Entropy Analysis of Support Systems in Multi-Channel Cryogenic Lines

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Abstract This work describes the methods for transporting cryogens through multi-channel transfer lines. It also presents examples of the use of cryogenic lines and of their designs, referring in detail to typical structural nodes found in cryogenic transfer lines. The second principle of thermodynamics and the Gouy-Stodola theorem are discussed from the perspective of their application in optimizing and evaluating heat and mass transfer devices. The next part of the work presents the internal structure of the selected 100 m multi-channel cryogenic transfer line. Several variants of the method of supporting process pipes have been presented. For each of the solutions, an entropy analysis was carried out in order to select the best design in terms of the entropy generated in the process pipes.

1. Introduction

In most existing cases, the medium transported in multi-channel cryogenic transfer lines is helium, which may be transferred in different thermodynamic states – liquid, gaseous and supercritical. This fact is due to the specific operation of helium-cooled devices examples are superconducting magnets which must be kept at cryogenic temperatures in order to assure the superconductivity of the coil cables.[1] In helium-cooled cryogenic devices, the medium – after its cooling capacity has been used – can be profitably transported back in an isolated pipeline to a cryoplant, where its parameters are restored, allowing it to be reused for cooling purposes.

The most typical, four-channel cryogenic transfer lines consist of two pipes (supply and return of the cooling medium proper), which have a temperature of 5 K, and of two warmer pipes (supply and return of helium for thermal shield cooling), which have a temperature of 40-80 K. Frequently, process pipes in one multi-channel transfer line carry cryogen having different thermodynamic parameters – for example supply pipes carry supercritical, high-pressure medium, while the return pipe may carry a low-pressure gaseous or two-phase medium. In addition, the pipe used for thermal shield cooling carries a gaseous medium within the temperature range of 40-80 K. Figure 1.1 shows a cross-section through a four-channel cryogenic transfer line with its basic elements indicated. The pipeline elements as shown in figures 1.1 are included in any multi-channel transfer line. Still, parameters such as the shape and number of supports or the design and cooling method of the thermal shield depend on a particular application.
Multi-channel cryogenic transfer lines used in helium transportation are constructed individually for a particular device they are intended to work with. Pipelines for helium transportation can reach lengths of hundreds of meters. [2] The number of process pipes, their cross-sections and the parameters of the transferred medium are dictated by the specific requirements of the devices in which the cryogen is used. Despite difficulties in designing universal solutions which might become a standard, cryogenic transfer lines include a number of commonly used structural elements. Although they have different shapes or principles of operation, such components of cryogenic transfer lines as supports, vacuum barriers and compensation bellows have very similar functions. Figure 1.2 shows all types of supports used in one- and multi-channel cryogenic transfer lines. The above property of multi-channel transfer lines allows their optimization by using minimum entropy production method.

Figure 1.1 Schematic view of the supporting system for a cryogenic transfer line.

2. Application of the second law of thermodynamics and the Gouy-Stodola theorem in improving the design of cryogenic transfer lines

The second law of thermodynamics implies that during each irreversible process, the sum of entropy of the system and its surroundings increases. For an integrated entropy generation, additional power \( P_{ad} \) necessary to overcome the irreversibilities accompanying the flow of cryogen can be calculated from the Gouy-Stodola theorem described by (1) where \( T_a \) is an ambient temperature. [3,4]

\[
P_{ad} = T_a \cdot \dot{S}
\]

(1)

From equation (1) it follows that thermal objects should be characterized by the lowest possible entropy flux \( \dot{S} \) increases, especially in the processes of heat exchange and medium transfer. In cryogenic transfer lines, entropy increase is caused by two processes: throttling of the medium in the process pipe and heat exchange due to temperature difference between the cryogen and the surroundings (2).

\[
\dot{S} = \sum_i \dot{S}_{\Delta T} + \sum_j \dot{S}_{\Delta P}
\]

(2)

Where: \( \sum_i \dot{S}_{\Delta T} \) – sum of entropy fluxes generated due to temperature differences, in W/K,

\( \sum_j \dot{S}_{\Delta P} \) – sum of entropy fluxes generated due to pressure drops in the pipeline, in W/K.

The processes of entropy generation in the process pipe of a cryogenic transfer line are shown in a simplified manner in figure 2.1.
Figure 2.1 Processes of entropy increase in a pipeline segment having length $dx$; $\dot{m}$ – mass flow rate of the transferred medium in kg/s, $\dot{q}$ – heat flux in W, $T$ – temperature of medium in K, $p$ – pressure in Pa, indexes $in$ – input value, $out$ – output value. [5]

Entropy due to heat transfer can be calculated from Eq. 3. The entropy stream is increasing with the decrease of the process pipe temperature, which makes this entropy source especially important in cryogenic conditions. The second entropy source is pressure drop caused by local and linear flow resistivities – Eq. 4 where $w$ is velocity of cryogen, $d$ is diameter of the flow channel, $\lambda_S$ and $\zeta$ are respectively linear and local flow resistance coefficients, $n$ is local flow resistance number.

$$\dot{S}_{\Delta T} = \frac{\dot{q}}{T} \frac{T + \Delta T}{T_0}, \quad \dot{S}_{sp} = \frac{\dot{m} w^2}{2 T_0} \left( \frac{\lambda_S}{d} + \sum \zeta \right)$$ (3,4)

Assuming that $\Delta T = T_A - T_C$, where $T_C$ is constant cryogen temperature, equation (3) takes a special form for cryogenic liquid transfer (5).

$$\dot{S}_{\Delta T} = \frac{\dot{q} \cdot \Delta T}{T_C^2 \left( 1 + \frac{\Delta T}{T_C} \right)}$$ (5)

Because this work uses entropy analysis to compare two support systems for process pipes in cryogen transfer lines having equal length, equal process pipe diameters and equal cryogen flow rates, the entropy fluxes generated due to flow resistances are equal in both cases and they will not be taken into account at the later stages of the comparative analysis of the support system.

3. Analysis of support systems in examples of multi-channel cryogenic transfer lines

Two 100 m long straight segments of multi-channel transfer lines L1 and L2 were compared in order to examine how changing the support systems for process pipes influences the entropy fluxes generated in the process pipes and the additional power required to overcome the irreversibilities which accompany the cryogen flow. Transfer lines differ in the design of sliding support systems for process pipes. Sliding supports are the most frequently used elements in cryogenic transfer lines and therefore they have been chosen as the object of this analysis.

The investigated cryogenic lines consist of four process lines, a thermal shield and a vacuum vessel. The process lines include two lines having a temperature of approximately 5 K: supercritical helium supply (5 K) and low-pressure gaseous helium vapors return (4.5 K). Pipes installed for thermal shield cooling have higher temperatures. Thermal shield cooling supply line has a temperature of 45 K, while radiation shield cooling return line is 60 K. The 60 K pipe is in thermal contact with the thermal shield of the pipeline, while the 45 K pipe supplies gaseous helium for cooling thermal shields in external devices. The parameters of the discussed cryogenic lines are included in Table 3.1.

Thermal shield support systems in transfer lines L1 and L2 will remain unaltered. In the case of transfer line L2, the design of strong fixed supports and weak fixed supports was modified only to an
extent required to allow changing the position of process pipes in the cross-section. As regards to thermal conductivity, both strong fixed supports and weak fixed supports remained identical to the elements used in the L1 transfer line. In both analyzed cases modifications apply solely to the sliding supports of process pipes – their design and method for carrying vertical loads.

Table 3.1. Operating parameters of transfer lines L1 and L2.

| Dimension (mm) | 5 K | 4.5 K | 45 K | 60 K |
|---------------|-----|-------|------|------|
| p [MPa]       | 0.35| 0.12  | 1.7  | 1.67 |
| T[K]          | 5   | 4.5   | 45   | 60   |

In the case of the L1 transfer line, a sliding support was used to simultaneously support all process pipes except for the 60 K thermal shield cooling pipe. Such solution is typical and allows both a reduction in the number of sliding support types and an easier assembly process of the transfer line. Such a support constitutes a thermal contact point between 3 process pipes and the thermal shield. The L2 transfer line has 3 types of sliding supports, each having different functions. In this solution, only the low-pressure vapor return pipe is in thermal contact with the thermal shield.

3.1. Support system for process pipes in the L1 transfer line

The initial model selected to carry out an entropy analysis of a support system for a multi-channel transfer line was a 100 m long pipeline with the cross-section identical as in the XATL1 line, which was used to supply the AMTF (Accelerator Module Test Facility) – a resonant cavity and cryogenic module testing station [6]. The tested components were used in the construction of the XFEL (European X-ray Free Electron Laser), which is located in the DESY research center in Hamburg. Figure 3.1 shows a cross-section through the L1 transfer line with process pipes indicated.

![Figure 3.1 Cross-section through the L1 transfer line.](image1)

The transfer line was designed of eight modules, each 12.5 m in length. Figure 3.2 schematically shows support methods for the process pipes in the L1 transfer line, as well as the types of supporting elements. Both ends of the test segments are equipped with strong fixed supports.

![Figure 3.2 Schematic view of a 100 m segment of the cryogenic transfer line L1 based on the XATL1 design solutions.](image2)
The L1 transfer line incorporates several types of process line supports, which carry loads to the thermal shield. Each of the eight pipeline modules has a weak fixed support, which defines the position of the process lines in relation to the vacuum vessel and the thermal shield. Apart from the fixed support, each module has three sliding supports. Both ends of the 100 m segment are equipped with strong fixed supports in order to transfer forces generated by the compensation bellows due to pressure in the process pipes. Figures 3.3 and 3.4 show the types and design of the fixed supports for process lines used in the L1 transfer line.

**Figure 3.3** Strong fixed support in transfer line L1.

**Figure 3.4** Weak fixed support in transfer line L1.

The design of the sliding support for the process pipes used in the L1 transfer line is shown in figure 3.6 in subsection 3.2.

### 3.2. Calculations of entropy fluxes generated in transfer line L1

In order to identify heat fluxes to the particular process pipes and to determine the resultant entropy fluxes, the support was subjected to thermal analysis. Each element of the model was assigned material properties, represented as a function of temperature. In order to determine the temperature field, boundary conditions were introduced by setting a temperature value inside each of the process pipes, as shown in figure 3.5. In order to allow thermal comparison between the supports in the L1 and L2 transfer lines, the influence of thermal radiation was not included. For process pipes protected by 10 layers of MLI the heat flux is negligible and amounts to 65 mW/m²[7]. The temperatures inside each of the process pipes were set in accordance with the values provided in Table 3.1. With the temperature field and heat flux densities in the whole model known, heat exchange paths between individual process pipes could be identified. The temperature field in the investigated model is shown in figure 3.6.

**Figure 3.5** Boundary conditions set for the process pipe sliding support in the L1 line.

**Figure 3.6** Temperature field for the process pipe sliding support in the L1 line.

Based on the determined values of heat fluxes to individual process pipes and using equation (5), the corresponding entropy fluxes were calculated. Table 3.2 includes the values of both heat fluxes and entropy fluxes.
Table 3.2. Heat fluxes to the process pipes and the generated entropy fluxes calculated for the sliding support of line L1.

|      | 5K supply | 4.5 K return | 45 K supply | 60 K return |
|------|-----------|--------------|-------------|-------------|
| Q    | W         | W/K          | W           | W/K         |
| S_{ST} | W         | W/K          | W           | W/K         |
| ΣS_{ST} | W         | W/K          |             |             |
| 0.24 | 0.051     | 0.53         | 0.12        | -0.19       |
| -0.004 | -0.58     | 0.008        |             | 0.152       |

The sliding support used in this model thermally connects pipes having a temperature of approximately 5 K with pipes for thermal shield cooling, which have temperatures of 45 K and 60 K. Such a connection results in heat flux in the location of the support, from the 45 K and 60 K pipes to the near 5 K pipes, causing negative entropy fluxes in the pipes for thermal shield cooling.

3.3. Support system for process pipes in the L2 transfer line

In order to avoid any unwanted thermal contacts in the sliding supports of the L2 line, additional types of supports were introduced as shown in figures 3.7. In this solution, the 45 K pipe was supported with an insulated support to the thermal shield, without involving the support plate for the 5 K pipe. Another solution, which thermally improves the sliding support system for the process pipes, is to use an additional support thermally connecting only the 5 K pipe to the cold helium vapor return pipe (4.5 K), which in this case acts as a support pipe.

The 4.5 K support pipe (G He return) is connected to the thermal shield with a separate support, with the use of rolling elements. This solution allows limited heat fluxes to the 5 K pipe. If the transfer line has more than 4 process pipes, in accordance with the presented support system all of the approx. 5 K pipes should be connected to the support pipe, and only the support pipe should be connected to the thermal shield. Due to its significant diameter, the pipe functioning as a support for supercritical helium transfer pipes is typically the low-pressure cold helium vapor return, and only this pipe is thermally connected through the support to the thermal shield. Reduction of heat fluxes to the supply pipes allows reductions in the amounts of helium flowing, entails compensations of lower heat fluxes and thus offers a possibility to use smaller-diameter process pipes.

3.4. Calculations of entropy fluxes generated in transfer line L2

Heat fluxes and the corresponding entropy fluxes for supports in the L2 transfer line were identified analogically to the procedure used in the sliding supports of the L1 transfer line. Figure 3.8 shows boundary conditions set for the thermal analysis of the supports. Figure 3.9 shows set temperature fields calculated for each type of the process pipe supports.
Figure 3.8 Boundary conditions set for the process pipe sliding supports in the L2 line.

Figure 3.9 Temperature fields calculated for the sliding supports in the L2 line.

The results served to calculate values of heat fluxes to individual process pipes and the corresponding entropy fluxes, as shown in Table 3.3.

Table 3.3. Heat fluxes to the process pipes and the generated entropy fluxes calculated for the sliding support system of the L2 transfer line (data provided for one support of each type).

|       | 5K supply | 4.5 K return | 45 K supply | 60 K return | \( \sum \dot{S}_{ST} \) |
|-------|-----------|--------------|-------------|-------------|---------------------|
| \( \dot{Q} \) | W/K       | W/K          | W/K         | W/K         | W/K                 |
| \( \dot{S}_{ST} \) | W/K       | W/K          | W/K         | W/K         | W/K                 |
| 0.002 | 0.003     | 0.45         | 0.10        | 0.376       | 0.007              | -0.826              | -0.011              | 0.095               |

The sliding support system used in the L2 line significantly reduced heat fluxes to the supercritical helium supply line (5 K), as the pipe was connected to the support pipe having a similar temperature. The heat flux to the vapor return pipe (4.5 K) was likewise reduced, as the 45 K pipe was connected directly to the thermal shield. Connecting the 45 K directly to the thermal shield causes increased heat fluxes to the pipe. These fluxes, however, are significantly less “harmful” than in the case of the near 5 K pipes.

4. Conclusions
This work presents two support systems for typical cryogenic transfer lines. The first of the presented systems has one type of sliding support, which is designed to connect 3 process pipes having
temperatures of 4.5 K, 5 K and 45 K. Simple design and assembly process are definitely the advantages of this support system. However, from the perspective of thermodynamics, a disadvantageous heat influx occurs between the pipe supplying thermal shields (45 K) and the pipes having the temperature of near 5 K. The second solution consists in supporting the thermal shield supply pipe directly against the thermal shield of the transfer line with the use of a dedicated support. In order to further reduce heat flux, the 5 K supply pipe was supported to the vapor return pipe (4.5 K), while the vapor return pipe was connected in another location and with another support to the thermal shield. This resulted in practically eliminating heat fluxes to the 5 K pipe through the sliding supports. The difference between the two presented systems was calculated by identifying the values of entropy fluxes generated in the 100 m segments of the presented L1 and L2 cryogenic transfer lines. Each of the segments has 24 sliding supports. Table 4.1 shows total values of entropy fluxes generated in individual process pipes. The Gouy-Stodola theorem (1) also served to calculate the additional power which is required to overcome the irreversibilities related to the identified heat fluxes and which may be an engineering parameter for comparing the two systems.

The results for the 100 m segments of the L1 and L2 transfer lines demonstrate that the use of an extended sliding supports system shown in the L2 design significantly reduces the additional power which would need to be supplied to the condensing unit if only one type of sliding support was used for the three process pipes.

**Table 4.1.** Comparison of entropy fluxes and additional power required to reduce them for the L1 and L2 transfer lines

|     | 5K supply | 4.5 K return | 45 K supply | 60 K return |
|-----|-----------|--------------|-------------|-------------|
|     | $\dot{S}_{ST}$ | $P_{Ad}$ | $\dot{S}_{ST}$ | $P_{Ad}$ | $\dot{S}_{ST}$ | $P_{Ad}$ | $\Sigma \dot{S}_{ST}$ | $\Sigma P_{Ad}$ |
| L1  | 1.13  | 334  | 2.78  | 821  | -0.09  | -25.3 | -0.18  | -54.5 | 3.65  | 1075 |
| L2  | -0.008 | -2.22 | 2.37  | 700  | 0.17   | 50.1  | -0.26  | -77.6 | 2.27  | 670  |

The calculations do not take into account a relative cryoplant efficiency versus Carnot ideal refrigerator (usually no more than 20-40 %) and therefore the actual gain due to reduced electricity consumption may be significantly higher. As sliding supports account for the majority of supports of different types used in all cryogenic transfer lines, designs of thermodynamically highly efficient support systems allow significant reductions of losses due to the transfer of cryogens.

5. References

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