Numerical Studies on Two-Phase Flow of Liquid Nitrogen to Cool HTS Power Cables

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Abstract. Liquid nitrogen is the foremost coolant when it comes to cooling HTS power devices due to its abundance and since it is more economical than other cryogens. Sub-cooled LN$_2$ is preferred over saturated LN$_2$ as it offers substantial advantages in terms of performance. However, in the cases where it is not possible to cool HTS power cables using sub-cooled LN$_2$, saturated LN$_2$ is the only option. Additionally, even when sub-cooled LN$_2$ is used for long length cables, the heat-in-leaks along with other core losses result in rise in temperature and an unavoidable two-phase flow affects the cooling characteristics of the cryogen. This paper deals with the modeling and numerical analysis of a two-phase flow through an HTS power cable cryostat to understand the temperature profile, the pressure drop per unit length, and required pumping power for circulation of cryogen.

1. Introduction

High Temperature Superconductors (HTS) are employed in various power devices such as HTS power cables, Superconducting Fault Current Limiters (SFCL), Superconducting Magnetic Energy Storage (SMES), HTS motors & generators and HTS transformers as they offer zero resistance below their critical temperatures.

HTS tapes used in HTS power cables have a transition temperature of 90-110 K [1] and are often cooled using cryogens like LN$_2$. A majority of the HTS power cables operating and being developed all over the world are cooled using LN$_2$ in the operating range of 65-77 K [2].

Currently, a 1 φ, single pass liquid nitrogen cooled HTS power cable is being developed at the Indian Institute of Technology (IIT), Kharagpur and its schematic is shown in figure 1. The space between the inner and outer corrugated pipes is usually evacuated to sub-atmospheric pressures to minimize heat-in-leaks from the ambient via conduction and convection. At times, even Multi-Layer super Insulation (MLI) is used to minimize the heat transfer via radiation. In spite of all these provisions, the heat-in-leaks are unavoidable and for long length HTS power cables, these leaks place a huge thermal load on the cryogen. Also, in the case of an AC excitation, core losses in the form of eddy current and hysteresis loss, and dielectric losses place an additional heat load on the cryogen. These heat loads, though undesirable, may result in a two-phase flow of N$_2$ inside HTS power cables.

The power transmission capacity may be affected as the critical current reduces due to the rise in temperature of the cable core [3]. This temperature rise results in two-phase of cryogen which enhances probability of voltage breakdown due to the presence of bubbles [4] [5] resulting in the occurrence of faults. In addition, this also affects the thermo-hydraulic characteristics of
Figure 1. Schematic of a 1 φ, single pass, LN$_2$ cooled HTS power cable
cryogen which in turn leads to the quench of superconductor in HTS cable. Finally, a two-phase flow results in high pressure drops leading to a higher pumping power requirement. Though studies on cryogenic fluid flow inside HTS power cables have been reported in various numerical investigations [6] [7] [8], there is not much work reported in open literature on the analysis of a two-phase flow inside HTS power cables. This work will help in predicting the time before failure (TBF) to which the HTS cable can effectively and safely transmit rated power under the event of deterioration of vacuum level between the inner and outer cryostats.

Thus, the objective of this work is to model and numerically analyze a two-phase flow inside a 1 φ, single pass, LN$_2$ cooled HTS power cable. The volume fraction, temperature rise, velocity contours, vectors, streamlines, pressure drop and corresponding pumping power were computed. Section 2 describes the specifications of the cable being analyzed. Section 3 describes the numerical approach undertaken to analyze the problem. Section 4 lists the results and the discussions.

2. Specifications of HTS power cable
A five meter HTS power cable is being developed at IIT Kharagpur. The specifications of the HTS power cable are shown in Table 1. The dimensions of the cable are shown in Table 2. These dimensions have been used for the present study as shown in figure 2.

| Specifications of HTS power cable being developed |
|-----------------------------------------------|
| Specifications                                 |
| Rating                                        |
| 11 kV, 1 kA                                   |
| HTS tape                                      |
| SuNAM SLBS04150                               |
| ($I_c = 150$ A at 90 K self-field)             |
| Dielectric                                    |
| PolyPropylene Laminated                        |
| Paper (PPLP)                                  |
| Coolant                                       |
| LN$_2$                                        |
Table 2. Dimensions of HTS power cable being developed

| Layer                  | Thickness | Outer diameter |
|------------------------|-----------|----------------|
| Copper former          | -         | 19 mm          |
| HTS tapes              | 0.14 mm   | 19.28 mm       |
| Semi-conducting layer  | 0.5 mm    | 20.28 mm       |
| PPLP layer             | 2.5 mm    | 25.3 mm        |
| Inner corrugated pipe  | 0.3 mm    | 63.4 mm        |
| Outer corrugated pipe  | 0.3 mm    | 102.2 mm       |

Figure 2. Cross sectional view and dimensions of HTS power cable

3. Numerical analysis
A numerical approach was undertaken to analyze the flow through the HTS power cable using ANSYS Fluent 18.2.

3.1. Computational domain
A two dimensional section at the top portion of the cable is considered for the present study. The dimensions of the fluid domain are shown in figure 2.
3.2. Governing differential equations and performance parameters
The following governing differential equations for the fluid domain are solved to capture the flow physics and compute the thermal characteristics of the two-phase flow.

**Continuity equation**

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0
\] (1)

**Momentum equation**

\[
\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \times \vec{v}) = -\nabla p + \nabla \cdot (\vec{T}) + \rho g
\] (2)

Since the flow domain is 2 dimensional, only the momentum equations in x and y direction are considered.

**Energy equation**

\[
\rho C_p \frac{\partial T}{\partial t} + \rho C_p (u \cdot \nabla T) = k \nabla^2 T
\] (3)

Since the flow is turbulent in nature, the standard k-\(\epsilon\) model was selected.

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon
\] (4)

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_1 \frac{\varepsilon}{k} (G_k) - C_2 \frac{\varepsilon^2}{k} + \rho \varepsilon^2
\] (5)

\[
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}
\] (6)

**Volume Of Fluid (VOF) model**

\[
\rho = \sum_{i=1}^{n} \rho_i \alpha_i
\] (7)

\[
\frac{\partial \alpha_i}{\partial t} + \vec{v} \cdot \nabla \cdot \alpha_i = 0
\] (8)

3.3. Boundary conditions
A uniform axial fluid velocity of 0.164 m/s, corresponding to a volumetric flow rate of 15 lit/min, was imposed at the inlet of the fluid domain. A constant temperature of liquid nitrogen at saturated condition (77 K and an absolute pressure of 1 atm) is defined at the inlet. No slip conditions (at a solid boundary, the fluid will have zero velocity relative to the boundary) are defined at the walls. At the outlet, discharge occurs to atmospheric pressure. A constant heat flux (corresponding to the heat-in-leaks from the ambient) is imposed at the inner surface of the inner corrugated pipe. Also, a constant heat flux (corresponding to AC losses) is imposed at the outer surface of the cable core. The corrugated pipe (outer wall) material is Stainless Steel (SS) while the inner former (electrical core) material is copper. The boundary conditions imposed on the fluid domain are shown in figure 3. Gravity was also considered in the present analysis in the form of acceleration defined in the negative direction of the Y axis.
3.4. Solution methodology
The governing conservative equations for the two-phase flow were solved using Finite Volume solver ANSYS Fluent 18.2. Multi phase transient simulation was performed. The governing equations for pressure, velocity and temperature were solved using the Pressure-Implicit with Splitting of Operators (PISO) algorithm. Convective terms were discretized using 2nd order upwind scheme. The flow is turbulent and standard k-\(\varepsilon\) model was chosen. The convergence criteria for all the conservative governing equations were set to \(10^{-6}\) [8] [9].

4. Results and discussions
The volume fraction, streamlines, velocity vectors and contours, temperature rise, pressure drop and corresponding pumping power required to overcome the pressure drop and circulate the cryogen were computed. The liquid volume fraction at the end of the various time durations are shown in figure 4. In the figure, 1.0 corresponds to a complete liquid phase while 0.0 corresponds to a complete gaseous phase. It was observed that, as the time progressed, the flow appeared to reach steady state after approximately 6 secs. The corrugations were filled with gaseous nitrogen and formed vortices as shown in figure 6. The streamlines near the inlet of the pipe are shown in figure 5 (a). It was observed that, near the inlet, the flow converged since the width of the inlet is greater than the cross-section at the end of the first corrugation. Also, no streamlines were observed inside the corrugation. This is because vortices were observed inside each of the corrugations as shown in figure 6. Since streamlines do not intersect or overlap, no streamlines were observed inside the corrugations. Velocity contours at the inlet, mid length and the exit were plotted as shown in figure 5 (b), (c) and (d). It was observed that even after the flow seemed to be fully developed, the velocity along the length increased. This may be attributed to the pressure drop resulting from fluid acceleration (or momentum change) which is often observed in two phase flows [10]. In two phase flows, as the gaseous nitrogen (GN\(_2\)) volume fraction increases, the density of the fluid downstream decreases. For mass to be conserved, the decrease in density is compensated by an increase in velocity, thus maintaining a constant mass flow rate. A variation of the velocity along a centre line (between the inner wall of the inner corrugated pipe and the core surface) with the length is shown in figure 7 (Case C). The
velocity was found to fluctuate along the length of the pipe. This is attributed to the varying cross-section due to the presence of the corrugations.

![Velocity vectors showing vortices in corrugations for constant ambient heat flux of 260 W/m²](image)

**Figure 6.** Velocity vectors showing vortices in corrugations for constant ambient heat flux of 260 W/m²

**Table 3.** Results of parametric study

| Case | Heat flux from core (W/m²) | Heat flux from ambient (W/m²) | Total heat load (W) | Temperature rise (K) | Velocity at outlet (m/s) | Total Pressure drop (Pa) | Required pumping power (mW) |
|------|---------------------------|-----------------------------|---------------------|----------------------|------------------------|------------------------|---------------------------|
| A    | 30                        | 26                          | 9.7                 | 0.76                 | 0.1997                 | 47.67                  | 11.9                      |
| B    | 30                        | 130                         | 38.9                | 2.11                 | 0.2079                 | 54.96                  | 14.49                     |
| C    | 30                        | 260                         | 75.4                | 3.21                 | 0.2150                 | 88.54                  | 22.13                     |
| D    | 30                        | 520                         | 148.4               | 4.9                  | 0.2398                 | 167.71                 | 41.92                     |
A parametric study was performed to study the effect of varying heat-in-leaks from the ambient and the results are tabulated in Table 3. When the vacuum in the outer jacket (between the inner and outer corrugated pipe) is destroyed due to the failure of the vacuum pumping system or damage to the outer corrugated pipe, warm air from the surrounding rushes into the annular space thus placing a heat-load on the cryogen. Case A corresponds to a heat load (from core) of 1.5 W/m and a heat load (from ambient) of 2 W/m [11]. These correspond to a heat flux of 30 W/m$^2$ and 26 W/m$^2$ respectively based on the geometry under consideration. Cases B, C and D correspond to situations where the heat fluxes are 5, 10 and 20 times the reference value (2 W/m). The corresponding total heat load, outlet temperature, outlet velocity, pressure drop were computed. Since the temperature, pressure and velocity vary long the radial direction at the outlet, a mass weighted average was computed for the same. The required pumping power was computed using equation 9 [12].

\[ W = q \Delta p \]  \hspace{1cm} (9)

where, \( q \) is the volumetric flow rate, \( W \) is the required pumping power, and \( \Delta p \) is the total pressure drop. The total pressure drop in a two phase flow is the summation of the frictional and the momentum pressure drops as shown in equation 10.

\[ \Delta p = \Delta p_F + \Delta p_M \]  \hspace{1cm} (10)

where, \( \Delta p_F \) is the frictional pressure drop, and \( \Delta p_M \) is the momentum pressure drop.

5. Conclusions
A two-phase flow through the annular flow passage of a one metre long HTS cable has been modeled and numerically analyzed. The pressure drop, velocity profiles, vectors, streamlines and the temperature rise have been computed. A parametric study has been conducted to
understand the effect of heat load on the thermo-hydraulic characteristics. For a volumetric flow rate of 15 lit/min, a temperature rise of 3.12 K and a pressure drop of 88.54 Pa were observed when the total heat load was 75.4 W. Two-phase flow should be avoided to protect and effectively operate an HTS power cable.

6. References
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