PHYS2020 Lab Report 1

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This investigation aimed at quantitatively expressing the efficiency of the common tipping bird kids toy through heat engine analysis. It was hypothesised that mechanical analysis of the DCM movement within the bird could be substituted into the Clausius-Clapeyron equation in order to derive a value for the temperature difference between the two bulbs, and further the Carnot efficiency of the engine. Subsequently, the procedure outlined that the drinking bird apparatus had a maximum Carnot efficiency of $(2.74 \pm 0.07) * 10^{-3}$. Experimental values for efficiency proved far lower, with $(9.5 \pm 0.2) * 10^{-4}$ and $(1.0 \pm 0.4) * 10^{-4}$ for ethanol and isopropanol respectively. It was hypothesised that increases to the Carnot efficiency, and subsequently the experimental values, would be achieved through both a length increase in the bird's connecting cylinder, resulting in a larger Δz, and by replacing the DCM with a liquid with a larger $\frac{\rho}{\mathcal{L}_{int} P_{int}}$. Despite the small efficiency, the drinking bird proves a valuable real-world resource, being able to estimate relative latent heats, as demonstrated by the $700 \pm 200 kJ/kg$ latent heat of isopropanol, closely mimicking the theoretically accepted value of 666kJ/kg. Additionally, the drinking bird is an effective teaching instrument, demonstrating a heat engine with more complex heat flows, as well as an example of a thermodynamic rebuttal to a 'perpetual motion' claim.

I. INTRODUCTION

It has long been misconstrued that the drinking bird experiment demonstrates the characteristics of a perpetual motion machine. Popularised in the 1940s by chemist Miles V. Sullivan and later refined in the Bell Laboratories, the bird persuades those without backgrounds in physics to believe it can seemingly repeat the process of tipping over to drink from a cup indefinitely [1]. From a thermodynamic perspective, a perpetual drinking bird must create work with no energy input, clearly contradicting the third law of thermodynamics, that energy cannot be created or destroyed. Despite trust in the third law providing a seemingly simple resolution to the perpetual motion claim, the actual thermodynamic processes involved in the drinking bird heat engine are anything but. It was, therefore, the purpose of this investigation to understand the thermodynamic processes involved in the bird heat engine further, evaluate its uses in the bigger picture, and analyse the efficiency of the bird heat engine, simultaneously proposing changes in order to optimise the process.

II. THEORY

A. Heat Engines

In thermodynamics, heat engines are defined as devices in which the thermal energy from a reservoir is converted into mechanical or electrical work [2]. However, this process is not entirely efficient, as seen in Figure 1, part of the thermal energy (Q_h) is dispersed as heat (Q_c) into the environmental cold reservoir due to real-world losses such as noise, friction and heat. We can quantify this efficiency as the ratio between the total thermal energy and the work done by the engine (W).

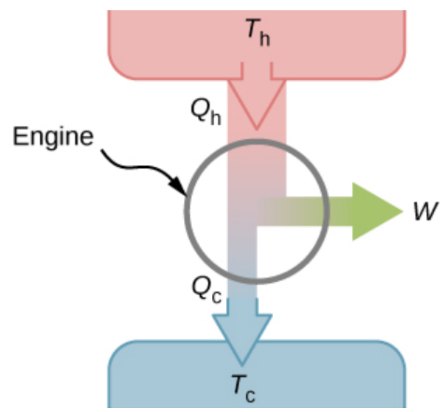

FIG. 1. Diagram depicting the energy flow of a heat engine, with thermal energy (Q_h) being converted into engine work (W) and heat loss (Q_c) [2].

$$\epsilon = \frac{W_{out}}{Q_h} = \frac{W_{out}}{W_{out} + Q_c} \quad (1)$$

Where ϵ is the efficiency of the heat engine. Note that we can rewrite this in terms of the heat loss as Q_h is the sum of the engine work and heat loss. By observation, equation 1 dictates that an engine under these conditions will be completely efficient should all thermal energy be converted to work. Despite this, in 1820 Sadi Carnot derived that heat engines cannot be completely efficient, and are instead bound by the temperature of the hot and cold reservoirs [3]. Within an ideal heat engine. This maximum efficiency is given by the Carnot equation:

$$\epsilon = 1 - \frac{T_c}{T_h} = \frac{T_h}{T_h} - \frac{T_c}{T_h} = \frac{\Delta T}{T_h} (2)$$

B. The Drinking Bird Heat Engine

The heat engine process of the drinking bird is deceivingly complex. As depicted in Figure 2, the drinking bird consists of two glass spheres(1) connected by a hollow cylinder (2). In its resting position, the bottom sphere is half-filled with dichloromethane (DCM)(4), separating the gas in the bottom sphere from that of the cylinder and head. The head sphere is covered with a felt layering (3) with the intended purpose of spreading any liquid "sipped" by the beak across to the rest of the head. The cylinder is situated with a holding axle which is allowed to freely rotate over the base of the bird (5).

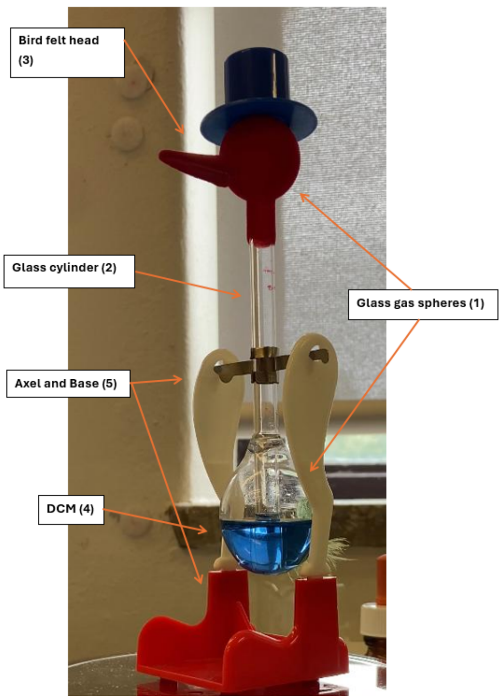

FIG. 2. Labeled diagram depicting the drinking bird heat engine used in the experiment

In this initial position, the system is in thermal equilibrium, with the temperature of the head gas equal to that trapped in the bottom sphere. Before analysing the bird on a thermodynamic scale, the purely mechanical process of the liquid moving can be quantified.

Heating the bottom sphere, or similarly cooling the head, the DCM will begin to rise up the cylinder by some height Δz. Mechanically, the DCM experiences a force downwards due to both gravity and the pressure of the head gas, whilst experiencing an upward force from the base gas. To quantify this we first understand:

$$F = PA \quad and\,thus: \quad P_{base}A = P_{head}A \,+\, \Delta z \rho g$$

Where g is the acceleration due to gravity, A is the cross-sectional area of the cylinder and ρ is the mass density of DCM. Simplifying the pressure difference between the base and head respectively to ΔP we find:

$$\Delta P = -\rho g \Delta z \quad (3)$$

And further, given $W = P\Delta V$ we find:

$$W_{out} = (\frac{1}{2}\rho g \Delta z)(\Delta z A) = \frac{1}{2} p g \Delta z^2 A \quad (4)$$

Thermodynamically, the DCM inside the bird exists in a saturated (vapour pressure) state such that it is in both a gaseous and liquid state, yet the rates of evaporation and condensation are equivalent. Should the temperature of the saturated vapour change, the system will undergo a net evaporation/condensation in order to maintain equilibrium, a process quantified by the Clausius-Clapeyron equation:

$$\frac{dP}{dT} = \frac{\mathcal{L}_{int}}{T\Delta\mathcal{V}}$$

Where $\mathcal{L}_{int}$ is the latent heat of the internal liquid and $\mathcal{V}$ is the difference between the substance liquid and gaseous molar volume. Significantly, the molar volume in the gaseous state is significantly larger than that of the liquid state and thus we can make the following translation:

$$\Delta\mathcal{V} \approx V_g \approx \frac{RT}{P} \quad and\,thus: \quad \frac{dP}{dT} = \frac{\mathcal{L}_{int}P}{RT^2}$$

Solving this differential we find:

$$\Delta P = \frac{\mathcal{L}_{int}P_{int}}{RT^2_{room}}\Delta T$$

Noticing the correlation between this pressure difference, and that derived mechanically, so follows:

$$-\rho g \Delta z = \frac{\mathcal{L}_{int}P_{int}}{RT^2_{room}}\Delta T \quad \rightarrow \quad \Delta T = \frac{-\rho g \Delta z R T^2_{room}}{\mathcal{L}_{int}P_{int}} \quad (5)$$

Before moving to more derivations, the thermodynamic procedure for the bird heat engine must be explored. After moistening the head of the bird with an external liquid of relatively low vaporisation temperature, the liquid spontaneously evaporates, removing with it heat from the bird head equivalent to:

$$Q_{evap} = \frac{m_{ext}}{M_{ext}}\mathcal{L}_{ext} \quad (6)$$

Where m_{ext} is the mass evaporated, M_{ext} is the molar mass and $\mathcal{L}_{ext}$ molar latent heat of vaporisation of the external liquid. Note that the work done to the DCM is a result of energy being drawn from the DCM (heat reservoir) to evaporate the external liquid, and thus Q_{evap} is equivalent to Q_h. Significantly, this removal of heat decreases the temperature of the head gas, which in turn produces a pressure difference between the head and bottom gasses [1]. Further, the pressure difference causes the DCM to rise by a height quantised in equation 3. Commonly used as a refrigerant, DCM has well-documented properties, notably, a latent heat of vaporisation of $29 * 10^3 J/mol$, pressure of $48.7 * 10^3 Pa$ and density of $1322 kg/m^3$ at room temperature [4] [5]. This process continues until the centre of mass is translated so high as to tip the bird over by the weight of the beak, tipping horizontally and opening a channel through the cylinder for the gasses to mix and return to equilibrium, thus restarting the process. The efficiency of this process is quantifiable through a combination of the mechanical work and evaporated heat calculated in equations 4 and 6 respectively, such that:

$$\epsilon = \frac{W}{Q_h} = \frac{W_{out}}{Q_{evap}}$$

III. METHOD

A. Uncertainties

In order to minimise the uncertainty of the final results, it was first observed that there were three significant locations of uncertainty. Firstly, it was identified that in order to proceed with calculations theorised previously, the height to which DCM rose within the bird during the drinking process (Δz) must be estimated. In an attempt to reduce uncertainty, it was concluded that callipers be used to conduct the measurement to an accurate 0.01cm. However, it was not the measuring instrument that would prove a limitation, but rather attempting the measurement whilst the bird was free to oscillate as the oscillating motion after the first dip paired with the limited time to adjust for the measurement was cause for inaccuracy. As such, it was proposed that the bird be kept in a stationary position, with the DCM being allowed to fully rise before all group members individually recorded a measurement for Δz. The average was taken and the uncertainty in the mean would be taken as the uncertainty in the measurement, an uncertainty far larger than the $\pm 0.005 cm$ from the Vernier scale-equipped caliper. Secondly, it was identified that due to the small scale of the external liquid mass being recorded, in addition to the oscillatory movement of the bird engine, large discrepancies in the mass would be encountered despite the digital scale being accurate to 0.001g. The team concluded that the most employable resolution would be to conduct three trials for both the ethanol and isopropanol experiments. Additionally, it was recognised that only for the first oscillation, during which the bird is stationary, would the system perform theoretically with no prior swing to affect the value of Δz at which the bird tips. However, it was concluded that to accurately represent the bird as a real-world heat engine, each trial would allow the bird to oscillate for approximately 10 cycles, off of which average values for Δm would be calculated, with the total uncertainty being that between the trials. Finally, it was observed that the temperature in the room was likely to fluctuate throughout the experiment. As such, despite the uncertainty of the digital thermometer being $\pm 0.05^o C$, it was reasoned by the group that this be raised to $\pm 1^o C = \pm 1K$ accordingly.

B. Apparatus

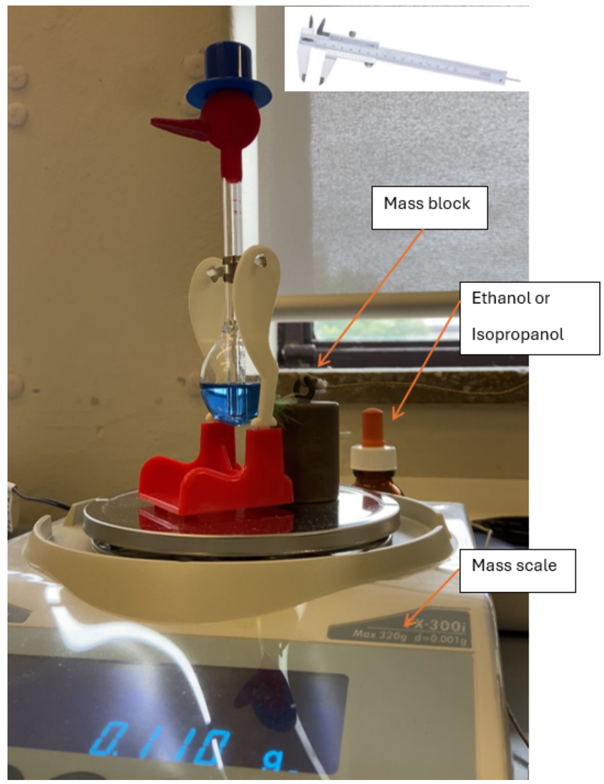

FIG. 3. Diagram depicting the experimental setup of the drinking bird, including blocking mass, external liquid and callipers.

Utilising the drinking bird previously described in Figure 2, the apparatus was situated atop a digital mass scale. Connected by USB, the scale provided its output to a computer, recording measurements every half a second into an Excel spreadsheet. Similarly, a mass block was also placed on the scale, prohibiting the oscillatory motion of the bird, which proved useful in the initial setup to estimate the DCM Δz value. This height was measured using the callipers shown at the top of Figure 3, with an attached Vernier scale of 0.02mm increments. Finally, a pipette was used to accurately place drops of ethanol or isopropanol into the felt head of the bird.

C. Procedure

In order to commence with the derivations observed above, it was recognised that the experimental procedure would need to accurately measure the height to which the DCM rose, the temperature of the room and the external liquid mass over the cycles. Initially, measuring the height to which the DCM rose was achieved by placing a mass block behind the bird, such that it was blocked from tipping. A pipette was then used to place five drops of ethanol onto the felt beak of the bird. The DCM was then left to rise until the system once again reached vapour pressure, at which point the height to which the DCM rose (Δz) was measured. All team members independently measured this value using high-precision callipers to reduce uncertainty as previously discussed. Additionally, a thermometer was present throughout the entire experiment, which was recorded, with slight variations considered in placing an accurate uncertainty. After the measurement was conducted, the system was left to evaporate the remaining ethanol, such that when reset to the initial position (figure 3) within which bulbs are in equilibrium and the DCM is at the lowest point and unmoving. To ensure accurate measurement of a large number of mass readings, the digital scale output was connected to a computer with an open Excel document and zeroed in. The recording was then begun by pressing print on the scales, at which point five drops of ethanol were placed on the bird's beak using a pipette. The bird was allowed to behave just as designed, the DCM rising before tipping and repeating. This process was allowed to continue uninterrupted for approximately 450 seconds, at which point the DCM experienced almost no change in height and the tipping terminated. Print was again pressed on the scale to discontinue mass recording and the bird was manually tipped to ensure equilibrium in the head and bottom bulbs. This process was repeated 3 times to ensure a large quantity of data was collated. Finally, the mass change of isopropanol was recorded, utilising the same process as just outlined, with ethanol substituted for isopropanol. Similarly, three trials were conducted and recorded in an Excel document.

IV. RESULTS

After conducting the initial Δz calliper measurement outlined previously, group members collectively determined an average with respective uncertainty of $(122 \pm 4) * 10^{-3} m$. Significantly, it was realised that this value proved enough to determine an average change in temperature of the internal liquid throughout a cycle, as outlined in equation 5. And thus followed:

$$\Delta T = \frac{-\rho g \Delta z R T_{room}^2}{\mathcal{L}_{int} P_{int}}$$

$$\Delta T = \frac{-1322 * 9.8 * (122 \pm 4) * 10^{-3} * 8.3141 * (295.2 \pm 1)^2}{29 * 10^3 * 48.7 * 10^3}$$

Which with appropriate uncertainty propagation:

$$\delta T = T\sqrt{(2 * \frac{\delta T_{room}}{T_{room}})^2 + (\frac{\delta z}{z})^2}$$

Resulted in $\Delta T = -0.81 \pm 0.03K$. Further, the Carnot equation (2) reveals the maximum efficiency of the drinking bird:

$$\epsilon = \frac{\Delta T}{T_{room}} = \frac{-0.61 \pm 0.02}{295.2} = (2.74 \pm 0.07) * 10^{-3}$$

Following these initial findings, the oscillatory procedure for ethanol was conducted to calculate the experimental efficiency of the drinking bird. The following ethanol mass over time plot was constructed from the experimental data using Excel:

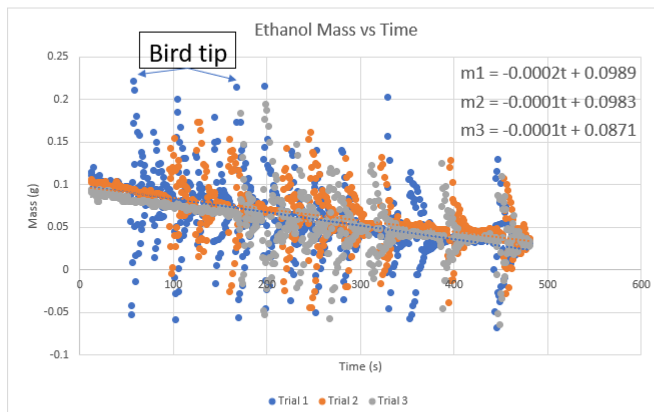

FIG. 4. Results for the three ethanol mass over time trials with respective linear regressions.

As outlined in Figure 4, all trials outline a similar reducing mass trend, with large mass spikes occurring approximately every 20 seconds. It is this oscillation that can be attributed to the tipping of the bird, sending the mass scales to large positive and negative values. However, the trends identified in the equations m_1, m_2 and m_3 show a correlation between the trials. In order to determine an average Δm value, it was first determined that the average change in mass between each cycle would be calculated for each trial, with the average between trials to be taken as the total Δm value. To demonstrate this calculation, first notice that each trial experienced the last bird sip approximately 450 seconds into the experiment. For trial 1, which experienced 13 cycles:

$$\Delta m_1 = \frac{\Delta m_{total}}{N} = -0.007g$$

Where m_{total} is the total change in mass over the 450-second period, and N is the number of cycles. Completing this for each trial, the average can then be constructed:

$$\Delta m_{ethanol} = \frac{\Delta m_1 + \Delta m_2 + \Delta m_3}{3} = -0.0061g$$

With corresponding uncertainty in the average:

$$\delta m_{ethanol} = \frac{\Delta m_{largest} - \Delta m_{smallest}}{2} = -0.001g$$

Thus for ethanol, an average change in mass of $(-0.006 \pm 0.001) * 10^{-3} kg$ was calculated for ethanol per cycle with appropriate significant figures. As was understood from equation 6, the heat lost due to evaporation is equivalent to:

$$Q_{evap} = m_{ext}\mathcal{L}_{ext}$$

Given the scientifically accepted latent heat of vaporisation for ethanol, $846 * 10^3 J/kg$, it was concluded that $5.1 \pm 0.8J$ of energy was used per cycle to evaporate the ethanol. Finally, noticing the connection between the efficiency in equation 1, and the mechanically calculated work in equation 4:

$$\epsilon = \frac{W_{out}}{Q_h} = \frac{\frac{1}{2}\rho g \Delta z^2 A}{Q_{used}} = 0.00095$$

With corresponding uncertainty:

$$\delta\epsilon = \epsilon\sqrt{(2 * \frac{\delta z}{z})^2 + (\frac{\delta A}{A})^2} = 0.00002$$

Thus, using ethanol as the external liquid, the drinking bird had an efficiency of $(9.5 \pm 0.2) * 10^{-4}$. Following the procedure outlined previously, in determining the latent heat of vaporisation of isopropanol, the oscillating drinking bird process was repeated and documented in Figure 5. Before doing so, however, the effective heat capacity of the engine must be estimated in order to calculate a relative latent heat of vaporisation for isopropanol. As outlined in equation 6:

$$C_{eff}\Delta T = \Delta m_{ext}\mathcal{L}_e xt - \Delta m_{int}\mathcal{L}_{int}$$

It was assumed that the mass of the DCM inside would change negligibly with respect to the external, and thus given the mass and mass latent heat of ethanol:

$$C_{eff} = \frac{\Delta m_{ext}\mathcal{L}_{ext}}{\Delta T} = 6266.67J$$

With appropriate uncertainty:

$$\delta C_{eff} = C_{eff}\sqrt{(\frac{\delta m_{ext}}{m_{ext}})^2 + (\frac{\delta T}{T})^2} = 1069.9J$$

Thus, the bird's heat engine has an effective heat capacity of $6 \pm 1kJ$ utilising ethanol as the reference.

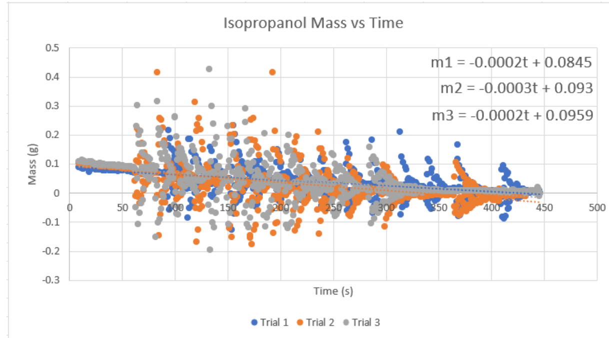

FIG. 5. Results for the three isopropanol mass over time trials with respective linear regressions.

Utilising the same average derivation outlined for the ethanol case, it was observed that $0.007 \pm 0.002kg$ of isopropanol was evaporated per cycle. Thus, given the effective heat capacity of the bird:

$$\mathcal{L}_{iso} = \frac{C_{eff}\Delta T}{\Delta m_{iso}} = 694kJ/kg$$

And uncertainty:

$$\delta\mathcal{L}_{iso} = \mathcal{L}_{iso}\sqrt{(\frac{\delta T}{T})^2 + (\frac{\delta m_{iso}}{m_{iso}})^2 + (\frac{\delta C_{eff}}{C_{eff}})^2} = 200kJ/kg$$

Thus, experimentally it was calculated that isopropanol had a mass latent heat of vaporisation of $700 \pm 200kJ/kg$ relative to the theoretically accepted value of $846kJ/kg$ for ethanol. Finally, the relative efficiency of the heat engine with isopropanol was calculated to be $(1 \pm 0.4) * 10^{-4}$ from the following:

$$\epsilon = \frac{\frac{1}{2}\rho g \Delta z^2 A}{m_{ext}\mathcal{L}_{ext}} \quad \delta\epsilon = \epsilon\sqrt{(2 * \frac{\delta z}{z})^2 + (\frac{\delta A}{A})^2 + (\frac{\delta m_{ext}}{m_{ext}})^2 + (\frac{\delta \mathcal{L}_e xt}{\mathcal{L}_e xt})^2}$$

V. DISCUSSION

Evaluation After first performing a movement-blocked tipping bird experiment, given the height to which the liquid rose, a difference in temperature between the top and bottom gas of $\Delta T = -0.81 \pm 0.03K$ was uncovered. Consultation of the Carnot efficiency found that under these conditions, the bird heat engine possessed a maximum heat efficiency of $(2.74 \pm 0.07) * 10^{-3}$. This result was then experimentally evaluated with ethanol as the external liquid through the procedure identified, which resulted in engine efficiency of $(9.5 \pm 0.2) * 10^{-4}$. Lily M and Yvonne S validate our findings in their 1993 report on the efficiency of the drinking bird, concluding a similar experimental efficiency of $2 * 10^{-4}$ and comparable Carnot efficiency of $11 * 10^{-3}$. Their findings strongly support the method utilised in this report, attaining similar results with a far more accurate setup, for example, thermometers for each bulb as opposed to a calculated value of ΔT.

Further following the procedure, an effective heat capacity for the bird was evaluated using known latent heat values for ethanol. Conducting the same procedure as before to find the mass evaporated, it was calculated that isopropanol had a relative latent heat of $700 \pm 200 kJ/kg$, a value whose bounds fall within the theoretically accepted value of $666 kJ/kg$ [6]. Additionally, calculations using this value satisfied the claim that the engine was extremely inefficient, proposing only $(1.0 \pm 0.4) * 10^{-4}$. Evidently, all trials of ethanol and isopropanol outlined that 99.905% to 99.99% of heat used to evaporate the external liquid was converted into work respectively. Importantly, however, this already low efficiency is capped by a similarly low Carnot efficiency, determining that this particular setup was extremely efficient. In order to increase the efficiency of the drinking bird, it is clear that the difference in temperature between the bottom and head bulbs must be maximised. Given the proportional relationship between the temperature difference and the height to which the DCM rose as outlined in equation 5, this efficiency increase can be achieved by lengthening the cylinder of the bird and thus a larger Δz. Additionally, replacing the internal DCM with a liquid with a higher relative $\frac{\rho}{\mathcal{L}_{int} P_{int}}$ is predicted to similarly increase the Carnot efficiency. Despite the poor efficiency, the drinking bird setup proved effective as a tool to determine relative latent heat values for the external liquid given a known value. This closely ties into the bird's effectiveness as a learning tool, the complex heat transfer from DCM which opposes that of a typical heat engine proves a great test for students' thermodynamic understandings. Additionally, the bird engine provides a clear example of thermodynamics ability to disprove 'perpetual motion' and other such claims, strongly validating the third law of thermodynamics.

VI. CONCLUSION

The aim of the experiment was to quantitatively determine the efficiency of the drinking bird heat engine. Commonly misconstrued as a perpetual motion machine, the report indicates the true thermodynamic processes within the engine, and quantises the extremely low efficiency of the machine, wasting 99.905-99.99% of the thermal energy taken from the DCM reservoir. Carnot efficiency of $(2.74.0 \pm 0.07) * 10^{-3}$ proved to limit the efficiency regardless, outlining that in order to increase the engine efficiency the temperature difference between the head and the bottom bulb must be increased. This is thought to be achieved by either increasing the length of the bird's cylinder, resulting in a higher Δz or replacing the DCM with an internal liquid with a higher $\frac{\rho}{\mathcal{L}_{int} P_{int}}$ value. Despite the inefficiencies, the procedure was effective in predicting the latent heat of vaporisation for isopropanol at $700 \pm 200 kJ/kg$, a range within which the theoretically accepted 666kKJ/kg was contained. Additionally, the drinking bird stands as an effective teaching device for thermodynamics students, detailing the subtly complexity of heat engines with heat flow differing from typical heat engines. Further, the bird provides a direct example of thermodynamics' ability to disprove claims such as perpetual motion.

[1] Mall of Peddlers, The fascinating history of the drinking bird novelty (2024), accessed: 2025-04-03.

[2] OpenStax, *University Physics II - Thermodynamics, Electricity, and Magnetism* (LibreTexts, 2024) Chap. Heat Engines, accessed: 2025-04-03.

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[4] *The Refrigerating Data Book: A Reference Book on Refrigerating, Heat and Power Engineering, Air Conditioning, and Domestic-Commercial Refrigeration*, 3rd ed. (The American Society of Refrigerating Engineers, New York, 1936).

[5] REMPEC – Maritime Integrated Decision Support Information System (MIDSIS-TROCS), Dichloromethane (2024), accessed: 2025-04-03.

[6] N. Oceanic and A. A. (NOAA), Isopropyl alcohol datasheet (2024), accessed: 2025-04-07.