A Noise Thermometer for Temperatures

from Above 300K to Below 4K*

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ABSTRACT

The description of a solid state noise thermometer is given and its use is discussed. Temperatures between 300K and 4.2K have been measured to better than 1% with a time constant of 5 seconds.

Introduction

One of the major problems in physics is the precise, reliable measurement of temperature. A practical thermometer should have a wide range, as few calibration points as possible, and should be simple to operate. It has long been recognized that the thermal noise developed across a resistive element could be the basis for a thermometer satisfying these requirements, however, the noise and complexity in associated electronic systems has limited the usefulness of the technique.^{1,2} There has been recent progress in the application of noise thermometry to the measurement of very low temperatures because of the development of superconducting quantum amplifiers with extremely low noise.^{3,4} We report here on a simple noise thermometer that operates in the temperature range complementary to that where superconducting devices have been so successful, 4K to above 300K.

Technique

In order to reduce the problems caused by amplifier noise and long term gain and bandwidth changes we have utilized the comparison technique used by Patronis et al.¹ This is illustrated schematically in figure 1. The input of the amplifier can be switched between R_s , the temperature sensing resistor, and R_c , a variable comparison resistor at the calibration temperature T_o .

The measuring procedure is as follows: First with R_s at the calibration temperature T_o , R_c is set so that the noise voltage measured on the AC voltmeter is the same when the amplifier input is connected to R_c or R_s . We shall call this value of the comparison resistor $R_c(T_o)$. Under these conditions the mean squared noise voltage at the amplifier input is

$$\overline{V_n^2} = 4kT_o R_s \Delta f_s + \overline{V_{an}^2} = 4kT_o R_c (T_o) \Delta f_c + \overline{V_{an}^2} \quad (1)$$

where

k = Boltzmann constant

$\Delta f_s (\Delta f_c)$ = bandwidth for sensing resistor (comparison resistor)

$\overline{V_{an}^2}$ = amplifier noise referred to the input

We have assumed that $\overline{V_{an}^2}$ is independent of source impedance, which was a valid assumption for our preamplifier since the source impedance was much lower than the input impedance. Simplifying we get

$$\frac{R_c (T_o)}{R_s} = \frac{\Delta f_s}{\Delta f_c} \quad (2)$$

We note here that $\Delta f_s \neq \Delta f_c$ since the cable capacitances for R_s and R_c are not necessarily the same. The 3dB point for the RC roll-off due to stray capacitance on R_c must be at least 12 times the upper 3dB point for the bandpass filter so that Δf_c is just the bandpass of the filter, independent of R_c .

When R_s is at the temperature T to be measured R_c is again set for a noise voltage equal to that of R_s . Equation (1) then becomes

$$\overline{V_n^2} = 4kTR_s \Delta f_s + \overline{V_{an}^2} = 4kT_o R_c (T) \Delta f_c + \overline{V_{an}^2} \quad (3)$$

and we have

$$\frac{R_c (T) T_o}{R_s T} = \frac{\Delta f_s}{\Delta f_c} \quad (4)$$

Combining equations (2) and (4) we get

$$T = \frac{R_c (T)}{R_c (T_o)} T_o \quad (5)$$

We have assumed for simplicity in the above that R_s is independent of temperature. Corrections for the fact that this is not strictly true will be discussed below. We see that only one calibration point is required.

Apparatus

A block diagram of the apparatus is shown in figure 2. A switching system is built into the preamplifier so that in addition to switching the input of the amplifier between R_s and R_c , R_s can be connected to an AC resistance bridge so that changes in its resistance with temperature can be monitored. The preamplifier is mounted directly on the top of a thin walled stainless steel probe for use in dip testing in standard liquid helium storage dewars. R_s is a 9090 Ω metal film resistor (International Resistance Company Type MEC). It has been found that this resistor changes by about 1% between 300K and 4K. The comparison resistor is a decade resistance box (General Radio Type 1432-N). Miniature coaxial cable (Belden #8700) is used to connect R_s to the preamplifier. R_s is thermally anchored to a brass block at the lower end of the probe.

a) Low-Noise Preamplifier - Since this is the most critical part of the system it warrants detailed discussion. A schematic of the preamplifier is shown in figure 3. It is a simple cascode circuit employing two field effect transistors (FET's) and is mounted inside two insulated metal boxes. The outer box is connected to the stainless steel probe which serves as an outer shield. The cable to R_c also has a double shield, the outermost being connected to the outer box. The preamplifier and input switch are mounted inside the inner box and the coaxial cables from R_c and R_s go into this box. This double shield arrangement keeps stray currents induced in the outer shield from mixing with the signal currents in the inner shield.

The FET's are Siliconix Type U243 and were selected for low noise from four purchased at different times, however, all four were useable, as was a Motorola MFE2102. Both types were intended for use as switches and have large transconductance, G_m .

Van der Ziel has shown that the white noise in a FET is primarily Johnson noise in the channel.⁵ The approximate mean squared noise voltage is inversely proportional to G_m , hence the types used are ideal. Also the FET's in the preamplifier are run at rather high dissipation because G_m is highest at high drain currents. The low frequency $1/f$ noise in these FET's caused no problems in the passband used.

A cascode circuit is used to reduce feedback capacitance from output to input. The 1000 ohm resistor in the FET drain circuit is wirewound to eliminate noise due to direct current. The 47 ohm resistors should be mounted close to the FET's in order to suppress high frequency oscillations. The preamplifier should be checked for oscillations with a high frequency oscilloscope. The power for the preamplifier is provided by a shielded, battery powered regulator.

The effective noise temperature of the preamplifier in the 5kHz-10kHz band is about 3K. This converts to a root-mean-squared noise at the input of about $1nV/\sqrt{Hz}$. The voltage gain is 31.

b) Filter amplifier and comparator detector - These circuits are shown in figure 4. The filter amplifier has a band pass of 5kHz-10kHz and is transformer coupled to the output of the preamplifier. The input stage is a low-noise FET (U243) to take maximum advantage of the preamplifier.

The comparison between the noise across R_s and that across R_c is done by a null detection system to avoid meter reading errors and to increase sensitivity and precision. The rectified noise voltage applied to the galvanometer

can be nulled against a variable offset voltage applied to the meter via the coarse and fine null controls.

The procedure then is to connect R_s to the preamplifier input and null the galvanometer with the coarse and fine null controls. The R_c is connected to the preamplifier input and the galvanometer is nulled by varying R_c . This then gives the value of R_c for the temperature being measured.

The output time constant of the rectifier is about 5 seconds. This is long enough to provide for a precise null reading but short enough to be convenient. At the lower end of the temperature range, where the amplifier noise is a major portion of the signal, the measuring precision can be increased by increasing this time constant.

The filter amplifier and comparator detector are powered by a standard ± 15 volt regulated power supply. All components except those on the FET input stage are non-critical.

Results and Discussion

A typical set of temperature measurements is shown in Table I. The values in the column labeled "Accepted Value" are based on vapor pressure measurements at liquid nitrogen and liquid helium temperatures. As can be seen, this noise thermometer is easily capable of better than 1% measurements over the range from 300K to 4.2K. Corrections for changes in R_s with temperature have been included in Table I.

The main reason for the development of this thermometer was to provide a standard for calibrating colloidal carbon thermometers in the temperature region from 4K to 20K where convenient fixed points are lacking. However, the simplicity of construction and operation recommend its use to temperatures above

300K as well as below. The high temperature limit is essentially the melting point of the probe or the sensing resistor.

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Table I. Typical Temperature Measurements

Temperature	Accepted Value	Measured Value	Error
Room Temp	296K	calibration point	
Liquid Nitrogen	77.26K	77.20K	0.1% low
Liquid Helium	4.196K	4.22K	0.6% high
Liquid Helium (λ -point)	2.17K	2.23K	2.7% high

FIGURE CAPTIONS

- Figure 1. Simplified block diagram of noise thermometer system illustrating comparison technique.
- Figure 2. Block diagram of noise thermometer system.
- Figure 3. Schematic of low noise preamplifier.
- Figure 4. Schematic of filter amplifier and comparator detector.
Capacitances are in μF , resistances are in $\text{k}\Omega$ and all diodes are 1N645.

Figure 1. Simplified block diagram of noise thermometer system illustrating comparison technique.

Figure 2. Block diagram of noise thermometer system.

Figure 4. Schematic of filter amplifier and comparator detector.

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