

The Heat Seeking Flame Probe

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Introduction:

The thermocouple is a standard temperature-measuring device. The Seebeck Effect, discovered by Thomas Seebeck in 1821, established that a difference in potential (ΔV : the “Seebeck voltage”) is generated when two wires of differing metallic compositions and at different temperatures (ΔT) are brought together at a junction.

Seebeck coefficients (S) for various combinations of alloys (named type B through K and N, R, S and T) have been well established in the literature (see figure 1).

The effect is described by the relationship

$$\Delta V = S \Delta T$$

The Seebeck coefficient for each probe is the inverse slope of the graphs in Figure 1 (next page). It is always measured with one wire of the thermocouple in an ice-bath reservoir for standardization.

We will be using a K-type probe to measure the “temperature” at various points within a candle flame. Figure 1 indicates an expected Seebeck coefficient of 0.04 mV/C° , or a temperature rise of $25 \text{ C}^\circ/\text{mV}$ for a K-probe used under standard conditions. Without using ice baths, electronic “cold junction compensation” could also be used to achieve a reference value as well as balance out thermocouple effects contributed to devices connected to the measuring probe.

Figure 1: Voltage-temperature characteristics for commonly used high-temperature thermocouple probes (from Dataforth Corp: document #AN107 page 5)

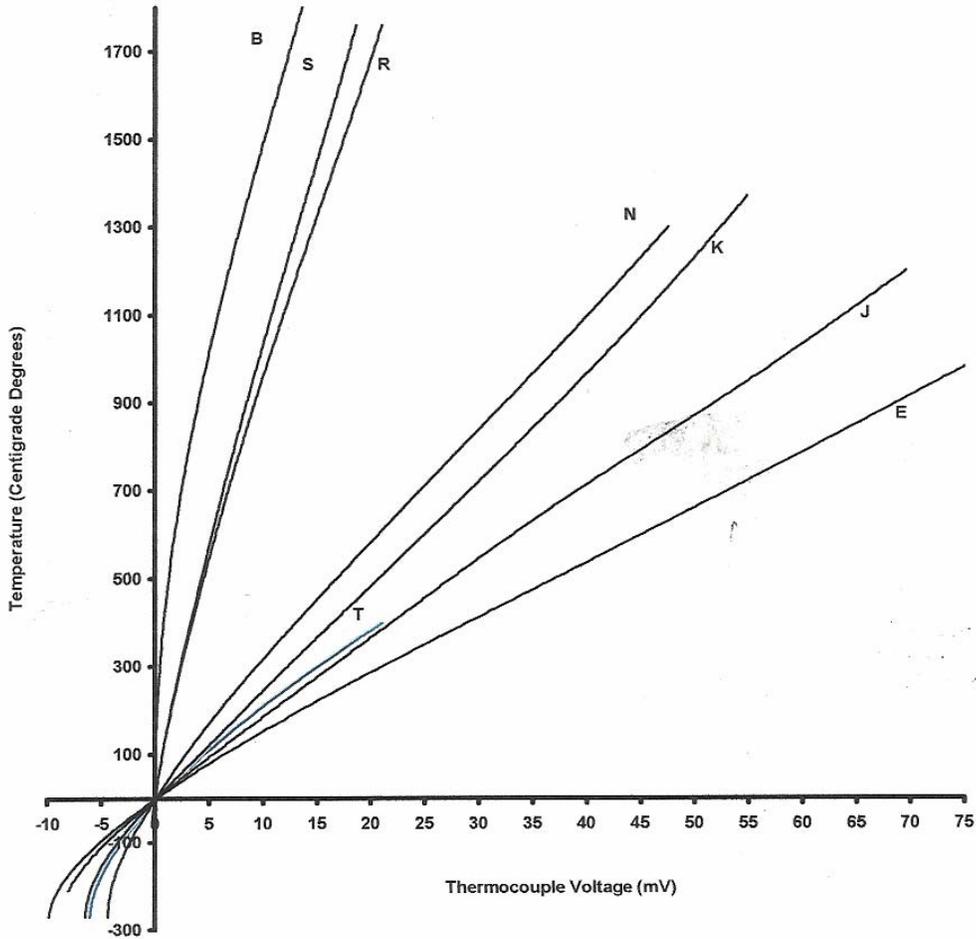


Figure 3
Voltage-Temperature Characteristics of B, E, J, K, N, R, S, and T Type Thermocouples

Flame temperatures are notoriously difficult to measure² due to their dynamic nature, air currents and the fact that the radiative transfer of heat that is going on from within the flame. Tables of flame temperatures often given in reference books are in fact often theoretical *adiabatic* temperatures calculated from bond energies, which are often as much as twice as high as what is actually measured in real, open flame systems where heat is constantly radiating away and is not adiabatically contained. While adiabatic candle flame temperatures as high as 1200 °C are listed in handbooks, high temperatures of 500-700°C are more typical.

Objective:

To design a Heat Seeking Flame Probe (HSFP), which will vertically traverse a flame, sampling different temperatures, until it locates the hottest section of the flame. This should be at the top of the center cone in a candle, Bunsen burner or propane flame. The apparatus will display the different temperatures detected on an LED display.

Project Description:

The objective of the project is to provide a straightforward and easy demonstration for students to see the temperature ranges in various parts of a flame. Since it is common to teach students that the top of the inner cone of a flame is the hottest point (and the most efficient place over which to position a beaker to quickly heat water) it would be helpful to demonstrate that with real numbers. The thermocouple provides an ideal output for a mechatronic probe to search for and display the point of maximum temperature in a candle flame. It would be more convenient to have a “plug in and go” device that would not require ice-baths, calibration, or an interface to a computer to give a read-out of flame temperature. The lack of an ice bath in our device would lead it to have a higher Seebeck coefficient (lower output voltage), and would probably cause drift in readings if long enough heating times caused significant heat conduction into the probe wires. With a one-time calibration of the device programmed into and controlled by a Basic Stamp program, the HSFP should prove to be a quick and easy way for students to see the temperature profile of a flame for the typical short time intervals of a few minutes used in most classroom demonstrations.

Materials and Methods:

- Basic Stamp 2 (Parallax Inc)
- Type-K thermocouple, 24 AWG, 36" long #5TC-TT-K-24-36 .
Composition: +Ni-Cr (yellow) and –Ni-Al (red) alloys
- Servo motor (Parallax)
- Analogue to Digital Converter ADC 0831
- Operational Amplifier 358N,
- LED 4-digit display and driver chip MAX219
- 3" spur gear and gear track
- Ring stand with clamp
- Plexiglas platform and wind-shielding box
- Aluminum assembly parts
- 8 inch candle

Experimental Thermocouple Data:

The tip of thermocouple alone was first inserted into water at various temperatures and its voltage output was measured with a digital multimeter. Results were found within the 3 mV range as shown in the table below:

Table 1: Thermocouple voltage outputs at various temperatures

Temperature (°C)	Voltage (mV)
3	-0.5
21	+0.1
36	+0.5
65	+1.5
82	+2.1

Circuit Design: Mechatronic Control

Since the output voltage above was so small, an operational amplifier was employed to raise the voltage output up to the 0 to 5 Volt level (Gain = 1000), so that the voltage could be properly read by an analog to digital converter (ADC). The binary output from the ADC could then be sent into a microprocessor, in this case the Basic Stamp 2 (see Figure 2). This input data was used to control the motion of the probe by attaching the probe to a motor and gear system as shown in Figures 2 and 3, as well as being sent to a LED display for students to see ongoing temperature readings

Figure 2: Flowchart of Signals and Actions in HSFb

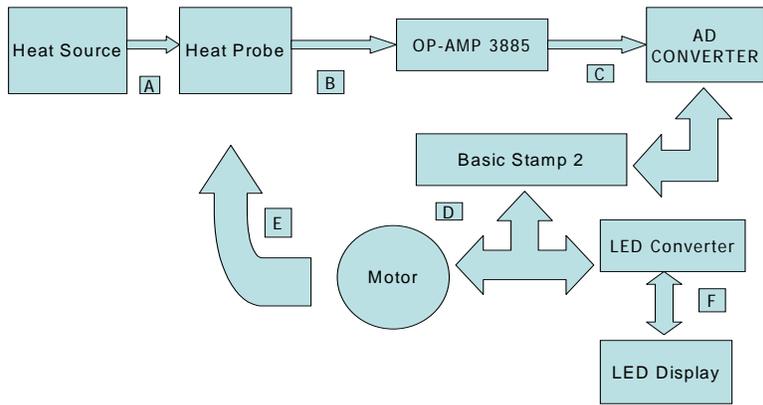
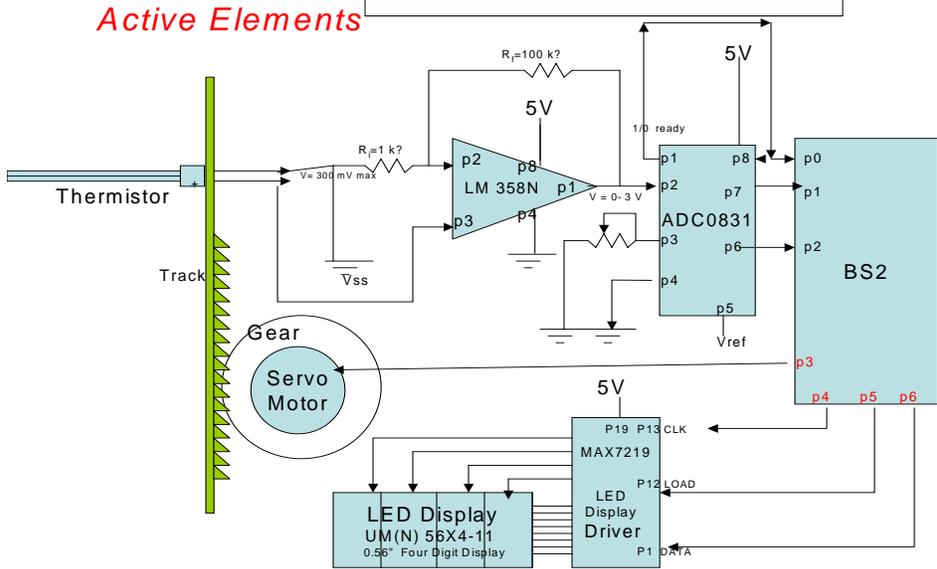


Figure 3: HSFb Circuit Layout



Experimental Data for HFSB Calibration:

The probe was inserted in water at various temperatures while the voltage across pins 1 and 4 of the operational amplifier were measured for calibration purposes. The following values were obtained:

Table 2: Amplified voltage outputs from HSFP circuit at various temperatures

Temperature (°C)	Voltage (Volts)
0	0.00
8.5	0.03
16	0.07
20	0.09
24	0.10
34	0.14
37	0.16
57	0.24

The above data indicates a 240 C° increment per volt measured. The gain was found to be appropriate since the candle flames were expected to peak near the 1000 °C mark, putting the operational output in the 0 – 5 Volt range.

Construction of the Mechanical Device:

The circuit was constructed on a standard breadboard and was mounted onto a Plexiglas base. The support rod and braces was made of aluminum. A large 3" plastic gear insured that a small rotation would easily traverse the flame height. A steel gear rack provided a rigid surface to mesh with the gear and support the thermocouple and its aluminum tube mounting sheath. A plastic box was built to surround the apparatus to minimize breeze effects on the candle. For maximum flexibility of candle type and position, a simple ring stand and clamp was used as a candleholder.

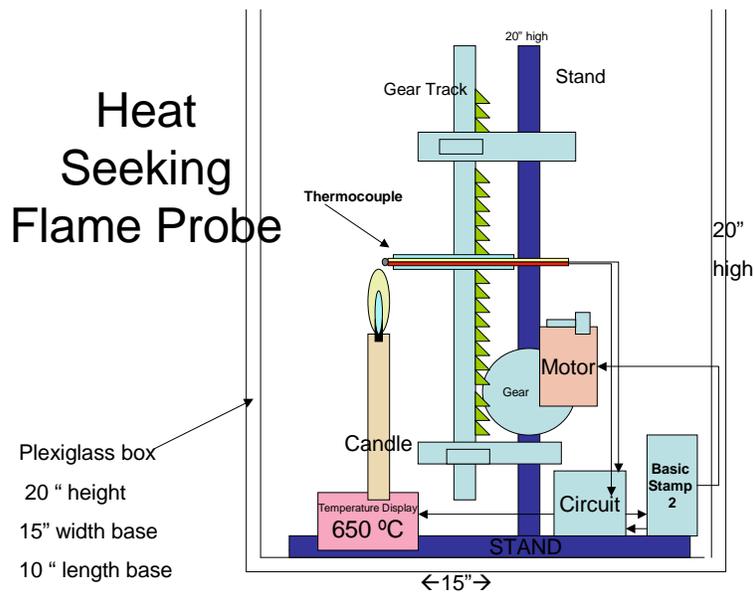


Figure 4: Schematic diagram of HSFP apparatus

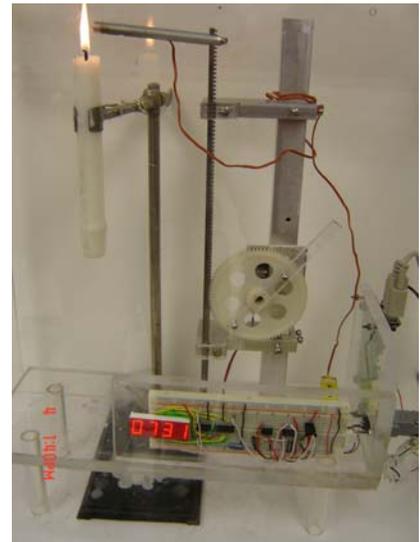


Figure 5: Photograph of HSFP

Programming the HSFP:

The Basic Stamp 2 is programmed in P-basic. A subroutine called “comparator” was written to take temperatures before and after each move of the motor, comparing temperatures (voltages) before and after each move. Starting the thermocouple at the base of the flame the motor keeps progressing upward as long as temperature keeps increasing. Any decrease in temperature causes the motor to reverse direction, causing it to oscillate around the point of maximum temperature.

Master Program for Heat Seeking Flame Probe

```
' {$STAMP BS2}
' {$PBASIC 2.5}
' MASTER PROGRAM
' Thermistor outputs voltage to OpAmp
' A TO D CONVERTER TO take OpAmp's amplified voltage, read it
' and display voltage and temperature
' Motor is told to move as a function of temperature
'nib = 2^4 or 16 word = 2^5 or 32
'----declarations
adcbits VAR Word 'take in temp as binary adc representation
          'of voltage
v VAR Nib 'voltage 1st digit
r VAR Nib 'for remainder calculation of decimal on voltage
v2 VAR Byte '2nd digit decimal voltage
v3 VAR Byte '3rd digit decimal voltage
temper VAR Word
calib VAR Byte '# degrees per Volt output from OpAmp
volts_placeholder VAR Word
tempnow VAR Word 'to compare each successive temperature measurement
tempthen VAR Word
n VAR Byte 'simple counter
position VAR Word
i VAR Byte
DATA_n CON 6 'LED
CLKled CON 5 'LED
Load CON 4 'LED

decode CON 9 'LED
brite CON 10 'LED
scan CON 11 'LED
switch CON 12 'LED

setup VAR Word 'LED
number VAR Word 'LED
index VAR Nib 'LED
temp VAR Word 'LED
odd VAR index.BIT0 'LED
```

```

'-----initialization -----
cs PIN 0
clk PIN 1      'wire from adc pin7 to bs2 pin 1
data_input PIN 2 'wire from adc pin 6 to bs2 pin 2
calib = 150     'set # degrees per Volt output from OpAmp
n = 0

'-----main routine-----

GOSUB initialize_motor_position 'set starting position
GOSUB TwoTemps                 'create 2 temperature values
DO
  DEBUG " in Main Routine",CR   'report program status
  GOSUB comparator             'compare values and have motor move up or down
  PAUSE 5                      'time for temperature to read
LOOP

'-----subroutines-----
*****

TwoTemps: 'takes temperature, moves motor forward,takes new temp
tempnow = adcbits 'reads probe voltage as binary #
tempthen = 0      'set up old temp value

*****
comparator: 'move motor, get new tempnow and compare to tempthen
DO
IF (tempnow < tempthen) THEN GOSUB back_motor ELSE GOSUB forward_motor
  ' above line comes back with old tem value in "tempthen"
tempnow = adcbits ' get new tempnow
IF position < 420 THEN GOSUB initialize_motor_position 'protect motor
LOOP
RETURN ' goes to main routine to repeat comparitor cycle indefinitely

*****
initialize_motor_position:
DEBUG "into intial_motor loop",CR
LOW 3      'standard servo signal is connected to pin 3
FOR i = 1 TO 50 'servo needs to pulse thru loop to reach new position
  PULSOUT 3, 1150 'sets probe to lowest position in flame = 1170
NEXT       '270 is highest position
PAUSE 10   'hold low signal to allow time for motor to read
DEBUG "motor initialized", CR, CR, CR
position = 1150
RETURN     'back to comparitor subroutine

*****
forward_motor:      'motors middle position is 720 with +/- 500 for +/- 90 degrees
DEBUG CR, "into FORWARD_motor loop",CR
tempthen = tempnow 'share value
position = (position-5) 'moves probe up 5 units
DEBUG ? position
FOR i = 1 TO 10     'servo needs to pulse thru loop to reach new position

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```

PULSOUT 3, position ' moves motor forward one unit
PAUSE 5             'gives servo motor time to respond
DEBUG ? i
NEXT                'hold low signal to allow time for motor to read
DEBUG "u p w a r d ",CR ' gives current status of program
GOSUB adc_input_data
GOSUB calc_volts    ' gives current status of program
GOSUB calc_temp
GOSUB LED_display   ' gives current status of program
GOSUB CRT_display
PAUSE 5             ' give a little time for temperature to read
RETURN              'back to comparitor subroutine

```

```

back_motor:
DEBUG CR, "into BACK_motor loop",CR
tempthen = tempnow
position = (position+5) 'moves probe down 5 units
DEBUG ? position
FOR i = 1 TO 10        'servo needs to pulse thru loop to reach new position
PULSOUT 3, position    ' moves motor backward one unit
PAUSE 5                'gives servo motor time to respond
DEBUG ? i
NEXT                    'hold low signal to allow time for motor to read
DEBUG "d o w n w a r d ",CR ' gives current status of program
GOSUB adc_input_data
GOSUB calc_volts        ' gives current status of program
GOSUB calc_temp
GOSUB LED_display       ' gives current status of program
GOSUB CRT_display
RETURN                  'back to comparitor subroutine

```

```

adc_input_data:        'take in an analog voltage from OpAmp
DEBUG "into ADC_INPUT_DATA loop",CR
HIGH cs                'sets pin 1 high initially
LOW cs                 ' this low tells adc to get ready to operate
LOW clk                'sets data input pin 2 to ready state
PULSOUT clk, 210       'sends a 420 us pulse on pin 2
SHIFTIN data_input, clk, MSBPOST, [adcbits\8]
'converts input analogue voltage into a digital voltage
RETURN                 ' back to former motor subroutine

```

```

calc_volts:
DEBUG "into CALC_VOLTS loop",CR
v = 5*adcbits/255      'converts binary back to analog voltage
r = 5 * adcbits//255
v2 = 10 * R/255        'v2 is tenth place
v3 = 100 * R//255      'v3 is the hundredth
v3 = 10 * v3/255
IF (v3>=5) THEN v2 = v2 + 1 'rounds v2 based on v3

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IF (v3>=100) THEN
  v = v +1
  v2 = 0
ENDIF
volts_placeholder = (v*100) + (v2*10) + v3
RETURN      ' back to former motor subroutine

*****

calc_temp:
DEBUG "into Calc_Temp loop",CR
temper = (230*v) +(23*v2) +(2*v3) 'no product allowed >65000

RETURN

*****

CRT_display:
DEBUG CR
DEBUG ? n
DEBUG ? position
DEBUG ? temper
DEBUG " voltage =", DEC1 v,".", DEC2 v2*10 + v3," Volts"
DEBUG " Celsius temperature = ", DEC temper,CR,CR
RETURN      ' back to former motor subroutine

*****

LED_display:
OUTPUT 4
OUTPUT 5
OUTPUT 6
OUT4=0
OUT5=0
OUT6=0

FOR index = 0 TO 7
LOOKUP index,[scan,3,brite,5,decode,$1F,switch,1],setup
SHIFTOUT DATA_n,CLKled,MSBFIRST,[setup]
IF odd = 0 THEN noLoad
PULSOUT Load,1
NoLoad:
NEXT

MaxDisplay:
number = temper

FOR index = 0 TO 3
temp = (number DIG index)
SHIFTOUT DATA_n,CLKled,MSBFIRST,[4-index]
SHIFTOUT DATA_n,CLKled,MSBFIRST,[temp]
PULSOUT Load,5
NEXT

RETURN      ' back to former motor subroutine

```

Results:

Temperature outputs were in the 200 degree range at the base of the candle, below the luminous flame, touching the wick. Temperatures quickly rose to 300-500°C as the inner cone was traversed. In the luminous region from the tip of the inner cone to the top of the upper cone, temperatures from 600-735 °C were recorded. This corresponds to data in the literature expected of candle flame temperatures. The program correctly adjusted motor motion to keep the probe in the hottest part of the flame.

Discussion and Conclusions:

The HSFP works admirably to demonstrate candle flame temperature profiles. It was found to have difficulty with Bunsen burner flames and propane torches. Temperatures of 800°C or more could not be measured because the Thermocouple-OpAmp circuit seemed unable to put out more than 3.2 volts, regardless of the temperature applied. This limitation may be inherent in our decision to not use a cold thermal reservoir;

since $\Delta V = S \Delta T$, the lack of a way of keeping one wire much colder than the other decreases ΔT , decreasing the available ΔV output of the thermocouple. The addition of a cold junction compensation element could possibly remedy the problem.

Nonetheless, the candle flame HSFP demonstration meets the objective of easily and clearly showing students how temperature varies within a typical flame. Other classroom applications for which the HSFP can be used in the teaching of Physics or Technology include teaching mechatronics design, thermodynamics, the concept of voltage, and thermoelectric phenomena such as the thermocouple itself. It is worthwhile for a teacher to have an HFSP on his shelf for a ready-to-use, once-a-year, instant demonstration in any Physics or Chemistry class when these topics arise.