Micro Cooling of SQUID Sensor

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Abstract: The aim of this work has been to realize a feasibility study of a cooling device for a SQUID sensor, using liquid nitrogen flowing through micro channels. The design consists of an epoxy cylindrical vacuum vessel skewed by a silicon microchannel heat sink. The SQUID sensor is situated directly on top of the microchannel heat sink. The device is used at room temperature and should be able to cool down the SQUID top surface under 80K. The main work consisted in optimizing the heat sink and vessel design, using thermal, micro-fluidic and mechanical three-dimensional numerical simulations, to match the SQUID sensor working conditions requirements. It has been shown, using COMSOL Multiphysics software that the 80K limit can be reached, using liquid nitrogen with an inlet temperature of 70K and flow velocity of 0.05 m/s, flowing in 100 μm by 1500 μm wide channels.

Keywords: SQUID, liquid nitrogen, micro channels.

1. Introduction

‘Biodiagnostics’ is a European project within the 6th Frame Program that aims at developing new medical diagnostic tools using Microsystems and supersensitive magnetic detection methods. One of the tasks is to investigate the feasibility of increased performance of today’s magnetic detection by using microtechnology (or MEMS, Micro ElectroMechanical Systems). MEMS technologies offer the possibility of miniaturization and batch fabrication creating complex devices on a chip.

The extreme sensitivity of the Superconducting Quantum Interference Device (SQUID) sensor, one of the detection methods in the project, is used for identification and analysis of low analyte concentration out of complex samples in bio-medical applications, for example immunoassays and magnetic resonance imaging. High-TC SQUID sensors need to be cooled down to 77 K; thus cryostats have to be utilized to obtain the working temperature. The current cryostats are fairly large in dimension and not so easy to handle especially for medical applications where a “portable”-like system would be preferable.

We look into the possibility of developing a new cooling method that is of smaller size than current available state-of-the-art cooling-systems and which will also lead to shorter measurement cycles of the system. The method is based on cooling the SQUID sensor by using liquid nitrogen flowing through micro-channels that are in very close contact with the sensor. The design consists of a cylindrical vessel and a silicon micro-channel heat sink. The vessel should be vacuum tight (the vacuum inside is at least 10^{-7} Pa) and good thermal insulator. The SQUID sensor is situated directly on top of the microchannel heat sink. The micro cooling channels should be able to cool down the SQUID sensor from room temperature to about 77 K; it should not introduce vibrations due to liquid nitrogen flow (vibrations cause noise in the SQUID’s signal output). The SQUID is sensitive to electromagnetic radiation thus all the materials used for the micro cooling system should be chosen accordingly.

2. Theory

When we talk about cooling, it means that there is heat to remove, or more exactly heat will be transferred from one point to another. Heat transfer occurs through conduction, convection, radiation or any combination of these.

2.1 Conduction

Conduction is the transfer of thermal energy from a region of higher temperature to a region of lower temperature through direct molecular communication within a medium or between mediums in direct physical contact without a flow of the material medium. Heat is transferred by conduction when nearby atoms vibrate. Conduction is greater in solids where atoms are in constant contact. In liquids and gases the molecules are usually further apart, which gives a lower chance of molecules colliding and passing thermal energy. The heat equation is given by

$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot \left(k \nabla T \right) = Q$$

Where ρ is the density, C the heat capacity, T the temperature, k the thermal conductivity and Q a heat source or heat sink.

2.2 Convection

Convection is the up and down movement of gases and liquids caused by heat transfer. As a gas or liquid is heated, it expands and becomes less dense and thereby rises. When the gas or liquid cools it becomes denser and falls. As the gas or liquid becomes less or more dense, rises or falls, it creates a convection current. Convection is the primary method by which heat moves in gases and liquids. To calculate the rate of convection between an object and the surrounding fluid, the heat transfer coefficient, h is introduced. Unlike the thermal conductivity, the heat transfer coefficient is *not* a material property. The heat transfer coefficient depends upon the geometry, fluid, temperature, velocity and other characteristics of the system in which convection occurs.

2.3 Radiation

Radiation is the transfer of heat through electromagnetic radiation. All objects radiate energy at a rate equal to their emissivity times the rate at which energy would radiate from a black body. No medium is necessary for radiation to occur.

2.4 Micro fluidics

The three primary conservation laws that are used to model thermo-fluidic dynamic problems are conservation of mass, momentum and energy. If we assume that the fluid particles are smaller than the size of the system and apply the fundamental relation of the dynamics of the material point, we derive the following equation for fluid motion [1]

$$\rho \frac{\partial u_i}{\partial t} = F_i + \frac{\partial \sigma_{ij}}{\partial x_j},$$

Where ρ is the density, u_i the velocity component along i, F_i the external force component along i and σ_{ij} the stress tensor. The equation for conservation of mass is given by

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial u_i}{\partial x_i} = 0$$

According to Stokes law, the stress tensor of a Newtonian fluid is linearly related to the deformation tensor. For the particular case of Newtonian fluids we thus obtain the Navier-Stokes equation

$$\rho \frac{\partial u_i}{\partial t} = F_i - \frac{\partial \rho}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j^2}$$

where μ is the dynamic viscosity of the fluid.

Several non-circular cross section shapes can be considered for micro fluidic channels. Injecting a liquid flow through these geometries is often difficult because of their irregular shape. Using the hydraulic diameter, D_h, is a method for approximating the flows through these geometries [2]. The hydraulic diameter is given by

$$D_h = \frac{4 \times CrossSectionArea}{WettedPerimeter} = \frac{4A}{P_{wet}}$$

For liquid flows in long straight micro channels of constant cross section the Reynold's number gives a good indication if turbulence will occur. It is given by

$$\mathrm{Re} = \frac{\rho D_h u}{\eta} = \frac{D_h u}{\nu}$$

where D_h is the hydraulic diameter, η and υ the dynamic and kinematic viscosity respectively. The particular Reynold's number at which transition from laminar to turbulent flow will occur depends on many parameters such as the channel geometry, aspect ratio, and surface roughness. It is expected to be between 1 000 and 2 000.

3. Simulations

Two different types of simulations have been performed, first a simulation including the heat transfer and micro fluidics models and secondly a mechanical characterization. All simulations have been performed with Comsol Multiphysics 3.3. The different application modes were taken from the Heat Transfer Module and the MEMS module.

3.1 Thermo-fluidic simulation

The problem was reduced to a 2D symmetrical model to reduce memory consumption and solution time. The first geometry, to the left in Figure 1, has only one liquid nitrogen input channel. The nitrogen is flowing right under the SQUID package and getting out at the opposite side of the vessel. For the second geometry in figure 1, a second cooling pipe has been added. The pipe follows the vessel walls in order to block the heat coming from the outside.

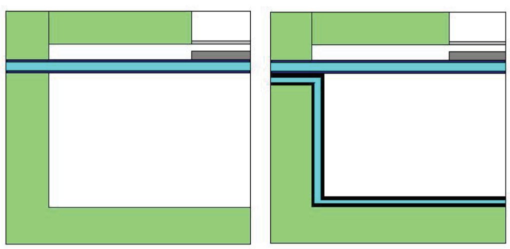

Figure 1. Basic unit cell for one channel geometry (left) and two channels geometry (right).

There are three main thermal boundary types included in this simulation. The outside boundaries of the vessel and membrane are exposed to the outside environment, i.e. a constant temperature. We will then suppose that the flow inlet boundary is at constant temperature, 67- 70 K, and that the flow outlet is a convective flux boundary. Heat transfer by radiation is included for all inside boundaries.

The channel inlet is set to be a flow velocity boundary with a value between 0.05 m/s and 0.6 m/s. These velocities will give a laminar flow. The channel outlet is set to be a flow pressure boundary with a value of 0 Pa. This means that there is no external pressure at the outlet to suck or push the flow. Further the flow at the micro-channel walls is assumed to be zero.

3.2 Thermo-mechanical simulation

Once the cooling performance of the device has been optimized we have to check how much stress it can support under the working conditions. Different geometries have been simulated in this part of the study. Each component has been analyzed separately. We have tried to estimate the minimum thickness that will support the internal depressurization and the temperature gradient from room temperature to 70 K.

4. Results

Many parameters are influencing the final performance of our device, e.g. the material properties of the device, the microchannel geometry and dimensions and the flow velocity.

4.1 Material properties

In order to reach the best performance of the device different materials have been considered, such as copper, phosphor bronze and manganin for the wires and silicon and SD-2 for the cover plate. As can be seen from Figure 2 the use of manganin wires will improve the cooling performance. Manganin wires are often used in cryogenic applications due to their low thermal conductivity. This type of wire will bring less heat from the outside environment to the SQUID sensor. Regarding the cover plate the performance difference was small between silicon and SD-2.

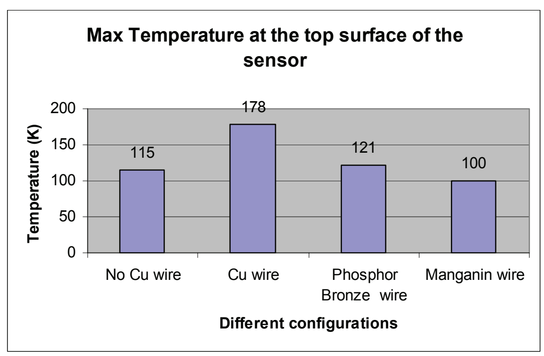

Figure 2. Max temperature at the SQUID sensor depending on the wire material.

4.2 Microchannel geometry and flow velocity

The microchannel geometry and the flow velocity are linked, as seen from the theory part. Changing the dimensions of the microchannel will affect the nitrogen flow and create a different pressure drop and be more or less efficient regarding the cooling performance. Following two different articles [3,4] we have used two different geometries for the micro-.channels; 100 µm by 500 µm and 100 µm by 1500 µm, and two different geometries for the cooler; one and two channels respectively.

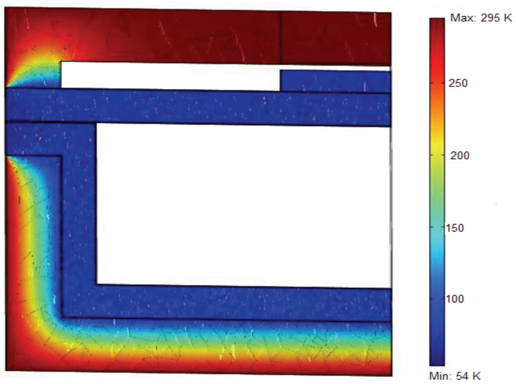

Figure 3. Temperature distribution in the unit cell for the two micro channels design using 100 µm by 500 µm micro channels.

The steady-state temperature distribution can be seen in Figure 3. The vacuum cavity is well insulating considering that the distance between the SQUID sensor and the sapphire window is 250 µm. The temperature at the bottom of the window is a little bit below 295 K and the maximum temperature at the top surface of the SQUID is around 80 K depending on the configuration.

4.3 Thermo-mechanical simulation

The stress distribution and the final displacement are shown for the vessel walls in Figure 4.
The highest stress is concentrated on the joint part between the upper and lower part. The maximum stress on the 2.5 mm thick vessel walls is below the yield point of the epoxy material used for the simulation. It is not recommended to decrease the thickness further due to the insulating function of the vessel walls.
More details of the behavior of our micro cooling system can be found in [5].

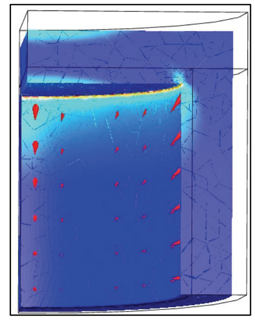

Figure 4. Stress distribution, displacement arrows and deformed shape of the vessel unit cell.

5. Conclusions

The results show that the 77 K limit can be reached with small resistance using liquid nitrogen with an inlet temperature of 70 K and flow velocity of 0.05 m/s, flowing in 100 µm wide, 1500 µm deep and 30 mm long channels. By using two micro-channels, the cooling is more efficient. Silicon shows to be a good material for micro channels because of its excellent thermal and mechanical properties (in particular around 80 K) and ease to fabricate by MEMS technology. Manganine wires show the best thermal properties.

6. References

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7. Appendix

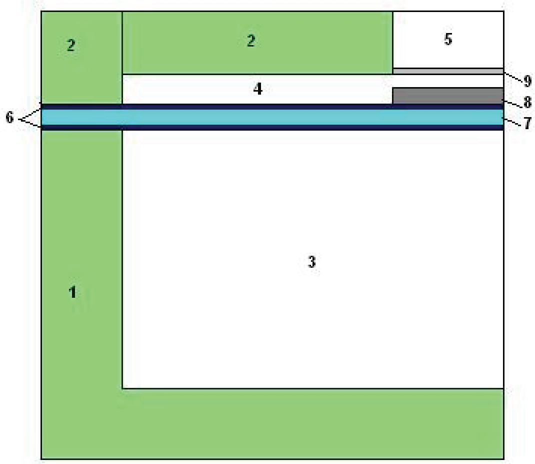

Figure 1. Subdomains in the unit cell used for the one channel geometry.

Table 1. Subdomain settings.

Sub-domains	Part name	Material	Specification
1-2	Vessel	Epoxy	
3-4	Vacuum cavity	Air, 10^{-7} Pa	
5	Sample area	Air	
6	Micro-channel Heatsink	Silicon	
7	Liquid flow	Liquid nitrogen	
8	SQUID	$SrTiO_3$	Heat source $Q= 1\ W/m^3$
9	Window	Sapphire	

Table 2. Boundary conditions

Category	Boundary Type	Specification
Thermal	Temperature	Outside boundaries: 300 K
		Heatsink inlet: 67 K
	Convective flux	Heatsink outlet
	Radiative	Inside boundaries
Flow	Flow velocity at inlet	$0.05<u<0.6$ [m/s]
	Flow pressure at outlet	0 Pa
	Wall boundaries	Microchannel walls
Thermal – Design options	High conductivity	Wire material properties
		Adhesive properties