**Laboratory #1: Heat Engine**

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**Abstract** *(typically around 200 words)*

**These instructions give you guidelines for preparing papers for AIAA Technical Journals. Use this document as a template if you are using Microsoft Word 2001 or later for Windows, or Word X or later for Mac OS X. Otherwise, use this document as an instruction set. Either way, you are required to adhere to these formatting standards. This first paragraph is formatted in the “Style Abstract” style (under the “Home” ribbon tab). In general, if you expand the “Styles” box, you can identify the style that you are to use by placing your cursor in the area of the template with the appropriate formatting. In this section, give a brief summary of the purpose or objectives of the lab and a very high-level description of the methods used to obtain the results that will be presented. Also present the most important results. The purpose of this section, generally, is to provide a synopsis of the paper that someone could use to determine whether they want to read the report.**

**Nomenclature**

Papers with many symbols may benefit from a nomenclature list that defines all symbols with units, inserted between the abstract and the introduction. If one is used, it must contain all the symbology used in the manuscript, and the definitions should not be repeated in the text. In all cases, identify the symbols used if they are not widely recognized in the profession. Define acronyms in the text, not in the nomenclature.

*Cp*= pressure coefficient

*Cx* = force coefficient in the *x* direction

*Cy* = force coefficient in the *y* direction

c = chord, *cm*

d*t* = time step, *s*

*Fx* = *X* component of the resultant pressure force acting on the vehicle, *N*

*Fy* = *Y* component of the resultant pressure force acting on the vehicle, *N*

* =* angle of attack, *deg*

*Θ =* boundary-layer momentum thickness

*ρ* =density, g/cm3

*Subscripts*

(You may use common subscripts on multiple variables. If you do so, include this section.)

cg = center of gravity

*G* = generator body

iso = waypoint index

T

**Introduction**

HE Ericsson cycle is an ideal, reversible, thermodynamic cycle. It was invented by John Ericsson in the late 1800s. Like a double-acting Stirling cycle or a Carnot cycle, the Ericsson cycle achieves the maximum theoretical efficiency in the ideal limit. Analyzing and quantifying heat engine cycles is important because it identifies areas for future development in heat engines. If a more efficient heat engine cycle could be developed and utilized widely, cars would be more efficient, ships would pollute less, and humanity would have a cheaper and better source of energy.

There are four processes in the ideal Ericsson cycle. The first is an isothermal compression from a cold uncompressed state to a cold compressed state. The second is isobaric heat addition, where the gas is maintained in a compressed state and heated to the hot compressed state. The third is an isothermal expansion, where the gas expands to the hot uncompressed state. The final process is an isobaric heat rejection, where the gas is cooled so it returns to the original cold uncompressed state. In this context, the terms ‘hot’ and ‘cold’ refer to the high and low temperature reservoirs or heat sources.

In the ideal limit, the Ericsson cycle operates with isothermal expansion and compression. This is the most efficient way to transfer heat. In addition, the Ericsson cycle uses regeneration. The heat is recycled between the hot and cold cycles, which minimizes energy loss.

However, the ideal limit is impossible to attain in a real Ericsson engine. True isothermal expansion and compression require infinite time. In addition, real heat exchangers are not perfectly efficient, so the regeneration is not perfectly efficient. Therefore, it is impossible to build an ideal Ericsson engine, and unrealistic to build an efficient one.

To quantify the error between an ideal and practical Ericsson cycle, this laboratory experiment compares the ideal Ericsson cycle with an experimental version of the cycle performed in the laboratory. A simple piston-cylinder setup is used. The system undergoes isobaric compression by placing a fixed mass on top of the cylinder. Next, it undergoes a quasi-isothermal expansion by heating the air in the cylinder. The mass is removed and the system undergoes isobaric expansion. Finally, a quasi-isothermal compression cools the gas to the starting temperature.

Based on collected pressure and temperature measurements, the efficiency of the laboratory Ericsson cycle is calculated. This is compared with the calculated efficiency for an ideal Ericsson cycle.

A simple uncertainty analysis is performed. Sources of uncertainty and error are identified and quantified. Conclusions are drawn about the performance of the experimental Ericsson cycle, and suggestions are made for improvements on accuracy in future experiments.

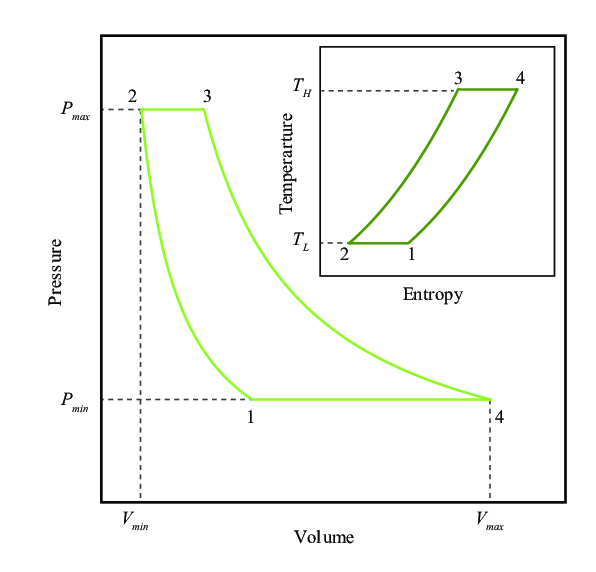
**Methods**

**Theory of the Ericsson Cycle**

As described in the Introduction, the Ericsson cycle consists of 4 steps:

1. Isothermal Compression
2. Isobaric Heat Addition
3. Isothermal Expansion
4. Isobaric Heat Rejection

Pressure-Volume and Temperature-Entropy diagrams help to characterize these cycles. The P-V and T-S diagrams for the Ericsson cycles are provided below:



**Figure 1: P-V, T-S diagram of Ericsson cycle [1]**

**I**n theory, all the heat absorbed from the high-temperature heat source is converted into work, and there are no viscous losses or internal or external efficiencies. This is clearly physically unrealistic, but .

The air in the Ericsson cycle is assumed to be ideal and calorically perfect. These assumptions hold for pressures and temperatures orders of magnitude on either side of room temperature and pressure (298K, 1atm). Therefore, the ideal gas law is used for analysis:

Under the assumption that air is not transferred into or out of the system, *n* is constant. *R* is a gas property, so for a cycle where air is not transferred in or out of the system:

Given these equations, an analysis is performed based on the ideal Ericsson cycle, as shown in Fig. 1. At state one, the gas properties are:

To move from state one to state two, mass is added to the piston. This performs an isothermal compression on the air. The added mass is 50g, as given in the laboratory manual. The conditions at the second state are then:

To move from state two to state three, the cylinder is immersed in the hot bath, which performs an isobaric heat addition. The same mass as state two is maintained. Therefore, the conditions at the third state are:

To move from state three to state four, the weight is removed from the top of the piston. The cylinder is maintained in the hot bath. This process is therefore an isothermal expansion. At state four, the gas state is defined with:

Finally, to move from state four back to state one, the cylinder is moved to the cold bath. This results in isobaric heat removal.

To analyze the efficiency of the cycle, the work out and heat in must be quantified. The work performed by a gas for any thermodynamic process is:

Evaluating this integral through each phase of the cycle results in an expression for the net work performed. Simplifications are possible based on the relationship between volume for each state, and the ideal gas law.

The heat added throughout the cycle comes from the cylinder immersed in the hot bath. This heat counteracts allows for isothermal work to be performed, as well as the gas temperature to rise from state two to state three. Therefore, the heat added can be quantified as:

In general, the thermal efficiency of a cycle is quantified as the ratio of the net work to the added heat. Thus, the efficiency of this cycle is:

The theoretical ideal efficiency, referred to as the Carnot efficiency, is given as a function of the hot and low temperatures:

Where the temperatures are in absolute temperature. The efficiency of this experiment will be lower since there is no regeneration mechanism.

In order to set up the experiment, the optimal hot bath temperature to provide a 40mm rise in the piston during the expansion must be calculated. Based on ideal gas theory, the temperature is calculated as:

Where the volume is yet to be determined.

***Discussions about model problems***

**Experimental Setup**

This section describes the components of the experimental setup. Equations used for analyzing and setting up the system are derived and explained. Pictures of components are included.

1. **Piston-Cylinder System**

This system consists of a piston, tubing, and a watertight cylinder. The piston contains air and has a travel height of 100mm. The piston has a stand on top which allows for weights to be added for isobaric compression or expansion. The small, air-tight tubing connects the piston to the watertight cylinder. The cylinder is made of brass and allows for the air in the system to be heated or cooled without direct application of heating or cooling to the piston. In this experiment, the heating and cooling is performed by immersing the watertight cylinder in hot or cold baths. The air temperature in the entire system asymptotically approaches the temperature of the bath. Once the temperature has leveled out, it is assumed that the temperature in the piston and tube is the same as the bath temperature.

The volume of air within the system must be known. The volume inside the piston is quantified with the diameter and height. The diameter is 32.5mm +/- 0.1mm. This value is obtained directly from the manufacturer specifications. The height is measured during the experiment and has an uncertainty of +/-1mm. It is difficult to accurately read the piston height, so a conservative uncertainty of 1mm was used instead of 0.5mm. Based on this, the volume is given as:

The volume inside the tube is obtained by measuring the length and diameter of the tube. The diameter is measured with high-accuracy digital calipers. The air-containing diameter is measured as 4.07mm with an uncertainty of 0.01 mm. The length is measured with a measuring tape. The length is measured as 1070mm with an uncertainty of 1mm. The tube volume is then:

The volume in the watertight cylinder was measured. The volume is composed of a cylinder, minus an internal plug cutout. Originally, dimensions were provided, but the provided uncertainties were very high. The external dimensions were remeasured. The internal dimensions were taken from the spec sheet, with uncertainties of 0.1in. The uncertainties for the external dimensions are +/- 0.1mm.

Together, the tube volume and cylinder volume are collectively referred to as *Vother*.

The air temperature in the piston is sensed with a 55000 series thermistor. This thermistor provides a 95% confidence interval uncertainty of +/-0.2 C/K in all measurements of temperature through operating ranges observed during the experiment.

1. **Pressure Transducer**

The system to measure pressure is composed of a National Instruments USB 6009 attached to a pressure gauge. The gauge is connected to the free end of a tube connected to the piston-cylinder system. The pressure gauge senses pressure changes as voltages, and these voltages are measured and read into LabView through the NI 6009. The pressure system must be calibrated for local atmospheric conditions.

An Excel spreadsheet is set up to calibrate the pressure transducer. Known weights are placed on the stand of the piston. These weights correlate directly with known pressure changes. The measured voltages and pressure changes are evaluated to decide on a linear fit for pressure, given voltage. The coefficients from the linear fit are fed into LabView, so that LabView displays a pressure reading directly, instead of a voltage reading. For this experiment, the pressure fit was:

According to system specifications, the pressure transducer has an uncertainty of 2%. No confidence interval is specified so 95% is assumed. This assumption is valid, because most part specifications provide uncertainty at a 2% level.

1. **Water Baths**

Two water baths are used in this experiment. One is maintained at a ‘cold’ temperature of 20°. The other is maintained at a hot temperature. The hot temperature is calculated based on a desired piston rise of 40mm, as described in the section of this report defining the Ericsson system. The water baths have a very high thermal mass, compared to the thermal mass of the piston-cylinder system. Therefore, it is assumed that the water baths maintain constant temperature throughout the cycle. Experimentally, it was observed that the temperature reading in the water baths did not change.

When this laboratory experiment was performed, the thermistors described in the lab manual were inoperative. As a result, the only way to quantify the temperature of the water baths was from the readout screens of the equipment. The uncertainty of the internal temperature sensors in the water baths was determined to be the same as the precision of the readout, as +/- 0.1°C at a 95% confidence interval.

**Results**

Equation 20 provides the method of calculating the temperature of the hot bath. A temperature of 46°C was calculated and used throughout the experiment. The cold bath is maintained at 20°C. This temperature is maintained across all five trials.

For each trial four states are recorded. The states are described in the Methods section. At each state, the temperature, pressure, and volume of the piston-cylinder system are measured. Because the piston-cylinder system has leaks, the leak rate is quantified and used to correct the data. A 50g weight is placed on the cylinder and the total air loss over 5 minutes is measured. This loss rate is used as the baseline loss. Because the air loss is driven by the pressure difference between the atmosphere and the piston, it is assumed that air is only lost when the weight is on the cylinder. This correction process is a response to the bias error induced by the air loss in the system.

The data for all five trials at each of the four states is presented below. The first state is achieved twice, at the start and the end. The second time the first state is achieved is referred to as the ‘fifth state’.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Trial – State | Elapsed Time (s) | Piston Height  [adjusted for loss] (mm) | Air Temperature (K) | Pressure Difference (Pa) | System Volume (cm3) | Total Volume Uncertainty (cm3) |
| 1-1 | 0 | 39.5 | 293.45 | 412 | 131.0731 | 2.223733 |
| 1-2 | 27 | 36 | 293.21 | 997 | 119.4591 | 2.21969 |
| 1-3 | 170 | 99.95 | 317.55 | 974 | 331.6648 | 2.343939 |
| 1-4 | 192 | 101.95 | 317.65 | 430 | 338.3014 | 2.349326 |
| 1-5 | 330 | 37.45 | 293.02 | 403 | 124.2706 | 2.221322 |
| 2-1 | 0 | 31 | 292.75 | 408 | 102.8675 | 2.214537 |
| 2-2 | 25 | 28.875 | 292.65 | 1028 | 95.81612 | 2.212572 |
| 2-3 | 165 | 91.775 | 317.65 | 1013 | 304.5376 | 2.322737 |
| 2-4 | 190 | 93.775 | 317.75 | 430 | 311.1743 | 2.327799 |
| 2-5 | 360 | 28.775 | 292.93 | 392 | 95.48429 | 2.212483 |
| 3-1 | 0 | 22.5 | 292.83 | 390 | 74.66191 | 2.207491 |
| 3-2 | 33 | 20.655 | 292.81 | 984 | 68.53964 | 2.206251 |
| 3-3 | 150 | 83.25 | 317.75 | 1024 | 276.2491 | 2.302106 |
| 3-4 | 165 | 85.75 | 317.95 | 432 | 284.5448 | 2.307994 |
| 3-5 | 350 | 15.75 | 292.95 | 390 | 52.26334 | 2.203464 |
| 4-1 | 0 | 30.5 | 293.55 | 411 | 101.2084 | 2.214063 |
| 4-2 | 28 | 28.48 | 293.4 | 983 | 94.50539 | 2.212221 |
| 4-3 | 150 | 86.25 | 317.55 | 970 | 286.204 | 2.309188 |
| 4-4 | 166 | 88.25 | 317.65 | 432 | 292.8406 | 2.314018 |
| 4-5 | 309 | 23.75 | 293.35 | 392 | 78.8098 | 2.20839 |
| 5-1 | 0 | 18.5 | 293.15 | 392 | 61.38868 | 2.204936 |
| 5-2 | 27 | 15.945 | 292.95 | 1024 | 52.91041 | 2.203561 |
| 5-3 | 134 | 78.69 | 317.4 | 1044 | 261.1176 | 2.291725 |
| 5-4 | 164 | 81.69 | 317.65 | 432 | 271.0725 | 2.298502 |
| 5-5 | 307 | 16.69 | 293.15 | 390 | 55.38255 | 2.203941 |

**Table 1: Raw data from five trials**

The measurements of temperature, pressure, volume, and time provide the basis for further analysis. Specifically, the work done, heat in, and efficiency are desired. The calculation to obtain these quantities is described in Equation 16-18. The mass is calculated using Equation 1, the ideal gas law. Five efficiencies are obtained, one per trial. These are presented below:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Trial Number | Mass of Air in System (g) | Net Work Done (J) | Net Heat In (J) | Efficiency | Uncertainty of Efficiency | Percent Uncertainty |
| 1 | 0.13311 | 0.092189 | 4.604117 | 0.020023 | 0.004109 | 20.523 |
| 2 | 0.10445 | 0.055366 | 3.405701 | 0.016257 | 0.005802 | 35.6921 |
| 3 | 0.07578 | 0.048397 | 2.571604 | 0.01882 | 0.007437 | 39.51852 |
| 4 | 0.10276 | 0.052563 | 3.327093 | 0.015798 | 0.005973 | 37.80621 |
| 5 | 0.06213 | 0.068929 | 2.464922 | 0.027964 | 0.006843 | 24.47242 |
| Average | 0.095646 | 0.063489 | 3.274687 | 0.019772 | 0.006033 | 31.60245 |

**Table 2: Net Work, Heat In, and Efficiency for five trials**

The above table contains some key trends. The average efficiency is 0.0198. The Carnot efficiency for the temperatures used in this experiment is defined by Equation 19, and it is 0.0815. The efficiency achieved in this experiment is only 25% of Carnot efficiency. However, this difference is expected. In the ideal limit, when it achieves Carnot efficiency, the Ericsson cycle includes a regenerative step to recover the heat. This regeneration was not included in the experiment, so much lower efficiencies are expected.

A comparison can also be made to the ideal full Ericsson cycle, without generation. Each state is calculated using the ideal gas law, and the hot and cold temperatures (Equations 1-16).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| State | Ideal Height (mm) | Ideal Air Temperature (K) | Ideal Pressure Difference (Pa) | Ideal Volume (cm3) |
| 1 |  |  |  |  |
| 2 |  |  |  |  |
| 3 |  |  |  |  |
| 4 |  |  |  |  |
| 5 |  |  |  |  |

**Table 3: States during Ideal Cycle Analyzed**

This experiment demonstrated the viability of the Ericsson cycle. However, its utility is in question. Typical heat engines can achieve thermal efficiencies on the order of 0.4-0.6. The most efficient engines typically achieve 50% of their Carnot efficiency. Improvements to this experimental setup including the addition of regeneration would increase efficiency as a percentage of the Carnot efficiency. In order to be a commercially useful heat engine process, the real efficiency of the Ericsson cycle would have to be similar to Otto, Diesel, and Brayton cycles.

The uncertainty of efficiency is also presented. The process by which it is obtained is described in the Uncertainty section. On average, the uncertainty is 31.6%, with a maximum of 39.5%. These large uncertainties are not unexpected. The system changes are quite small from a macro perspective, and quantifying the changes requires precise measurements.

The uncertainty section reveals that the largest numerical contribution to uncertainty is measurements of the volume. This is expected. Pressure and temperature were measured digitally, whereas volume was measured by eye. In particular, the measurement of the height of the piston was imprecise. To decrease the percent uncertainty, a digital method for volume measurement could be used. Alternatively, more precise calipers and measurement tools could be used. In particular, a better method for measuring the piston height would greatly decrease the uncertainty of the system.

This section describes the obtained results. You need to show that you obtained these results using the methods and equations presented in the previous section. So don’t just drop a final number. Instead, present your raw data, then refer to the equations from the Methods section that you apply to this raw data, and finally present the calculated results. All calculated results (as well as relevant raw data) in this section require uncertainty values. The calculation of uncertainties should be presented in the next section. Results need to be interpreted and discussed in this section. If results are different from expected, this should be adequately discussed. If they are as expected, this should be mentioned as well. Don’t ascribe variances to “human error” in your report. If human error was a significant source of error, you need to go back and redo the lab.

Present all plots and relevant numerical calculations here. Be sure to follow proper format for figures, including scales, axis units, and figure labels. Determine likely sources of precision and bias error and estimate their magnitudes based upon what you have learned in class and homework. Identify, for all labs, the greatest source of uncertainty, making sure to justify your assertion.

A graph of a function

AI-generated content may be incorrect.

**Fig. 1 Magnetization as a function of applied fields.**

Line drawings must be clear and sharp. The must be large enough to be legible. *Use of colors to highlight details is encouraged.* Make sure that all lines and graph points are dark and distinct and that lettering is legible; 8- to 10-point type is suitable for artwork that is sized to fit the column width (3 ¼ in.). Keep the lettering size and style uniform both within each figure and throughout all of your illustrations. Place figure captions below each figure, and limit caption length to 20-25 words. If your figure has multiple parts, include the labels “a),” “b),” etc., below and to the left of each part, above the figure caption. Please verify that the figures and tables you mention in the text actually exist. When citing a figure in the text, use the abbreviation “Fig.” except at the beginning of a sentence.

Figures should have no background, borders, or outlines. In the electronic template, use the “Figure” style from the pull-down formatting menu to type caption text. You may also insert the caption by going to the Insert menu and choosing Caption. Make sure the label is “Fig.,” and type your caption text in the box provided. Captions are bold with a single tab (no hyphen or other character) between the figure number and figure description.

Use the Table drop-down menu to create your tables; See the Table 1 example for table style and column alignment. If you wish to center tables that do not fill the width of the page, simply highlight and “grab” the entire table to move it into proper position.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Table 1 Transitions selected for thermometry** | | | | | | |
|  | Transition | | |  |  | |
| Line | ν″ |  | *J*″ | Frequency, cm-1 | *FJ*, cm-1 | *G*ν, cm-1 |
| a | 0 | P12 | 2.5 | 44069.416 | 73.58 | 948.66 |
| b | 1 | R2 | 2.5 | 42229.348 | 73.41 | 2824.76 |
| c | 2 | R21 | 805 | 40562.179 | 71.37 | 4672.68 |
| d | 0 | R2 | 23.5 | 42516.527 | 1045.85 | 948.76 |

**Uncertainty Calculations**

Given an arbitrary function of many variables, the overall uncertainty of the function is given by:

To obtain the overall uncertainty of the efficiency, multiple intermediate uncertainties will be determined.

The uncertainty of the volume of the cylinder, piston, and tube will be determined first. The uncertainty of a generic cylinder volume is given by:

Where for the cylinder in question, uncertainty due to the plug must also be included. The uncertainties of dimensions for each part are described in the methods section. The uncertainty of the tube section volume is 0.0696cm3. The uncertainty of the watertight cylinder is 1.3cm3. The uncertainty of the piston depends on the piston height and is calculated as shown above. To obtain the total volume uncertainty, the contribution from the piston, tube, and cylinder are summed.

The uncertainty of the pressure is obtained simply as 2% of the current pressure. The uncertainty of the thermistor-measured temperatures is +/- 0.2K, whereas the uncertainty of the bath temperatures is +/- 0.1K.

The full equation for efficiency is:

Partial derivatives with respect to each variable must be taken. With all uncertainties known, the overall uncertainty can be computed. The equation for overall uncertainty of the efficiency is

The partial derivatives which make up this uncertainty are:

In the above equations, the quantities X and Y are defined for convenience and are:

This overall formula is expensive to evaluate. A Python script was used to compute the uncertainty of the efficiency. The script is included in the appendix. The results are different for every run, but trends were identified.

The inclusion of various terms in the uncertainty equation lends itself to a sensitivity analysis. This analysis looks at which components contribute most to the uncertainty. To perform the analysis, the magnitude of each term in the overall uncertainty equation is compared. As an example, the first run had uncertainty contributions of:

|  |  |
| --- | --- |
| Quantity | Uncertainty Associated with Quantity |
|  | 2.922210664298975e-10 |
|  | 3.463549683432539e-10 |
|  | 7.682269856564957e-06 |
|  | 9.199065950534889e-06 |

**Table X: Uncertainty Sensitivity Analysis**

The table demonstrates that the volume is the largest contribution to uncertainty. The compressed volume contributes to the uncertainty more than the uncompressed volume.

In the results section, the relative uncertainty is expressed as a percentage. This percentage is obtained as:

**Conclusion**

Although a conclusion may review the main points of the paper, it must not replicate the abstract. A conclusion might elaborate on the importance of the work or suggest applications and extensions. The conclusion should emphasize the most important results and answer/address the problems/questions stated in the introduction. Do not cite references in the conclusion. Note that the conclusion section is the last section of the paper to be numbered. The appendix (if present), funding information, other acknowledgments, and references are listed without numbers.

**Appendix**

1. **Python Uncertainty Calculations**

The source code to compute the uncertainty of efficiency is presented below:

import numpy as np

def uncertainty\_eta(R, cp, Th, Tc, V1, V2, sigma\_Th, sigma\_Tc, sigma\_V1, sigma\_V2):

    # Compute X and Y

    ln\_V = np.log(V1 / V2)

    X = R \* (Th - Tc) \* ln\_V

    Y = cp \* (Th - Tc) + R \* Th \* ln\_V

    # Compute partial derivatives

    d\_eta\_dTh = (Y \* R \* ln\_V - X \* (cp + R \* ln\_V)) / Y\*\*2

    d\_eta\_dTc = (Y \* (-R \* ln\_V) - X \* (-cp)) / Y\*\*2

    d\_eta\_dV1 = (Y \* (R \* (Th - Tc) / V1) - X \* (R \* Th / V1)) / Y\*\*2

    d\_eta\_dV2 = (Y \* (-R \* (Th - Tc) / V2) - X \* (-R \* Th / V2)) / Y\*\*2

    print((d\_eta\_dTh \* sigma\_Th) \*\* 2 )

    print((d\_eta\_dTc \* sigma\_Tc) \*\* 2 )

    print((d\_eta\_dV1 \* sigma\_V1) \*\* 2 )

    print((d\_eta\_dV2 \* sigma\_V2) \*\* 2)

    # Compute overall uncertainty using propagation of errors

    sigma\_eta = np.sqrt(

        (d\_eta\_dTh \* sigma\_Th) \*\* 2 +

        (d\_eta\_dTc \* sigma\_Tc) \*\* 2 +

        (d\_eta\_dV1 \* sigma\_V1) \*\* 2 +

        (d\_eta\_dV2 \* sigma\_V2) \*\* 2

    )

    return X/Y, sigma\_eta

R = 287.101  # Specific gas constant for air (J/kg·K)

cp = 1005   # Specific heat capacity of air at constant pressure (J/kg·K)

Th = 273.15 + 46    # Hot temperature in K

Tc = 273.15 + 20    # Cold temperature in K

V1 = 61.38868395   # Initial volume in cm³

V2 = 52.91040895    # Final volume in cm³

# Uncertainties

sigma\_Th = 0.2  # Uncertainty in Th (K)

sigma\_Tc = 0.2  # Uncertainty in Tc (K)

sigma\_V1 = 2.223733448 # Uncertainty in V1 (cm³)

sigma\_V2 = 2.219690495 # Uncertainty in V2 (cm³)

# Compute uncertainty in eta

eta, sigma\_eta = uncertainty\_eta(R, cp, Th, Tc, V1, V2, sigma\_Th, sigma\_Tc, sigma\_V1, sigma\_V2)

print(f'Efficiency: {eta}')

print(f"Uncertainty in η: {sigma\_eta}")

**References**

Almost every report requires references. If you use any of the images from the Canvas site, refer to it. If you use an online calculator, refer to that, if you use uncertainty/calibration information for measurement instruments, refer either to the Canvas site or to the manufacturer website where you found that information. References should be presented as a numbered list which can be referred to in the text [1].

[1] Example of how to use reference in the text

[2] Second entry in the references list

[3] Lab description on MAE4400 Canvas site

[4] Manufacturer website, [www.example.com](http://www.example.com), visited on 1/10/2023

1. Insert Academic Level, Department Name, and A number. [↑](#footnote-ref-1)