Design and thermodynamic performance analysis of multichannel cryogenic transfer line for XFEL AMTF

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Abstract. The XATL1 cryogenic transfer line for XFEL/AMTF is dedicated for transferring cryogenic cooling power from helium refrigerators to a cryogenic test facility by means of the continuous flows of cold helium in supercritical and gaseous state. The external envelope of the transfer line contains 4 cold process lines and a common radiation shield, as well as the system of supports and thermal contraction compensators. The XATL1 was designed and manufactured within the Polish in-kind contribution to the XFEL project. The line has been under operation since year 2012. The paper presents a design, including supporting and thermal compensation systems, of the XATL1 line. The line performance analysis based on the Second Law of Thermodynamics has been done, and the output has been compared with the design assumptions.

Keywords: Multichannel cryogenic transfer line; Optimization; Second Law analysis.

1. Introduction

European X-ray Free Electron Laser (XFEL) being currently under construction in Hamburg, Germany, will be composed of about 100 cryogenic modules, each holding eight superconducting cavities and one superconducting magnets assembly. Before their installation in the XFEL underground tunnel the cavities and cryogenic modules will be tested at their nominal operation conditions in the dedicated Accelerator Module Test Facility (AMTF). The cryogenic system of that facility is supplied with cryogenic cooling capacity from helium refrigerator located about 167 m from the AMTF hall. The cooling capacity, specified as the sum of 3 kW at 40 K, 0.5 kW at 4.5 K and 0.8 kW at 2.0 K, is provided by means of two cold helium continuous streams: pressurized gaseous helium at 40 K and supercritical helium at 4.5 K. For that reason the AMTF hall is connected with the helium refrigerator by multichannel cryogenic transfer line XATL1. The line is located on a pipeline bridge, approximately 8 m in height, and exposed to weather conditions.

2. XATL1 line design

2.1. Internal structure

An arrangement of process lines in the XATL1 is presented in Figure 1. The line consist of four process pipes, which constitute 4.5 K/5.0K and 40/80 K cryogenic circuits . The 4.5K/5.0K circuit is composed of the SHe supply and GHe return pipes, while the pipes supplying and returning from
thermal shield compose the 40/80 K circuit. The thermal shield is thermalized at 80K by means of thermal bridges coupled with the thermal shield return pipe. The function of the shield is to gather the radiation heat flux from the vacuum jacket, which temperature can vary from 260K to 310K, due to external weather conditions.

2.2. Line routing
The routing of the cryogenic transfer line XATL1 is shown in Figure 2. The line runs from the Valve Box located in a helium refrigeration hall to the Subcooler Box located inside the AMTF hall. The line is located on the piping bridge 8 m above the ground level. The cryoline XATL1 has two long straight sections connected by a 150 deg elbow and it is ended with three short sections, two vertical and one horizontal, which include three 90 deg elbows. Its total length is equal to 167 m and exceeds the direct distance between the Valve Box and Subcooler Box by 11 m only.

2.3. Supporting and thermal compensation systems
The supporting and thermal compensation systems of the external envelope are schematically presented in Figure 2a. The supporting system consists of two fixed supports (VLA) that block all the possible movements (vertical, lateral, and axial) in respect to the piping bridge, 21 sliding supports allowing for axial movements only (VL) and 2 sliding supports blocking the line movements only in vertical directions (V). The external envelope compensation system consists of two axial expansion joints (one for each straight section) and one lateral expansion joint (at the sub-cooler connection).

Figure 1. Cross section of the cryogenic transfer line XATL1.

Figure 2. Supporting and thermal compensation systems of the XATL1 external envelope and process lines.
The supporting and thermal compensation systems of each process pipe are shown in Figure 2b. Each linear module includes a set of one fixed (LA) and four sliding supports (L) as well as one axial compensator (CA). The other modules have different supporting structure. Each process pipe in module E150, apart from two sliding supports (L) and one axial compensator (CA), includes two fixed supports (LA) separated by a flexible hose (H). The section composed of three E90 modules contains two fixed supports (LA), two sliding support (L) and one metallic flexible hose.

The proposed layout of supports and compensators was used as an input data to a numerical thermo-mechanical analysis that allowed for checking the mechanical stability of the line exposed to all the possible operation conditions and failure modes. The analysis was also used for the specification of the parameters of the crucial elements of supporting and thermal compensation systems [1].

3. Thermodynamic performance analysis of XATL1

3.1. Theoretical background

In order to compare the specified and operation performance of the XATL1 the Second Law of Thermodynamics is used. In this analysis method it is essential to identify all entropy streams generated in a single process pipe. As it follows from equation (1), for a flow of the fluid which temperature is significantly different from the environment temperature, there are two basic entropy sources, namely the heat transfer \( S_{ST} \) and the flow friction pressure drop \( S_{SP} \) generated entropies.

\[
\dot{S} = \sum_i \dot{S}_{ST} + \sum_j \dot{S}_{SP}
\]  

(1)

The heat transfer generated entropy can be calculated from equation (2):

\[
\dot{S}_{ST} = \frac{Q(T_H - T_C)}{T_C^2 \left(1 + \frac{T_H - T_C}{T_C}\right)}
\]

(2)

where: \( Q \) is the heat transferred, \( T_H \) and \( T_C \) is a high and a low temperature, creating temperature difference for a heat transfer process.

The entropy stream is increasing with the decrease of the process pipe temperature what makes this entropy source especially important in cryogenic conditions.

The second entropy source is pressure drop caused by local and linear flow resistivities, and it can be calculated from equation (3):

\[
\dot{S}_{SP} = \frac{q_m w^2}{2T_C} \left(\frac{\lambda_s L}{d} + \sum_n \zeta_n\right)
\]

(3)

where \( q_m \) is a fluid mass stream, \( w \) is the fluid velocity, \( \lambda_s \) is a linear pressure drop coefficient, \( L \) is the length of the flow duct, \( d \) is the duct hydraulic diameter and \( \zeta \) is the local pressure drop coefficient.

Entropy generation processes in the XATL1 are schematically depicted in Figure 3 where heat fluxes to process pipes, heat exchange between the process pipes and pressure drop caused by flow resistivities are indicated.

For the calculated entropy generation, additional power \( P_{ad} \) necessary to overcome the irreversibilities encountered in the line, can be calculated from Gouya-Stodola theorem described by equation (4) [2,3]:

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

(4)

where \( T_A \) is environment temperature.
3.2. Thermodynamic analysis of XATL1 line based on specification data.

Technical specification has provided requirements regarding maximum linear heat flux to and mass stream in the particular process lines of the XATL1. Based on this data the total heat flux and flow pressure drop have been identified. Next the generated entropy stream and power necessary to overcome the irreversibilities have been calculated.

Table 1 collects the specified thermodynamic parameters of helium in the XATL1 line process pipes as well as calculated theoretical thermodynamic properties of the pipes.

Table 1. Specified thermodynamic parameters and theoretical thermodynamic performance of the XATL1 process pipes; \( q_m \) - helium mass flow, \( q_l \) - specified maximum linear heat flux to process pipe, \( Q \) - total heat transfer to process line, \( T \) - helium temperature, \( p \) - helium pressure, \( \Delta p \) - flow pressure drop, \( S_{\Delta p} \), \( S_{\Delta T} \) and \( S \) - entropy generated due to pressure drop, heat flux and total entropy stream.

|     | \( q_m \) | \( q_l \) | \( Q \) | \( T \) | \( p \) | \( \Delta p \) | \( S_{\Delta p} \) | \( S_{\Delta T} \) | \( S \) | \( P_{ad} \) |
|-----|----------|----------|--------|-------|-------|---------|------------|------------|------|--------|
| 4.5K | 0.092    | 0.15     | 24.9   | 4.5   | 3.5   | 0.040   | 0.00       | 5.22       | 5.22 | 1.57   |
| 5K  | 0.092    | 0.15     | 24.9   | 5.0   | 1.2   | 0.280   | 0.53       | 4.67       | 5.20 | 1.61   |
| 40K | 0.014    | 1.5      | 249    | 40    | 17    | 0.003   | 0.00       | 3.11       | 3.11 | 0.93   |
| 80K | 0.014    | 1.5      | 249    | 80    | 16.8  | 0.007   | 0.00       | 2.28       | 2.28 | 0.69   |

From Table 1 it can be found that the entropy generated due to friction is negligible when compared to the entropy generated in heat transfer processes.

3.3. Thermodynamic analysis of XATL1 line based on experimental data

The preliminary estimations of the head loads to the XATL1 process pipes have been done during the commissioning tests performed between 10.08.2012 and 11.08.2012 (Figure 4 and 5). During the measurements an isolation vacuum of XATL1 line was of about 1·10^{-6} mbar. The direct measurement of the mass flow in the 40K/80K circuit was not available because a sensitivity of the standard flow meters of the HERA plant did not allow to measure the incoming mass flow. The mass flow rate was estimated using the inherent flow characteristics of the control valve installed in sub-cooler. This control valve has equal percentage relation between the valve opening and the flow rate under constant pressure conditions. The valve has range ability of 50:1 and flow coefficient \( k_{v,t}=2.5 \text{ m}^3/\text{h} \).
Figure 4. Experimental data registered for XATL1 40K and 80K process lines.

The measured data and calculated thermodynamic parameters for the 40K/80K circuit are presented in Table 2. The values of the measured parameters have been averaged for each test period.

Table 2. Measured thermodynamic parameters and calculated operational thermodynamic parameters of 40K and 80K process pipes; $q_m$ - helium mass flow, $T$ - helium temperature, $p$ - helium pressure, $Q$ - total heat transfer to the process pipe, $S$ - total generated entropy stream, source of thermodynamic properties of helium - [4].

|                  | $q_m$ (g/s) | $T_{in}$ (K) | $T_{out}$ (K) | $p$ (bar) | $h_{in}$ (kJ/kg) | $h_{out}$ (kJ/kg) | $\rho$ (kg/m$^3$) | $Q$ (W) | $S$ (W/K) | $P_{Ad}$ (kW) |
|------------------|-------------|--------------|---------------|-----------|------------------|------------------|-----------------|--------|-----------|-------------|
| 40K Period I     | 9.73        | 44.79        | 44.68         | 13.8      | 238.87           | 238.30           | 14.35           | -5.49  | -0.02     | -0.06       |
| 40K Period II    | 9.73        | 44.88        | 44.76         | 13.8      | 239.35           | 238.74           | 14.29           | -4.53  | -0.02     | -0.06       |
| 80K Period I     | 9.73        | 49.08        | 59.14         | 12.9      | 261.56           | 314.60           | 12.25           | 516.26 | 7.82      | 2.35        |
| 80K Period II    | 9.73        | 50.38        | 63.77         | 12.8      | 268.40           | 338.90           | 11.88           | 524.66 | 7.44      | 2.23        |

Due to very low mass flow in the 40K/80K circuit, the entropy generated by the pressure drop can be neglected. As the thermal shield is thermally coupled with 80K process pipe, the heat flux to 40K process pipe is very low. The heat from 40K process pipe is transferred to 4.5K and 5K pipes, what creates a negative entropy generation balance for this pipe, not compensated by negligible pressure drop. Because almost all heat flux to the 40K/80K circuit is transferred to the 80K pipe only it can be found that there is large difference in the specified (Table 1) and measured (Table 2) entropy generation for 40K and 80K. Nevertheless, sums of the specified and measured entropy generation for 40K/80K circuit are comparable.

The 4.5K/5K circuit is equipped with flow meter installed in the sub-cooler. This allowed to carry out direct measurements of incoming mass flow. Measured data for the 4.5K/5K circuit are presented in Table 3. The values of the measured parameters have been averaged for each test period.

Table 3. Measured thermodynamic parameters and calculated operational thermodynamic parameters of 4.5K and 5K process pipes, source of thermodynamic properties of helium - [4].

|                  | $q_m$ (kg/s) | $T_{in}$ (K) | $T_{out}$ (K) | $p$ (bar) | $h_{in}$ (kJ/kg) | $h_{out}$ (kJ/kg) | $\rho$ (kg/m$^3$) | $Q$ (W) | $S$ (W/K) | $P_{Ad}$ (kW) |
|------------------|-------------|--------------|---------------|-----------|------------------|------------------|-----------------|--------|-----------|-------------|
| 4.5K Period I    | 0.015       | 4.89         | 5.21          | 4.2       | 3.84             | 5.65             | 127.43          | 26.43  | 4.75      | 1.43        |
| 4.5K Period II   | 0.012       | 4.84         | 5.28          | 4.2       | 3.62             | 6.10             | 128.28          | 29.95  | 5.37      | 1.61        |
| 5K Period I      | 0.015       | 4.43         | 4.46          | 1.0       | 22.3             | 22.54            | 15.38           | 3.43   | 0.71      | 0.21        |
| 5K Period II     | 0.012       | 4.42         | 4.48          | 1.0       | 22.21            | 22.74            | 15.48           | 6.41   | 1.32      | 0.40        |

Due to mechanical strength requirements, the 4.5 K, 5 K and 40 K process pipes have been thermally and mechanically bridged in XATL1 multichannel line. In spite of use of low thermal
conductivity materials and additional thermal resistors, the experimental data show that there is parasitic heat transfer between the pipes.

![Figure 5. Experimental data registered for XATL1 4.5 K and 5. K process lines](image)

4. Conclusions

The Second Law of Thermodynamics analysis of XATL1 line has shown that entropy generation resulting from pressure drops in the process pipes is negligible in comparison with heat transfer induced entropy fluxes. It indicates on the possibility of the line design optimisation by reducing the process pipes diameters. This would allow to decrease parasitic heat fluxes to process pipes, while keeping the pressure drops at acceptable level.

**Table 4.** Comparison of additional power necessary to overcome the irreversibilities accompanying cryogen flow through the line for operating data and the technical specifications

|            | 4.5K | 5K  | 40K | 80K | Σ    |
|------------|------|-----|-----|-----|------|
| $P_{Ad}$ – operational data (average of periods I and II) | kW   |     |     |     | kW   |
| $P_{Ad}$ – technical specifications            | 1.52 | 0.30| 0.00| 2.29| 4.11 |

The comparison of entropy generation resulting from measurements and the line specification data allows the evaluation of the line thermodynamic performance. Entropy-free energy required to compensate irreversibilities for specified and operational data is equal 4.8 kW and 4.11 kW respectively – see Table 4. Hence the measured thermodynamic performance of the line is about 5% better than the specified.

5. References

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Acknowledgements

The authors would like to thank DESY MKS Group for help in experimental data acquisition. The work has been supported by statutory funds from Polish Ministry of Higher Education and Science.