University of Tasmania

Second-year laboratory work

KYA212

Entropy changes in rubber

July 29, 2025

Contributors to this experiment, its documentation, and support materials include I. D. Kelly, A. J. McCulloch and G. S. C. Stewart.

Safety

General information regarding lab safety can be found on POLUS, the lab website, whereas experiment-specific safety considerations are listed here.

Hazards

This experiment involves heating water within an exposed and unsecured metal container, so care must be taken around the apparatus to avoid the possibility of severe burns. You must ensure that the water does not reach boiling point, and that the water jacket is not filled to the top acknowledging the expansion of water upon heating.

A risk assessment for this activity has been undertaken and approved by the relevant university authority; it can be accessed here.

Summary

The relation between work, temperature and entropy is investigated through the amount of work required to stretch a rubber band at different temperatures. Temperature is controlled by an encapsulating water jacket, whilst the work is determined using a strain gauge and displacement sensor at the ends of the rubber band.

Experiment objectives and learning outcomes

The primary objective of this experiment is to demonstrate the connection between work, energy, entropy, and temperature within a simple physical system.

Following this experiment, it is expected that you will:

- Understand how entropy relates to the relative amount of order/disorder within a system, explained by its physical properties
- Develop an intuition for non-linear sensor calibration and polynomial data fitting

Introduction

The theory of entropy has advanced into one of the most fundamental descriptions underlying the physical universe. Enabling us to quantify the innate randomness within a system, it has revolutionised our basic understanding of how things evolve with time, and helps to explain much of what we observe in everyday life. As a metric, it has found far-reaching disciplinary significance, grounding the principles of information theory, applicable for analysing societal behaviours and economic trends; even supporting hypotheses for the final fate of the universe. However, this widespread relevance has also corresponded to an inherent vagueness behind the concept, which has ultimately hindered many from gaining a grasp of its physical intuition. Simple experiments to elucidate entropy in an observable sense are few and far between: one conducive avenue is enabled by the thermodynamic properties of a rubber band, which provides both a clear qualitative and quantitative illustration of the connection between entropy and system disorder.

Notions of entropy organically crystallised in the 19^{th} century from discussions regarding the thermodynamic processes dictating the efficiency of steam engines. Preliminary insights proposed an equivalence between heat and work within mechanical systems; this was built upon by German physicist Rudolf Clausius and his study of the *Carnot cycle*, who in the 1850s and 1860s introduced a term to describe the dissipative loss of usable energy when work is performed [1]. Coining the state function *entropy* from the prefix '*en-*' (from energy) and the Greek word '*trope*' (meaning 'turning' or 'change') , these mathematical ideas refined interpretations of energy conservation and set forth the modern basis of classical thermodynamics [2]. These elegant formulations hold to this day, and demonstrations using rubber bands have been relied upon for several decades to translate this theory into real observable physics for teaching purposes [3, 4, 5].

Such evidence should be encouraging to all that results gleaned from this relatively simple experiment should corroborate with theoretical assumptions. It is instructive (and advised) to refer to your lecture notes and the above resources before conducting this experiment: this will not only ensure that the requisite knowledge of thermodynamic theory is fresh in the mind, but also help guide a diligent methodology and interpretation of the obtained results.

Background

Pre-lab exercises

Pre-lab questions can be found sprinkled through the introductory section. These are to be completed and submitted *before* you commence a new experiment. The information needed to complete the exercises is contained in the experiment background section, your course notes, or in the appendices; however, your own independent research is highly encouraged. Make sure to include references where material has been foraged from elsewhere; this is not only "good form", but making notes of this kind - where to find useful information - is essential should you need to return to the origin of some information.

Context

Entropy can sometimes have an ethereal quality, typically used loosely to describe the amount of (dis)order in a system and used to justify the reversibility of a process. As one advances in the study of thermodynamics, the *second law of thermodynamics* makes an appearance, and this is usually when one starts to get an inkling that something is a bit strange.

Prelab 1 *An illustrative exercise*

Provide a concise statement of the second law of thermodynamics and how it connects to entropy.

Prelab 2 *A cure for the viral video*

A video of some nails in a box being shaken went viral some years back, and still makes the rounds online in various on-line communities with esoteric interests, such as /r/oddlysatisfying. Regard said video[a] and comment on why it is often stated that this must be fake, and explain why it is real with explicit reference to the entropy of the system.

[a]The animation can be also be accessed via https://polus.utasphys.cloud.edu.au/partII/entropy/

Thermodynamics

The theoretical grounding of this experiment is found entirely within the fundamental laws of thermodynamics. Starting from this basis and relying on a small amount of calculus, one can arrive at a simple formulation relating changes in entropy to the measurable parameters of temperature and the extension length of the rubber band. You are going to do this here.

Prelab 3 *Helmholtz free energy*

What is the *Helmholtz free energy*? How does it differ from other similar thermodynamic quantities? Why must we use it here?
Working from the first law of thermodynamics and the definition of the Helmholtz free energy F, show that the incremental change dF in a stretched rubber band in terms of the tension force applied f, and the entropy S and temperature T of the system is

$$dF = fdl - SdT \tag{1}$$

NOTE: You will need to make the assumptions that the change in volume of the rubber band is negligible when stretched and that the process is reversible. Are these reasonable assumptions? Justify your response.
You are also allowed to sigh that the conventions around denoting force, tension, temperature, and Helmholtz free energy conspire perfectly when used together.

Prelab 4 *Guiding one's experimental methodology*

With your new-found expression from prelab 3, show that the change in entropy per unit length l of the rubber band under constant temperature $\left(\frac{\partial S}{\partial l}\right)_T$ can be related to $\left(\frac{\partial f}{\partial T}\right)_l$, which quantifies the change in force per unit temperature at constant length. Without specifically referring to the set-up here, how would one generally look to measure $\left(\frac{\partial f}{\partial T}\right)_l$ and in turn infer changes in S in an experiment?

Prelab 5

Give an intuitive explanation how the strain and displacement sensors convert their respective measurements into voltage.

Apparatus

This experiment centres around a thermally stable water jacket (Fig. 1) which contains a heating element that is used to control the temperature of the housed water volume via an external temperature controller. At opposite ends of the water jacket are the strain and displacement sensors, which respectively enable measurements of tension and displacement in terms of voltage. The outputs of these sensors can be fed into a Pico data logger, which in turn can be connected to a computer via a USB Type-B connection for digital display. Stiff wire hooks enable a rubber band to be stretched between the two sensors through the water jacket.

Alongside the water jacket you will need the following additional items to calibrate and carry-out your measurements. These are shown in Fig. 2

1. Distance **calibration rods** with known lengths
2. 50 g **weights**
3. **Mass hanger**
4. Digital **scales**
5. **Calipers**
6. Heating element **temperature control** system
7. A ***picoscope 2000*** is provided for data logging and for which operational details can be found on POLUS

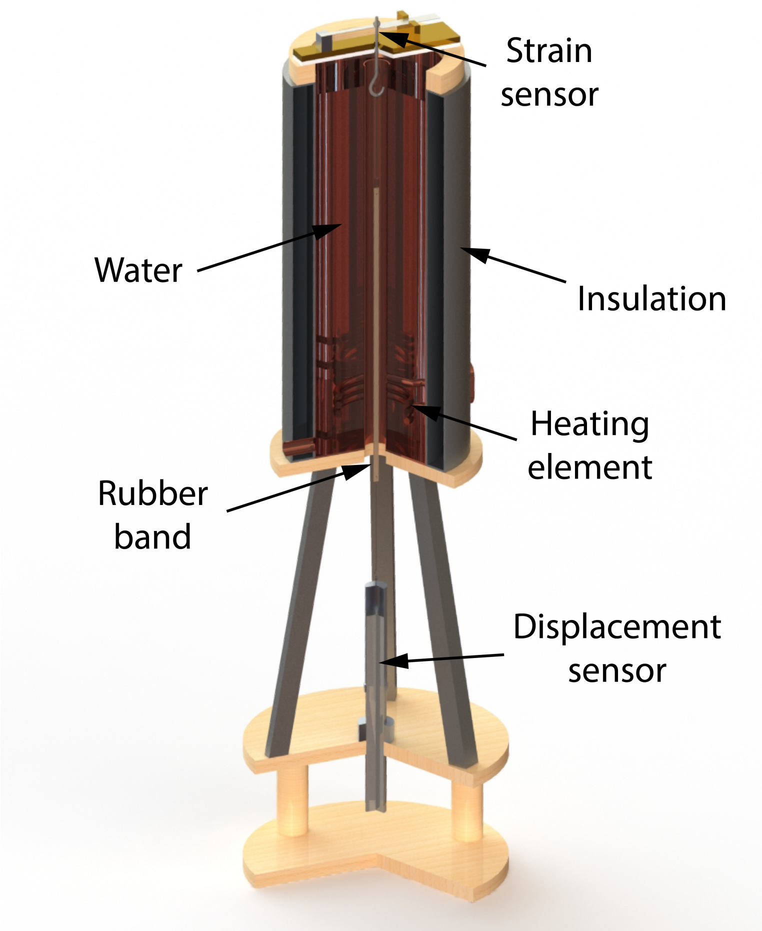

Figure 1: A schematic cutaway of the water jacket apparatus, illustrating the internal elements surrounding the rubber band, in between the strain and displacement sensors.

Experiment

Equipped with a healthy base of knowledge regarding the experimental apparatus and relevant physics, it is now time to design and execute your experiment.

Exercise 1 *Executing the experiment*

Formulate an experiment that will enable you to quantify changes in the entropy of the rubber band in terms of its extension. Key things to consider in your methodology are:

- How would one approach calibrating the sensors to relate their voltage readings to force and displacement?
- What is the most practical and time-efficient approach for taking measurements?
- What temperature range is feasible using the water jacket apparatus?
- What is a suitable range of extension lengths, considering the limits of elasticity of a rubber band and the range of the displacement sensor?
- Considering the above and the available time you have to conduct this experiment, what is an appropriate set of measurements, and taken at what intervals?

Figure 2: Other items useful to this experiment.

- How should uncertainty be approached in this experiment?

Once you have a clear plan, discuss it with a demonstrator.

Hints:

- Refilling the water jacket will require a careful removal of the wooden ring supporting the strain sensor assembly - make sure that the displacement sensor is detached from the rubber band before lifting.
- It is recommended to fill the water jacket to about $1.5 - 2\,\text{cm}$ from the top; do not fill right to the top, acknowledging that water expands upon heating. Make sure that the water does not boil.
- There is a tap at the bottom of the water jacket to enable drainage if needed.

- Old rubber bands may be left behind from previous experiments, potentially useful for some practice runs, but may not ideal for taking your own measurements. A conceptualisation of hysteresis may also be valuable to consider in your methodology.
- Should a looped rubber *band* be used?

Analysis

You should now have a whole bunch of data, but it needs to be made meaningful. Recall what is you primary goal of this experiment, and plan out how you are going to get there. Some guidance and prompts for discussion are provided below.

Exercise 2

1. You have data sets for strain and displacement,and you should have calibration measurements to convert the measured voltages to the relevant quantities. Your first task will be to examine the tension versus extension at a given temperature.
2. Hopefully, you are confident that you need now investigate the behaviour of the tension versus temperature at given lengths. This task is the crux of the analysis, so be sure to discuss how you plan to do this with a demonstrator before getting too lost in the weeds.
3. What is the entropy change in a rubber band when stretched?
4. Are there any sources of systematic error in this experimental set-up, and how might you predict whether these errors will limit the applicability of your findings to expected theory?
5. A rigorous quantitative analysis of uncertainty for the change in entropy may prove difficult to obtain analytically, but a reasonable attempt can be made based on measurement errors and any possible systematic effects, as well as derived from fits to your data.
6. Is *hysteresis* and the age of the rubber band an important consideration for this experiment? Justify your answer.
7. Discuss why or why not rubber is a suitable material for this experiment. Moreover, interpret of your results in relation to theories of rubber elasticity and crystallisation.

Exercise 3 *Quick and dirty*

You have been looking in detail at what happens when a rubber band is stretched at different temperatures. Let us perform a much simpler experiment: grab a rubber band, hold it on your upper lip (the philtrum and surrounds a quite sensitive to temperature) and rapidly stretch the rubber band. Can you detect a temperature change? How does this compare to your results and subsequent analysis?

References

[1] William H. Cropper. Rudolf clausius and the road to entropy. *American Journal of Physics*, 54(12):1068–1074, 1986.

[2] Wayne M. Saslow. A history of thermodynamics: The missing manual. *Entropy*, 22(1), 2020.

[3] G. Marx, J. Ogborn, and P. Tasnadi. Rubber as a medium for teaching thermodynamics. *European Journal of Physics*, 5(4):232–237, 1984.

[4] Warren Hirsch. Rubber bands, free energy, and le chatelier's principle. *Journal of Chemical Education*, 79(2):200A, 2002.

[5] D. Roundy and M. Rogers. Exploring the thermodynamics of a rubber band. *American Journal of Physics*, 81(1):20–23, 2013.

Appendix