A miniature low-cost, radiation resistant levelsensor for cryogenic liquids

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1. Introduction

For the liquid Hydrogen/Deuterium PYPtargt [1] a liquid level sensor was sought which was both small (< 5 mm diam.) and radiation resistant. Several types of liquid levelsensors exist based upon the difference in resistance or capacitance between electrodes, or pressure in the liquid and gas phase. These are all rather bulky. For liquid Nitrogen, diodes are commonly used. The forward voltage-current characteristic is very temperaturesensitive and serves as a thermometer. These sensors are small but the semiconductor is radiation sensitive. Therefore another solution was sought.

2. Principle of operation

The temperature of a heater in a medium is given by:

\[ T = T_{\text{medium}} + \frac{P}{S \cdot a}, \]  

(1)

where \( a \) is the heat transfer coefficient, \( P \) the power dissipated in the heater and \( S \) the surface area in contact with the medium. When the liquidlevel passes the heater, the value of \( a \) changes drastically and hence its temperature. The heat transfer coefficient \( a \) consists of two components: 1. the conductance of heat between the heater/thermometer and the surface of the sensor, and 2. the heat transfer between the surface of the sensor and the bulk of the medium. It is the latter component that varies by an order of magnitude between liquid and gas (e.g. Nitrogen 50 times, Hydrogen 15 times at normal boiling point).*

3. Realisation

As heater an ordinary resistor (220 ohm, 1/5 W) is used. Its temperature is measured by thermally coupling a standard PT100 platinum resistor (Hereaus PT100 GX518) onto it. A thin copper wire holds the two components together and the assembly is covered by a thermally conducting, insulating varnish (GE7031). This varnish is known to be watertight and resistant to low temperatures after curing. The surface showed no cracks under the microscope after repeatedly dipping into liquid Nitrogen. The dimensions of the sensor are 5 x 4 x 3 mm³; its mass is only 0.2 g.

The heater resistor showed a negative temperature coefficient: at 20K its resistance is 230 ohm. The electrical diagram is shown in fig.1. The sensor behaves like a four-lead resistor with a very large lead resistance at one side. Thus, the wires that are commonly used in low temperature thermometry, e.g. 0.1 mm phosphor-bronze (36AWG), are also suitable here.

*When the liquid is boiling the heat transfer in the liquid is much enhanced, on the other hand, exploding bubbles may cool the sensor when it is in the vapour immediately above the liquid, so also increasing the heat transfer.
Although the standard DIN IEC 751 curve extends only to -200 °C, individual calibration of a PT100 is possible to 30 K. We could not achieve long term calibration within 1 K below 20 K; this does not prohibit its use as a level sensor, as the signal (change in temperature) can be made large enough by using more heating power. It can easily be derived that at low temperatures where $R_{\text{heater}} \gg R_{\text{sensor}}$ the signal, $\Delta V$, which is the difference between the sensor voltages in the gas and the liquid is:

$$\Delta V = I^3 \left( \frac{c}{S} \frac{R_{\text{tot}}}{a} \right) \left( \frac{1}{a_g} - \frac{1}{a_l} \right)$$  \hspace{1cm} (2)

where $I$ is the current through sensor and heater, $c$ the temperature coefficient of the PT100 resistor, $R_{\text{tot}}$ the series resistance of heater and PT100, while the indices $g$ and $l$ indicate the gas and liquid, respectively.

A current of 15 mA was mostly used. A high current is advantageous as can be seen in eq. 2. The current is limited by either the maximum allowable heat input in the cryogenic circuit or the maximum temperature that will be reached when the sensor is in gas or in vacuum. The value given above is based on the latter limit.

4. Test results

4.1. Liquid nitrogen

The sensor was put into Dewar with liquid nitrogen, below the liquid level. Due to the continuous evaporation, the liquid level will eventually pass the sensor. This process is shown in fig. 2 for two power levels. The voltage measured over the platinum resistor is converted to temperature, using the standard curve. Even with the smallest heating power (0.2 mW) a clear signal is obtained, typically 17 mV in liquid vs. 33 mV in gas. The continuous rise of the sensor temperature in the gas is in this case caused by the rising temperature in the Dewar.

4.2. Liquid hydrogen

A copper vessel held at 18 K, was filled with hydrogen at 1 bar and monitored with a set of sensors. Fig. 3 shows the response of one of the sensors during condensation. A voltage drop of 21 mV (at a current of 11 mA) signals the passage of the liquid level. Fig. 4 shows the temperature of three sensors during heating up of the vessel to 21 K. Two sensors are within 5 mm at the same height, whereas the other is 3 cm lower. An equilibrium temperature of 34 K is calculated for this sensor in gas. As can be seen from the figure, the actual temperatures are ~ 1 K lower. This is due to the heat conduction via the fastening of the sensors. When all the hydrogen is evaporated, the temperature of the last sensor shows a 13 K rise in one sampling interval of 20 s. This is in agreement with a calculated thermal time constant of the order of one second.

* Such calibrated sensors are commercially available, e.g. at LakeShore
4.3. water
An obvious medium to test the sensor is water/air at room temperature. However, adherent water increases the heat capacity in such a way that no signal is obtained when the sensor is brought out of the water until all this water is evaporated. From air into water the signal is $\Delta T = 11 \text{ K}$ for $P = 50 \text{ mW}$.

5. Additional uses

Without changing the wire connections inside the cryostat, the sensor can be used for other measurements as well.

5.1. temperature sensor
By lowering the bias current, the temperature difference between the sensor and the medium can be made small. When several power levels are used, extrapolation to zero power, and thus zero temperature difference, is possible. In this way even gas temperatures can be measured. With the standard DIN curve the above method gave 77.42 K for the temperature of boiling liquid Nitrogen (77.36 K). This is well within the accuracy of the curve (0.55 K).

5.2. flow indicator
In a stagnant liquid, the heat transfer takes place by natural convection. In a moving liquid, the heat transfer is much enhanced and is a weak function of the velocity: $Nu \approx Re^{1/2}$.

Although the velocity dependence is small, a detectable difference exists. Fig. 5 shows the temperature difference between the sensor and water at various velocities. The curve represents the theoretical values with the sensor dimensions adapted to obtain a best fit. Note that the water temperature was measured with the same sensor by simply lowering the current (and thereby the heating power) through it.

6. Conclusion

A small low-cost sensor was developed for use as a level indicator. It was successfully tested from room temperature down to 20 K in liquid hydrogen. In several experiments with a liquid Deuterium target [1,2] it served as a safety device to signal the boiling dry of the liquid circulation loop. During commissioning of the target the temperature of the liquid was measured with the same sensor. In the HARP neutron detector [3] four sensors at different positions watch the pressure head of the liquid Hydrogen converter.
References

Figure captions.

Fig.1  Electrical diagram of the sensor. The sensor voltage is measured via the leads labelled \( V_+ \) and \( V_- \). The lead \( I_+ \) and \( I_- \) are connected to a power supply. For use as a level sensor, the stability of the power supply is not critical. When the sensor is used as a thermometer, a stable current source is required.

Fig.2  Temperature of a sensor in a Dewar with liquid Nitrogen. Initially the sensor is submerged, but due to the continuous evaporation the sensor eventually ends above the liquid. Two measurements are shown: with a heater power of 16 mW and 0.2 mW, respectively.

Fig.3  Sensor voltage in condensing Hydrogen. The heater power was 30 mW. The liquid level can be seen to be rising until after appr. 100 s the sensor is totally submerged. Note that the response time of the sensor is < 1 s, see text.

Fig.4  Temperature of three sensors during heating-up of a vessel with liquid Hydrogen. The dashed lines correspond to sensors that are within 0.5 cm at the same height. The solid line represents a sensor which is 3 cm below the others. Apparently one of the sensors is never fully submerged. Note the fast rise of the signal of the third sensor in the last minute (13 K within one sampling interval of 20 s).

Fig.5  Velocity dependence of the sensor temperature. The points show the temperature difference between water at various velocities and a fully submerged sensor. The curve shows the result of calculations with the dimensions of the sensor slightly adapted to obtain a best fit. The sensor power was 99 mW.
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Fig. 2  Temperature of a sensor in a Dewar with liquid Nitrogen.
Fig. 3  Sensorvoltage in condensing Hydrogen.
Fig. 4  Sensor temperature during heating-up of a vessel with liquid Hydrogen.
Fig. 5  Velocity dependence of the sensor temperature.