Designing a cryogenic recirculating superheated liquid detector for dark matter search

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Introduction

Superheated liquid bubble chambers employ superheated liquid as active target material. Impinging particles scatter off nuclei in the detector liquid and this energetic perturbation causes bubble nucleation. In this manner, such chambers have been used a particle detectors and presently this technology is being pursued as promising dark matter detectors [1].

In operating bubble chambers a practical issue is the evaporation of the liquid upon formation of bubbles. Conventional recovery relies on pressure cycles. Re-pressurizing however leads to discontinuous operations and requires non-trivial setups. An alternative scheme is to condense the bubbles, thus creating a continuous recirculating system. We discuss this scheme here, focusing on the cryogenics and electrothermal control of the chamber.

Experimental setup

The chamber consists of multiple connected volumes. The bottom most volume is the main detector volume (DV). The top most volume is the condenser volume (CV), and the intermediate volumes maintain a smooth temperature gradient. The DV must be maintained at 25°C and the CV is at -30°C to sustain the superheated liquid, and then for condensing the bubbles. Each volume is thermally tied to temperature stages spanning -30°C to 25°C. See Fig. 1.

Thermoelectric control

A thermoelectric system is designed to maintain the CV temperature at 30 ± 2 °C.

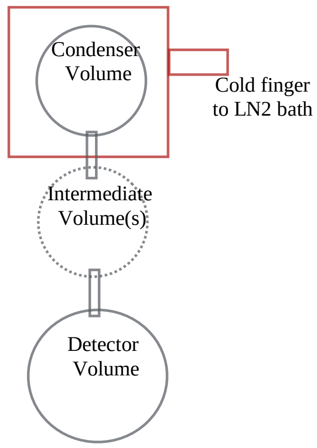

Figure 1: Schematic of experimental setup

In this scheme the whole volume sits inside a machined copper block, with good thermal connection. The copper block has an extended cold finger which is inserted into a liquid nitrogen (LN2) dewar. This bath at -196 °C allows conductive cooling. The copper block also has 8 heaters, and silicon diode temperature sensors to monitor the temperature and provide the appropriate amount of heating power.

Feedback mechanism is used for the thermoelectric control. The heating power is made to depend on the temperature of the CV, particularly the temperature difference between the desired value and the measured temperature. We have explored several methods for the feedback, such as Pulse Width Modulation and High Power Operational Amplifiers. Thus we cool the CV with LN2, measure the temperature and apply sufficient heat to prevent overcooling.

Simulation results

Initially this thermoelectric control is simulated in two ways. Steady state thermal modeling was done via ANSYS to inform us of the power requirements and the spatial temperature anisotropy expected from this setup. Fig 2 and 3 show the results in detail, and we note that for this system heating of ~100W allows steady state operations.

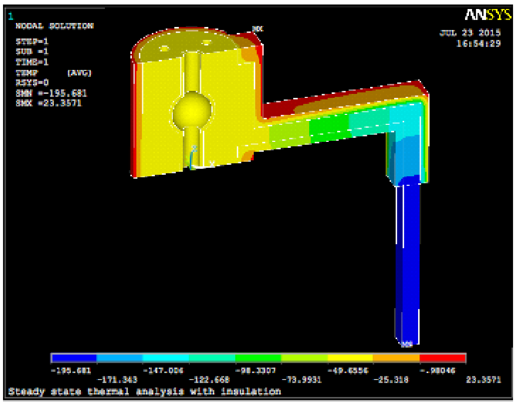

Figure 2: Steady state simulation of full CV stage with cold finger in LN2 and heaters in the copper block.

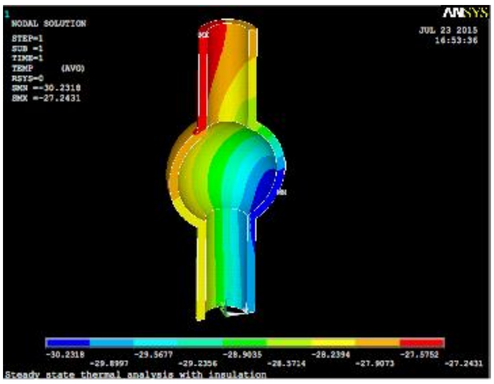

Figure 3: Temperature gradients along the CV boundaries.

As the steady state simulations demonstrate, using 100 W of heating power it is possible to balance the LN2 cooling to obtain temperatures in the desired range, and with spatial anisotropies within the acceptable error margins (± 2°C). Following this, simulations of the electronics with feedback control was performed to understand the control and stability of the process.

The electronics assumes a lakeshore Si diode with < 0.5°C gaussian noise, connected to a high power (OPA541) operational amplifier capable of providing > 120 W of heating power. The proposed circuit is shown in Fig 4.

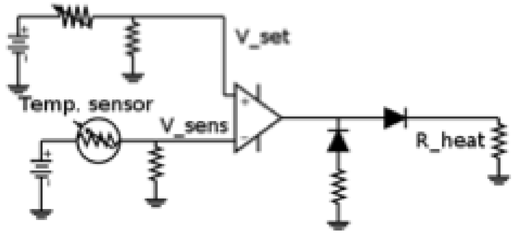

Figure 4: Control electronics schematic.

Vsens is the measured temperature in voltage. Vset is the voltage corresponding to the final desired set temperature. The op-amp linearly amplifies the temperature difference, the diode network at the output ensures heating when the measured temperature is less than the set temperature. Folding in various physical material constants and sensor noise from standard data sheets, a first order power balance calculation provides the time variation of the temperature.

We see that the temperature stabilizes in about 30 mins, having started at room temperature. The 1 sigma fluctuation on the final temperature is < 0.05°C, including sensor noise and parasitic power fluctuations. The amplifier circuit can be easily replaced by Power Width Modulation circuit and should have similar time constants, however the final 1 sigma noise may be slightly higher at ~ 0.1°C, well within the desired range.

References

1. C. Amole et al. (PICO Collaboration), Phys. Rev. Lett. 114, 231302 (2015).