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Thermal performance of multilayer insulation around a horizontal cylinder

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Abstract

Thermal performance of multiplayer insulation (MLI) is affected by contact pressure between adjacent layers. In order to evaluate the thermal performance of the MLI fabricated in the horizontal cryostats of superconducting magnets, it is important to investigate the contact pressure in the MLI. In case of a horizontal cryostat, the MLI is wound around horizontal cylindrical surface and is compressed at the upper part of the cylinder due to the MLI self-weight. At first, a single thin film wound around the horizontal cylinder was analyzed to evaluate the contact pressure acting on the cylinder. The analysis has been extended to the multiply wound film around horizontal cylinder, in order to investigate the distribution of contact pressure between adjacent layers. By using experimental data obtained with a flat panel calorimeter, the results of this analysis have been applied to evaluate the thermal performance of MLI around a horizontal cylinder. And the non-dimensional contact pressure parameter P^* has been introduced as a useful parameter to evaluate and compare the thermal performance among different kinds of MLI.

Keywords: Multilayer insulation; Cryostats (F); Superconducting magnets (F); Heat transfer (C); Transmission lines (F)

1. Introduction

Horizontal cryostats are widely used in many fields of applied superconductivity, for example, the beam transport magnets and detector solenoid magnet for high energy particle accelerators, MRI solenoids for medical application and superconducting power transmission lines. In order to maintain the superconducting coil below the critical temperature and reduce the cryogenic heat load, MLI is employed in the thermal barrier of horizontal cryostats. In this case, the MLI is placed around the horizontally supported cylindrical cold body. If the MLI is properly wound around the cold body, avoiding the excess tension in the film, contact pressure between the films is due to the weight of the MLI itself and becomes higher at the upper part of the cylinder. In case of a large-scale detector solenoid magnet, it is of concern that the total weight of MLI is such as to degrade its thermal performance by self-compression.

Under sufficiently low pressure in the vacuum chamber, heat transfer in MLI is governed by thermal radiation and by contact heat transfer between layers. Cunnington [1], Inai [2], and Ohmori et al. [3,4] studied experimentally degradation of thermal performance of MLI by increasing the contact pressure between the adjacent layers. If we utilize the data obtained in the laboratory scale calorimeter to the design of the thermal barrier of a horizontal cryostat employing MLI, we have to relate the experimental condition of contact pressure with the pressure generated in that cryostat. The contact pressure together with the layer density is a very important parameter of heat flux through the MLI in the direction normal to the reflective films. Jacob [3] reviewed the experimental studies of MLI and

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Nomenclature

a coefficient defined in Eq. (27) [W/m^2]
b coefficient defined in Eq. (27), dimensionless
C constant defined by Eq. (10) [Pa]
$F(\theta_d)$ function defined by Eq. (11), dimensionless
H sag of the film below the cylinder ($= -r - y(0)$) [m]
H^* non-dimensional sag parameter ($= H/r$)
N total number of layers
$P(\theta)$ pressure between a single film and a horizontal cylinder [Pa]
$P^*(\theta)$ non-dimensional contact pressure parameter ($= P(\theta)/w$)
P^*_{max} non-dimensional maximum contact pressure parameter ($= P(0)/w$)
P^*_{mean} azimuthally averaged value of $P^*(\theta)$
P_i contact pressure for ith layer of multi-layer film [Pa]
$P^*_i(\theta)$ non-dimensional contact pressure parameter for ith layer ($=P_i(\theta)/w$)
$\widehat{P}^*_i$ average value of $P^*_i(\theta)$ over the whole circumference
$\widehat{P}^*_{ave}$ average value of $\widehat{P}^*_i$ from 1st layer to Nth layer.
q heat flux in the direction normal to the layers [W/m^2]
r radius of the cylinder [m]
S circumferential length of thin film [m]
S_A total film length in region A [m]
S_B total film length in region B [m]
S_e excess circumference defined by Eq. (17) [m]
S^*_e non-dimensional excess circumference parameter ($=S/2\pi r - 1$)
s film length in region B [m]
$T(\theta)$ tension per unit length in region A [N/m]
$T(x)$ tension per unit length in region B [N/m]
$T^*(\theta)$ non-dimensional tension parameter ($=T(\theta)/wr$)
w specific weight of thin film, or specific weight of one layer of MLI [Pa]
x horizontal coordinate [m]
y vertical coordinate [m]

Greek symbols
θ azimuthal angle measured from the top of the cylinder
θ_d departure angle
$\varphi(x)$ inclination of the film in region B

Superscripts and subscripts
$*$ non-dimensional
A region A
B region B
d departure
e excess
i layer number

summarized heat flux data in 16 reports. There are only eight reports that show data relating to layer density.

In order to predict the thermal performance of MLI around a horizontal cylinder by utilizing the data obtained by the laboratory scale calorimeter, contact pressure between adjacent layers in the MLI is studied. For the most simple case of MLI in horizontal cryostat, a single thin film wound around a horizontally supported cylinder is analyzed to understand the characteristics of contact pressure acting on the surface of cylinder [4]. Based on the results of the single film analysis, the contact pressure in multi-layered films around the horizontal cylinder is considered.

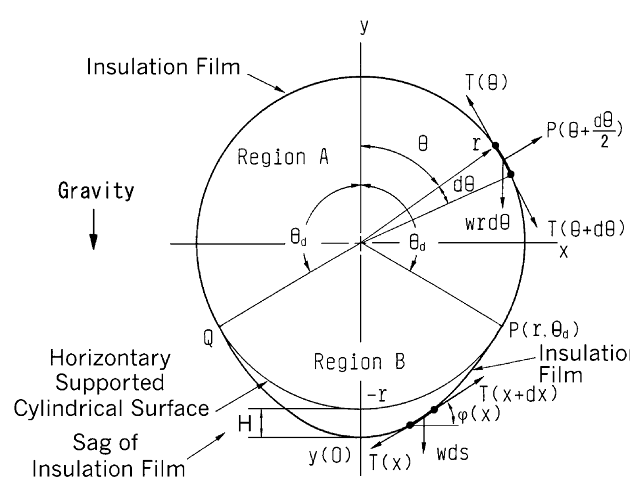

Fig. 1. Single insulation film wound around the horizontally supported cylinder.

2. Analysis of single-layer film

The object of this section is to derive equations which describe the tension $T(\theta)$ acting on a single thin film around a horizontal cylindrical surface, and the pressure $P(\theta)$ between the film and the cylinder as illustrated in Fig. 1. The azimuthal angle θ is measured from the top of the cylinder whose radius is r. The film has the specific weight w [Pa]. The friction between the film and the cylinder is neglected. As the circumferential