Entropy analysis of support systems in multi-channel cryogenic lines

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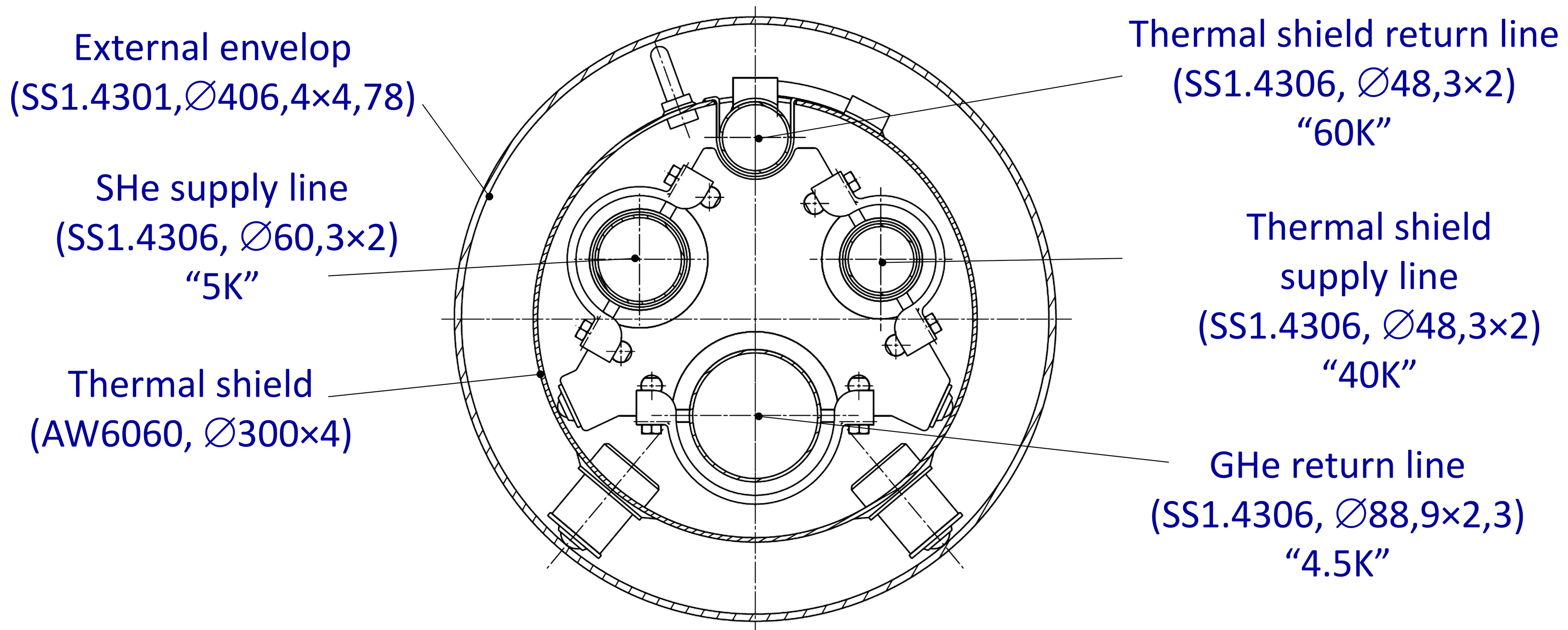
BACKGROUND

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. 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. The above property of multi-channel transfer lines allows their optimization by using minimum entropy production method. Sliding supports are the most frequently used elements in cryogenic transfer lines and therefore they have been chosen as the object of this analysis.

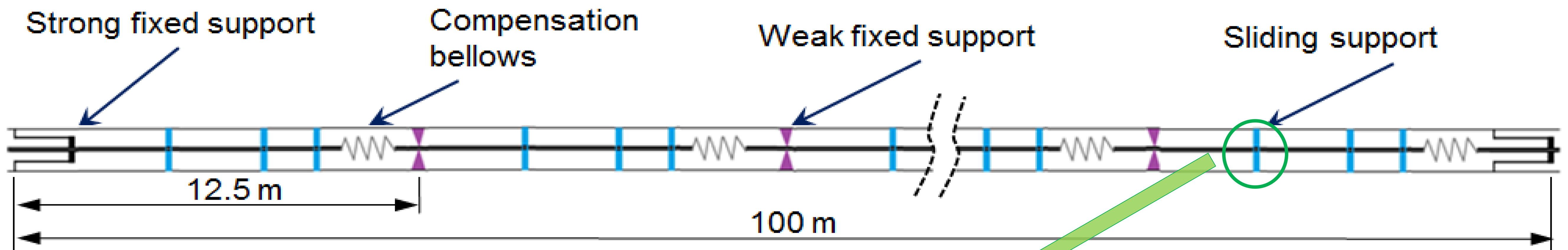
INTERNAL STRUCTURE OF THE CRYOGENIC TRANSFER LINE 1 – L1



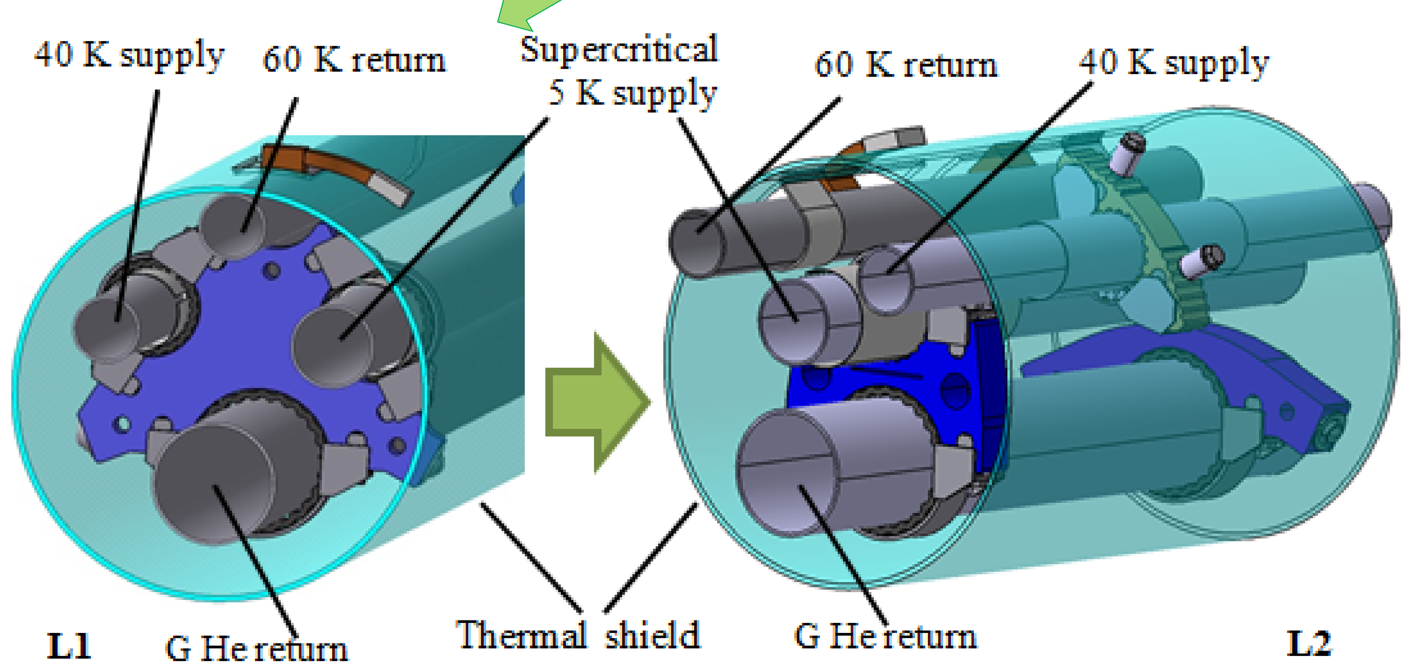
The investigated cryogenic lines consist of four process lines, a thermal shield and a vacuum vessel. The process lines include two lines having a temperature of approximately 5 K: supercritical helium supply (5 K) and low-pressure gaseous helium vapors return (4.5 K). Pipes installed for thermal shield 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.

- four process lines,
- two cryogenic circuits at 4,5 K and 45/60 K

METHOD OF ANALYSIS



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. Transfer lines differ in the design of sliding support systems for process pipes. 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.



Support structure No. 1   Support structure No. 2

METHOD OF ANALYSIS

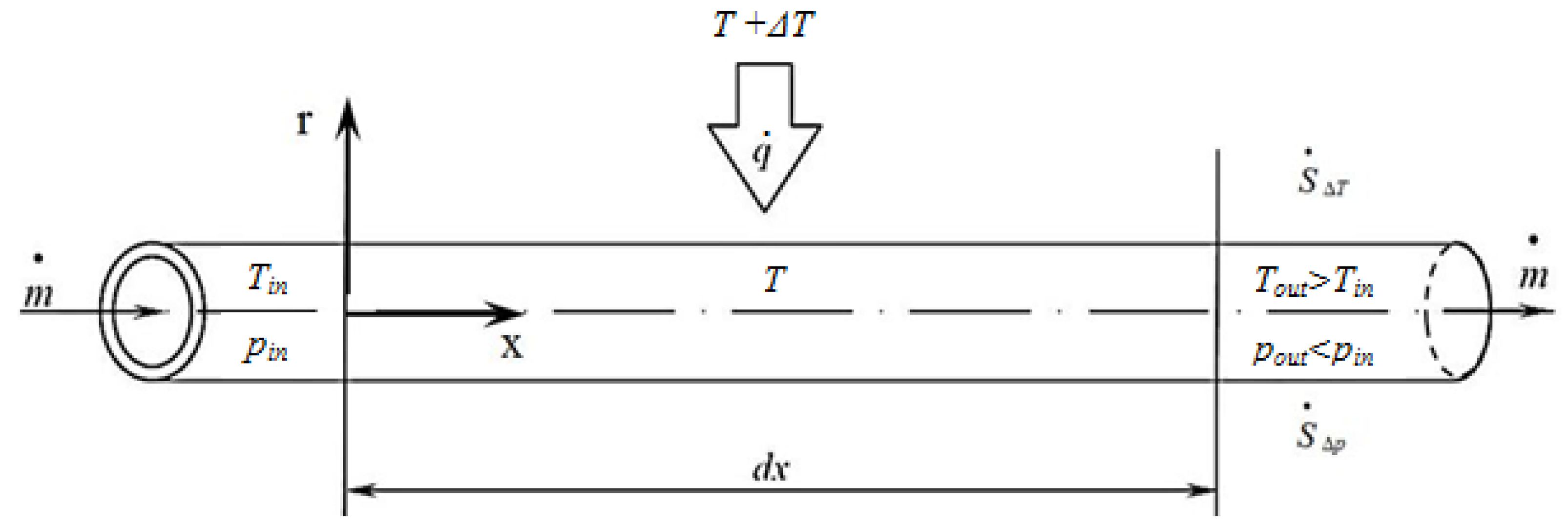
As it follows from Eq. 1, there are two basic entropy sources in case of fluid flow which is characterized by the temperature significantly different from the temperature of environment, namely heat transfer and pressure drop.

$$\dot{S} = \sum_i \dot{S}_{\Delta T} + \sum_j \dot{S}_{\Delta p} \quad (1)$$

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

$$\dot{S}_{\Delta p} = \frac{q_m w^2}{2T_C}\left(\lambda_S \frac{L}{d} + \sum_n \zeta_n\right) \quad (3)$$

$$P_{Ad} = T_A \cdot \dot{S} \quad (4)$$

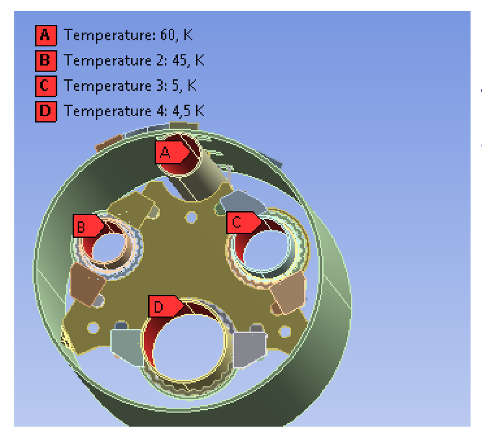


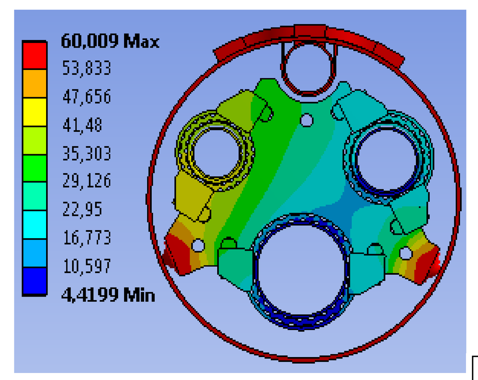
Heat transfer generated entropy can be calculated from Eq. 2. The entropy stream is increasing with the decrease of the process pipe temperature what makes this entropy source especially important in cryogenic conditions. Because this work uses entropy analysis to compare two support systems for process 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.

For an integrated entropy generation, additional work necessary to overcome the cryogen flow accompanied irreversibilities can be calculated from Gouya-Stodola theorem

THERMAL ANALYSIS BASED ON THE MES CALCULATIONS

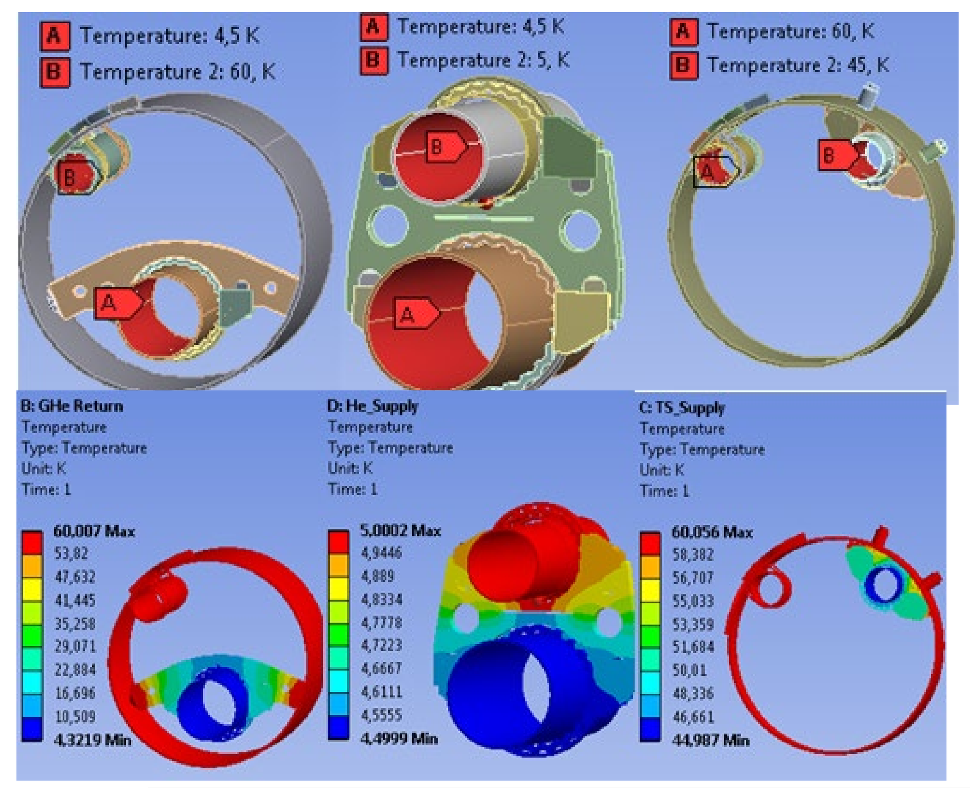
In order to identify heat fluxes to the particular process pipes and to determine the resultant entropy fluxes, the support was subjected to thermal analysis. Each element of the model was assigned material properties, represented as a function of temperature. In order to determine the temperature field, boundary conditions were introduced by setting a temperature value inside each of the process pipes, as shown in figures below





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 approx. 5 K pipes, causing negative entropy fluxes in the pipes for thermal shield cooling.

„5K" supply		„4.5 K" return		„45 K" supply		„60 K" return		
$\dot{Q}$ W	Ṡ W/K	$\dot{Q}$ W	Ṡ W/K	$\dot{Q}$ W	Ṡ W/K	$\dot{Q}$ W	Ṡ W/K	ΣṠ W/K
0.24	0.051	0.53	0.12	-0.19	-0.004	-0.58	-0.008	0.152



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 vapors 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 approx. 5 K pipes.

„5K" supply		„4.5 K" return		„45 K" supply		„60 K" return		
$\dot{Q}$ W	Ṡ W/K	$\dot{Q}$ W	Ṡ W/K	$\dot{Q}$ W	Ṡ W/K	$\dot{Q}$ W	Ṡ W/K	**ΣṠ W/K**
-0.0016	-0.003	0.45	0.10	0.376	0.007	-0.826	-0.011	**0.095**

CONCLUSIONS

	„5K" supply		„4.5 K" return		„45 K" supply		„60 K" return			
	Ṡ W/K	P_{Ad} W	Ṡ W/K	P_{Ad} W	Ṡ W/K	P_{Ad} W	Ṡ W/K	P_{Ad} W	ΣṠ W/K	**ΣP_{Ad} W**
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**

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 cryogenic fluids.

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. Importantly, the calculations do not allow for the efficiency of condensing units and therefore the actual gain due to reduced electricity consumption in the condensing unit may be significantly higher.