Numerical analysis of temperature stratification in a subatmospheric cold helium line

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Introduction

In last decades the technology of superfluid helium has become very advantageous for large-scale scientific facilities dedicated to high-energy physics. Superconducting cavities or magnets are usually immersed in helium baths at a temperature of 1.8 to 2.0 K. This temperature is produced by a JT cycle where the return line works at a subatmospheric pressure of 16 to 31 mbara. The subatmospheric line lengths can reach even several thousand meters. The helium flows in the subatmospheric lines are driven by cold compressors or vacuum pumps. Due to a limited pressure drop requirement the line diameters can exceed even 300 mm. Since the thermal conductivity of the line material is very small and the flow rate at some operation conditions can be much lower than at the normal operating conditions, a thermal stratification in the helium flow can appear together with a significant temperature gradient along the pipe circumference. These phenomena can affect the thermo-hydraulic behaviour of the line as well as the operation of the entire cryogenic system.

The paper presents the numerical simulations of cold helium vapour flows in a long straight line. The stratification phenomenon is discussed and the potential temperature gradient in the pipe wall is evaluated.

Numerical modelling of the temperature stratification

The model takes into account steady-state three-dimensional convection processes in the fluid region as well as steady-state three-dimensional conduction in the solid tube. In the calculations, helium is considered as the ideal, incompressible gas. For all these assumptions for the fluid region the governing equations describing the thermal-flow processes is composed of the transport equations of:

\[ \nabla (\rho U) = 0 \]

- mass:

\[ \nabla \cdot (\rho U) = -\nabla p + \nabla \cdot \tau + S_M \]

- momentum:

\[ \nabla \cdot (\rho (U \otimes U)) = \nabla \cdot (k \nabla T) + \nabla \cdot (U \cdot \tau) + U \cdot S_M + S_E \]

- total energy:

\[ \nabla \cdot (kS \cdot \nabla T) = 0 \]

The solid domain:

Heat flux imposed on the entire external surface of the pipe. The calculations were performed for the heat flux of 0.1 W/m² and 0.15 W/m². The numerical investigation of the temperature stratification phenomenon consisted of 20 (5x2x2) numerical simulations in total.

Results and discussion

The calculations were carried out for five values of mass flow rate: 5, 10, 20, 30 and 40 kg/s and two values of static helium pressures: 3.2 K and 4 K. For all analysed cases the average static pressure of 27 mbar was applied at the pipe outlet cross section. The heating of the flow medium is modelled via constant heat flux imposed on the external surface of the pipe. The calculations were performed for the heat flux of 0.1 W/m² and 0.15 W/m². The numerical analysis of temperature stratification in the flowing helium revealed a certain temperature stratification in the flowing helium.

Boundary conditions

Some abnormal operation modes characterised by significantly smaller helium flows, the temperature stratification can affect the thermo-hydraulic behaviour of the line. Then, the temperature sensors, which are usually fixed to the external surface of the line, may not provide the precise information about the real temperature of the flowing helium.

Model geometry and numerical procedures

The numerical model consists of two domains, namely fluid and solid domains. The fluid domain is a straight horizontal cylinder, which is 40 m in length and 267.2 mm in inner diameter. This region is surrounded by the solid tube made of stainless steel 304L, which wall thickness is equal to 2.9 mm. The numerical algorithm applies the element-based Finite Volume Method. In the calculations of advection terms (fluxes) the High Resolution Scheme is used, whilst for solving the pressure and velocity fields the Shear-Stress-Transport turbulence model is applied. Both the HRS and SST assure a sufficiently high accuracy calculation procedure.

Conclusions

The obtained results revealed a certain temperature stratification in the flowing helium. This stratification is inversely proportional to mass flow rate and can affect the temperature distribution in the process line wall. In the present study the maximum temperature difference reaches 0.18 K for the 4 K helium vapour flow (at 27 mbar) with the mass flow rate of 5 g/s. For higher mass flow rates the temperature difference is much smaller and decreases to only a few mK for 40 g/s.

In some abnormal operation modes characterised by significantly smaller helium flows, the temperature stratification can affect the thermo-hydraulic behaviour of the line. Then, the temperature sensors, which are usually fixed to the external surface of the line, may not provide the precise information about the real temperature of the flowing helium.