Fiber Bragg grating sensors for a mass flow determination in a rotating liquid neon cooling channel

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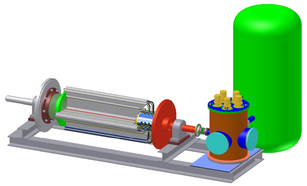
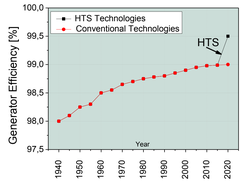
Background

Increasing market for High Temperature Superconducting (HTS) applications offers new perspectives due to advantages of HTS:

- High current carrying capacity combined with higher efficiency
- Option of using other coolants than helium (e.g. Nitrogen @ 77 K, Neon @ 27 K or Hydrogen @ 21 K)
  - ➔ Chance of improvement of generator efficiency about 0,5% with the use of HTS instead of conventional technologies





Objectives

- Which thermodynamic conditions are developing in a rotating cooling channel? How does the heat transport in the fluid take place?
  - ➔ Based on a literature study a model is created to simulate the thermodynamic behavior of a given rotating cooling device.
- Which measurement techniques can be applied to validate this model in a practical measurement? Crucial points therefore are: large momentum and forces, sensor installation, wiring, signal tapping, accuracy.
  - ➔ Preliminary investigations of differently modified FBG sensors in different setups.

Theoretical Considerations

Model

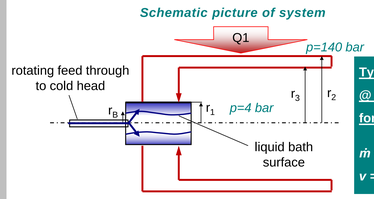
General assumptions

- Heat input = const., only at periphery
- No radial heat transport along cooling channels through solids
- Isentropic compression → negligible mass transport in single space element (true for small heat inputs)
- Reversibility of process
- Secondary flows neglected (e.g. due to Coriolis force)
- Heat transition into channels not considered

Imposed properties to model

- Assumption for calculation of mass flow in outer channels: density difference in both arms towards periphery → pressure difference, balanced by flow friction
- Flow direction defined, not reversible
- 2 thermic induced mass flow cycles modelled (thermosiphon effects): a) reservoir to cold head, b) reservoir to rotor periphery
- Flexible set of channel diameters

Schematic picture of system



Typical result @ r_2 and 60 Hz for d = 0,01 m:

$\dot{m}$ = 0,25 kg/s, v = 2,5 m/s

Typical set of input parameters

Input Parameters	
Input Pressure [Pa]:	110000
Rotation/Frequency [s^{-1}]:	60
Total Permanent Heat Load Q1 [W]:	500
Radius r2 [m]:	0,42
Radius r3 [m]:	0,37
Radius r1 [m]:	0,15
Radius Bath Surface rB [m]:	0,14

Default Setting for Thermosiphon Channels				
Channel Diameter d [mm]:	5	6	10	12
Channels per Strand [-]:	2	2	1	1
Number of Strands [-]:	2	2	2	2

Simulation Results

Basic results

- Large maximum pressures along outer diameter r_2 = 0,42m:
  94 bar @ 50 Hz;
  136 bar @ 60 Hz;
  185 bar @ 70 Hz
- Ratio of mass flow rates: cold head / cooling channel ≈ 1…8 %
- Channel diameter + pressure ↓ → ΔT ↑ (rotational speed ↓ → pressure outer diameter ↓)
- Channel diameter + pressure ↓ → mass flow rate ↓

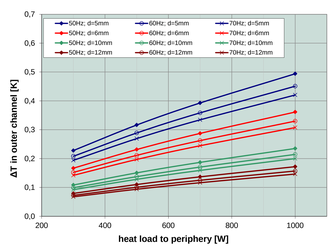


Figure 1: ΔT in outer channel at different rotational speeds and channel diameters d

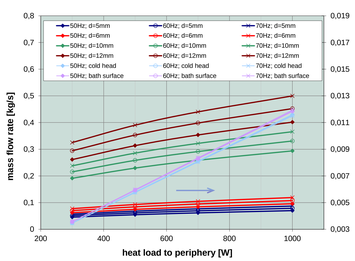


Figure 2: Mass flow rate at different rotational speeds and channel diameters d

Results with additional heat input for mass flow determination

- The temperature variations range within 1/100 K accuracy → high sensitivity of temperature measurement system required
- Due to thermosiphon effect: temperature increase leads to increase of mass flow rate → error created
  - ➔ least error with thin channels

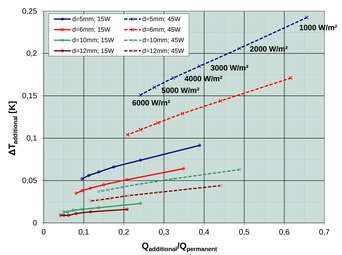


Figure 3: Additional heating; ΔT due to relative heating - at different permanent heat loads (inlet pressure 1,1 bar; rotational speed 60 Hz)

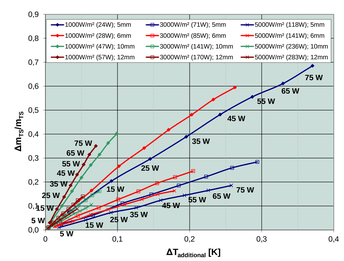


Figure 4: Additional heating; relative Δm depending on ΔT - at different permanent heat loads (inlet pressure 1,1 bar; rotational speed 60 Hz)

Conclusion

- A thermodynamic model has been developed to study the process parameter and their influence in the HTS rotor cooling.
- Based on the modelling results possible electrical and optical sensing systems were identified.
- At KIT, an optical based sensing system (FBG) was investigated for its thermal characteristics at 30 K.
  - To enhance the sensitivity various coating materials have been studied and the errors associated with rotation were determined.
  - The vacuum tight optical rotating feed through has been validated for its functionality at high rotating speed and the mechanical strength of the FBG sensor has been verified.

Investigation of Fiber Bragg Gratings

Options for the mass flow measurement system

Suitable methods for HTS Generator application
- Constant heating power method: Very good absolute measurement accuracy
- Heat pulse method: Very high measurement resolution and time response

Possible sensors for temperature measurement at 30 K
- Cernox
- TVO
- Platinum resistance sensors

Advantages
- Commercially available
- Well known characteristics

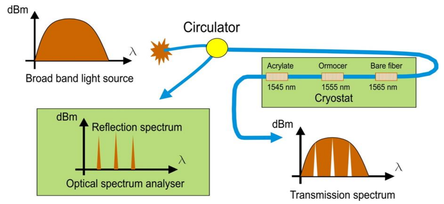
Disadvantages
- Signal transmission from high speed rotating system limited
- High speed rotating vacuum tight feed through required
- Sensor installation and wiring elaborate

Alternative sensor
- Fiber Bragg grating sensors

Advantages
- Small in size and can be multiplexed
- Immune to electromagnetic interferences
- Easy signal transmission and commercially available high speed rotating vacuum tight optical feed through

Disadvantages
- Not sensitive below ~120 K
- Sensor characteristics and mechanical properties need to be investigated at 30K

Study of bare and polymer coated FBG sensors



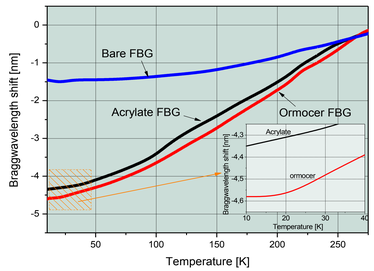
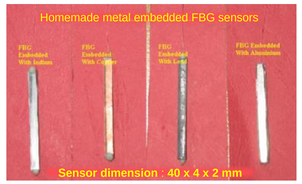


Figure 5: Thermal response of bare and polymer coated FBG

Sensor Type	Sensitivity @ 30 K	System Accuracy @ 30 K	Temperature Resolution @ 30 K
Bare FBG	~ 0 pm	-	-
Acrylate FBG	6 pm	0,33 K	0,0833 K
Ormocer FBG	8 pm	0,25 K	0,0625 K

Study of metal embedded FBG sensors



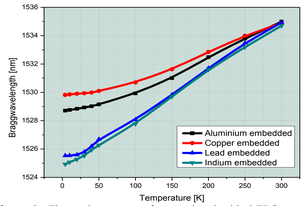
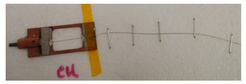


Figure 6: Thermal response of a metal embedded FBG sensors

Sensor Type (Embedded)	Sensitivity @ 30 K	System Accuracy @ 30 K	Temperature Resolution @ 30 K
Al-E-FBG	22 pm	0,09 K	0,022 K
Cu-E-FBG	18 pm	0,11 K	0,027 K
Pb-E-FBG	33 pm	0,06 K	0,015 K
In-E-FBG	33 pm	0,06 K	0,015 K

Study of metal coated FBG sensors



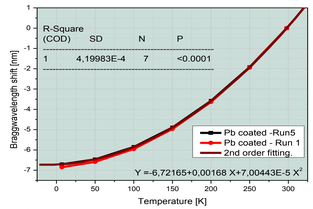


Figure 7: Thermal response of lead coated FBG sensor

Sensor Type (Coated)	Sensitivity @ 30 K	System Accuracy @ 30 K	Temperature Resolution @ 30 K
Pb-C-FBG	24 pm	0,083 K	0,020 K

Investigation of mechanical property and sensor survivability for high speed rotation

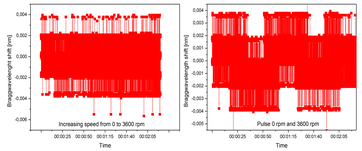


Figure 8: Braggwavelength shift versus rotational speed

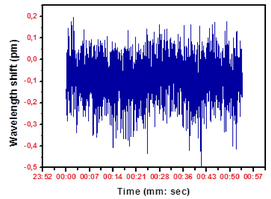


Figure 9: Effect of centrifugal force

Sensor type	Sensitivity @ 30 K [pm]	Shift due to Rotation [pm]	Estimated Error due to rotation K
Acrylate FBG	6 pm	± 6 pm	± 1 K
Ormocer FBG	8 pm	± 6 pm	± 0,75 K
Pb-E-FBG	33 pm	± 6 pm	± 0,181 K
Pb-C-FBG	24 pm	± 6 pm	± 0,25 K

Set-up to investigate the sensor rotational error and its survivability for applied centrifugal force due to rotation