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Mathematical Model for a Novel Cryogenic Flow Sensor using Fibre Bragg Gratings

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Abstract

In this work, a mathematical model is presented for a newly developed cryogenic flow meter which is based on fibre Bragg grating (FBG) principle. The principle of operation is to use the viscous drag force induced by a flowing fluid on an optical fibre placed transverse to the flow. An optical fibre will have a 5 mm long grating element inscribed in it and will be placed so that the sensor is at the centre of the pipe. The fibre will act as the bluff body, while the FBG sensor will pick up the bending strain induced in the fibre due to the drag force. The amount of bending strain which can be measured as a shift in Bragg wavelength can be calibrated to provide the mass flow rate. Here a mathematical model is being presented to predict the operation of the sensor and to calculate the sensor characteristics so that the sensor design can be optimised. The sensor exhibits an exponential relationship between sensitivity and mass flow rate. It is also seen that the sensitivity depends greatly on the fluid properties such as density and viscosity.

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Keywords: Flow meter; Fibre Bragg gratings; Low temperature measurement; Sensors; Cryogenics

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1. Introduction

It is essential to understand the thermodynamic process and the cooling efficiency in most of the cryogenic and superconductor applications. The flow characteristics of coolant flowing in the cooling channels can give the thermos physical behaviour of the system. Hence the accurate measurement of fluid flow characteristics plays prominent role in any machinery that comprises a fluid flow or convection heat transfer. It is preferable to have a flow measurement which does not affect the flow characteristic during the measurement. The mounted meter, ideally should not induce a pressure drop or change the temperature of the flow. The brittle behaviour of materials at low temperatures and the thermal stresses due to large changes in temperature restrict the use of many existing designs and materials for these applications. The pressure drops due to the introduction of the measurement device also pose a serious concern in cryogenic flows. The chances of cavitation are quite high in case of cryogens, since the temperature of flow is very near to its saturation temperature. This makes mass flow meters based on differential pressure, such as laminar flow meters or orifice meters a bad solution for such applications. Additionally, the new applications like high temperature superconducting generators which rotate at 3000 rpm, which is cooled small diameter tubes.

There are other intrinsic difficulties associated with the use of traditional sensor technologies in superconductors and space applications. The absence of gravity restricts use of many flow measuring methods such as rotameters. The high electromagnetic fields present in superconductors will introduce errors in the commonly used electronic flow meters. Other requirements for such applications include small size, remote sensing capabilities, replicability, long life etc.

Nomenclature

λ_b	Bragg wavelength
Δ	Grating period
η_{eff}	Effective refractive index
$\Delta\lambda_b$	Bragg shift
$\dot{m}$	Mass flow rate
ρ	Density of fluid
A	Cross sectional area
F_d	Drag force
C_d	Drag coefficient
A_p	Projected area
d_f	Diameter of fibre
L	Length of fibre
E_{eff}	Effective Young's modulus
P_e	Strain-optic coefficient
P_{11},P_{12}	Components of strain-optic tensor
n	Refractive index
ν	Poisson's ratio
α	Thermal expansion coefficient
ξ	Thermo-optic coefficient

The above problems could be solved by using an optical based FBG measurement system. FBG has been recently getting more popular in cryogenic and superconductor fields for different applications (Jicheng Li et. al., 2015).

1.1. Fibre Bragg Grating Sensors

A fibre Bragg grating (FBG) is an optical filter embedded in an optical fibre, by means of placing a set of gratings at specified distances. A grating is an area of altered refractive index, placed in a homogeneous domain.