p_{LHe,sim}$ and $\Delta p_{GHe,sim}$) in [5].

The highest losses over the flow path occur in the liquid line, which account for about 2/3 of the entire pressure loss due to the higher fluid density. Figure 2 (b) illustrates the pressure loss of the system Δp_A and the pressure head of the pump at different pump speeds versus the transfer rate. The decanting process can be accelerated by increasing the rotational speed n_{Pump}. At 18,000 rpm the pump delivers 20 l/min with a total efficiency of 60% (including motor bearing and ohmic losses of the drive) and thus fills a standard mobile dewar vessel in 5 min. In comparison to a single flow transfer line, which can deliver 4 l/min using 400 mbar overpressure in the reservoir dewar [1], the dual flow transfer system presented here can speed up the decanting process by factor 5! In principle, the pump motor can operate at 25,000 rpm, allowing even higher decanting speeds. However, this was not tested in order to protect the motor's ball bearings from higher loads. Up to this point, 31 fillings had been carried out without any deterioration in the pump's performance.



(a) Pressure loss of liquid and gas line

(b) Transfer performance at variable pump speeds

Figure 2. Experimental results on pressure loss and transfer performance

3.3. Static heat leak

The static heat leak into the liquid line with and without cold gas return is determined by the zero-delivery-case. After pre-cooling all pipe sections, the mass flow was reduced until the mass in the target dewar remains constant. In this state, the liquid in the liquid line evaporates entirely and leaves the line as saturated gas. The recovery flow meter was used to determine the rejected mass flow of gas, which corresponds to the mass flow in the liquid line. The measurement was carried out for at least 10 min after reaching a stable dewar mass. Table 2 shows the heat leak and specific values for the technical reference from Dittmar et al. [1] and the respective values for the dual flow transfer line.

Table 2. Static heat leak on liquid line in single and dual flow operation

	Configuration	$\dot{Q}_{s,LHe}$ [W]	$\dot{Q}_{s,LHe}/A_{L,i}$ [W/m^2]	$\dot{Q}_{s,LHe}/l_h$ [W/m]	Dimensions
Single flow transfer line	Reference: optimized transfer line [1]	3.78 ± 0.41	68.16 ± 7.4	1.73 ± 0.19	$D_o = 34$ mm, $D_i = 8$ mm, $l_h = 1.9$ m
Dual flow transfer line	Single flow operation	9.49 ± 0.25	89.91 ± 2.41 (+32%)	3.39 ± 0.09 (+96%)	$D_o = 50$ mm, $D_{i,h} = 12$ mm, $l_h = 2.8$ m
	Dual flow operation (reduced)	5.51 ± 0.17	52.18 ± 1.65 (-23%)	1.98 ± 0.06 (+15%)	

In single flow operation, the cold gas generated in the target dewar is rejected at the bottleneck of the dewar and is directed to the recovery (V3 opened, V1 and V2 closed). In this case, the maximum heat flow occurs since the gas is not cooling the liquid line especially in the critical coaxial section. However, the total static heat leak during decanting cannot be measured since no accurate measurement of the mass flow, e.g. cold turbine flow meter, has been installed. Hence, the reduced dual flow operation was used, where the rejected gas was guided through the gas line in the recovery system, only passing the coaxial section in the target dewar (V1 and V3 opened, V2 closed), the flexible section and finally the valve V1. Neglecting the influence of the second coaxial section in the reservoir dewar, this heat flow is considered to be the maximum heat leak in the dual flow operation during decanting.
The dimensions of the pipe work are significantly larger compared to the reference configuration. Therefore, specific values for the heat leak are given taking into account the outer surface area of the internal flexible lines $A_{L,i}$ and the horizontal length of the transfer line l_h. The comparison shows that the specific static heat leak $\dot{Q}_s/A_{L,i}$ in dual flow operation is even lower (-23%) than the value of the reference line despite less favorable dimensions. In single flow operation, this specific heat leak increases by 32%, as expected. Comparing the length-reduced specific values ($\dot{Q}_s/l_h$), both configurations show higher heat leaks compared to the reference.

3.4. Transfer losses
The transfer losses were monitored during the decanting of several dewars in series starting from roughly 60 mbar overpressure in the reservoir dewar. The overall transfer loss for a series of 5 decantings is 4%. In figure 3 the evaporation loss and its shares are displayed.

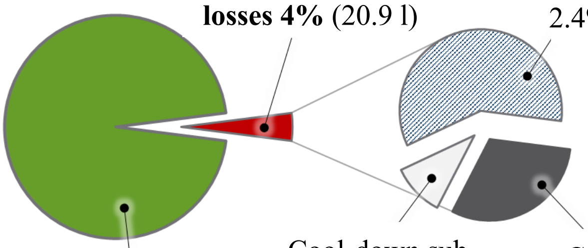


Figure 3. Overall transfer losses for 5 complete decanting procedures and shares

Cool-down loss The cold mass of the transfer system is 4.7 kg. Consequently, in a perfect cool-down process by using extremely low mass flows, 2.1 l_{LHe} (equivalent to 1.6 m^3 helium gas at ambient temperatures) must evaporate as a total minimum by using the latent and entire sensible heat of the helium. The current cool-down loss of the first filling with 6.4 l_{LHe} (+68% vs theoretical minimum) is a compromise between process time and efficiency. Best practice is that the pump speed remains constant at low speeds (6,000 rpm) during the pre-cooling. To further reduce the cool-down loss, either the pump speed could be lowered or the speed could be dynamically adapted to the temperatures in the lines. After the first decanting, pre-cooling is carried out during the purging process, causing another 0.5 l_{LHe} evaporation loss for each filling procedure.
Depressurization loss At the end of the decanting process, the pressure inside the target dewar increases (over 100 mbar overpressure at high filling rates) due to liquid entering the gas line. Before decoupling, the target dewar was depressurized and the flash gas (equivalent to 2.5 l_{LHe}) was rejected to the helium recovery. This loss contributes the highest share of 2.4% to the overall losses and can be lowered by optimization of the stop criterion and the filling rate. During the decanting procedure, the pressure of the reservoir dewar can change to some extent, depending on e.g. the initial filling of the

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reservoir, the applied filling rates, the position of the gas inlet relative to the bottle neck of the target dewar and the chosen temperature limit for precooling. This behavior will be analyzed in a later publication in depth.

Energy savings As a result of the decanting efficiency, the combined electrical energy input of the main cycle compressor (2 kWh/l_{LHe} specific drive power for liquefaction) and the adjacent recovery compressor (37 kW drive power for 87 m^3/h intake flow) decreases drastically by 28%, resulting in electrical energy savings of 111 MWh at a standardized helium consumption of 140,000 l_{LHe}/a. When operating in the German electricity network, the presented decanting system can save up to 48 tons of carbon dioxide emissions and over 45,000 € in energy costs per year, not including the time savings and productivity improvements for technical staff.

4. Conclusion and Outlook

A robust high-performance decanting system for liquid helium has been successfully developed for routine operation at the low temperature lab at TU Dresden University of Technology. Energy savings of 28% can be achieved, resulting in much less operational and environmental costs. Additionally, the decanting speed is accelerated up to factor 5 depending on the applied rotational speed of the pump. Further optimization of the system operation will focus on the cool-down and depressurization losses as well as the investigation of the part-load behavior.

5. References

[1] Dittmar N et al. 2016 Characterisation and optimisation of flexible transfer lines for liquid helium. Part I: Experimental results *Cryogenics* **75** DOI: 10.1016/j.cryogenics.2015.11.005

[2] Berndt H, Doll R, Jahn U, Wiedemann W 1988 Low Loss Liquid Helium Transfer System, Using a High Performance Centrifugal Pump and Cold Gas Exchange *Advances in Cryogenic Engineering* **33** p 1147-1152

[3] Berndt H, Doll R, Wiedemann W 1990 Two Years' Experience in Liquid Helium Transfer with a Maintenance free Centrifugal Pump *Advances in Cryogenic Engineering* **35** p. 1039 – 1043

[4] Doll J et al. 2023 Development and Characterization of a Centrifugal Pump for Low-loss Liquid Helium Transfer *17th Cryogenics 2023, IIR Conference Dresden* DOI: 10.18462/iir.cryo.2023.148

[5] Doll, J et al. 2023. Development of a dual flow transfer system with a centrifugal pump for liquid helium. Proceedings of the Cryogenic Engineering Conference. Honolulu.

[6] Lemmon EW, Bell IH, Huber ML, McLinden MO 2018 NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP **10.0** (Gaithersburg: National Institute of Standards and Technology, Standard Reference Data Program)

Nomenclature

$A_{L,i}$	Outer surface area of internal pipes	A	Plant
h	Specific enthalpy (kJ/kg)	BP	Bypass
l_h	Horizontal length	el	electrical
m	mass	GHe	Gasous helium (saturated)
$\dot{m}$	Mass flow (kg/s)	LHe	Liquid helium (saturated)
n	Rotational speed (min^{-1})	MLI	Multi layer insulation
p	Pressure (mbar)	i	internal (pipe)
Δp	Pressure lift (mbar)	o	outer (pipe)
$\dot{Q}$	Heat flux (W)	RD	Reservoir dewar
$\dot{V}$	Flow rate (l/min, l/h)	sim	simulated
T	Temperature (K)	TD	Target dewar
t	Time (s)	TL	Transfer line (pump discharge port)
ρ	Density ($kg\ m^{-3}$)	V	valve
		s	static