

Thermodynamics of Hurricanes Revisited

Pirooz Mohazzabi, Julia Ann Smith Jones, Andrea Citati

Department of Mathematics and Physics, University of Wisconsin-Parkside, Kenosha, WI
Email: mohazzab@uwp.edu

How to cite this paper: Mohazzabi, P., Jones, J.A.S. and Citati, A. (2022) Thermodynamics of Hurricanes Revisited. *Journal of Applied Mathematics and Physics*, 10, 2508-2515.
<https://doi.org/10.4236/jamp.2022.108169>

Received: July 5, 2022

Accepted: August 23, 2022

Published: August 26, 2022

Copyright © 2022 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Hurricanes and tropical storms are heat engines operating between warm tropical oceans and the cold upper troposphere. The purpose of this article is to examine the existing theories for hurricanes and tropical storms, and to discuss their validity. It is argued that contrary to previous claims that hurricanes are Carnot engines, these systems operate at efficiencies considerably below their maximum thermodynamic efficiency. As such, the validity of the current theories of thermodynamics of hurricanes remains questionable, and the phenomenon continues to be a geophysical enigma.

Keywords

Hurricane, Tropical Cyclone, Thermodynamics, Heat Engine

1. Introduction

Conversion of energy is a process that takes place continuously, either naturally in the universe or artificially by humans on Earth. In stars, for example, nuclear energy is continuously converted into heat and electromagnetic energy through thermonuclear fusion. On Earth, we convert chemical energy into heat and eventually into mechanical energy in internal combustion engines or convert electrical energy into chemical energy by charging batteries. During the process of energy conversion, any form of energy can be completely converted into any other form except when the energy to be converted is heat.

The history of conversion of heat into mechanical energy or work goes back to the invention of the heat engine [1] [2] [3]. Initially, the heat engine concept was to invent a device that would absorb heat from a hot region and convert it all to mechanical work. This idea never worked, and today we know why. According to the second law of thermodynamics, for a heat engine to work it must also be in contact with a cold region so that part of the heat absorbed by the engine from the hot region is rejected to the cold region.

Figure 1 schematically shows a heat engine. The engine is in contact with a hot and a cold region at the same time. Regardless of its internal structure, the engine absorbs some heat Q_H from the hot region at temperature T_H , exhausts part of it Q_C to the cold region at temperature T_C , and converts the difference between the two heats $Q_H - Q_C$ into work W , as shown in **Figure 1**, *i.e.*,

$$W = Q_H - Q_C \quad (1)$$

Therefore, the efficiency of the heat engine, or the fraction of the heat intake that is converted into work, is given by

$$\eta = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H} \quad (2)$$

One of the statements of the second law of thermodynamics is the Clausius inequality [4] [5],

$$dS \geq \frac{dQ}{T} \quad (3)$$

in which dQ is the heat absorbed by a system during a process, T is the absolute temperature of the system, and dS is the change of the entropy of the system. Therefore, for the heat engine shown in **Figure 1**, since the engine absorbs Q_H at the constant temperature T_H and exhausts Q_C at the constant temperature T_C , we have

$$\Delta S \geq \frac{Q_H}{T_H} - \frac{Q_C}{T_C} \quad (4)$$

But since entropy is a state function, in one cycle of the engine, we have $\Delta S = 0$, therefore,

$$\frac{Q_H}{T_H} - \frac{Q_C}{T_C} \leq 0 \quad (5)$$

Since all quantities in this equation are positive, it reduces to

$$\frac{Q_C}{Q_H} \geq \frac{T_C}{T_H} \quad (6)$$

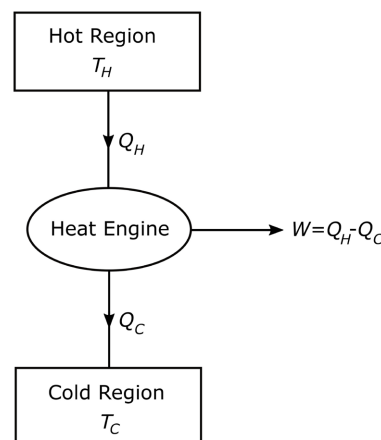


Figure 1. Heat engine.

Multiplying both sides by -1 , and changing the inequality sign, we get

$$-\frac{Q_C}{Q_H} \leq -\frac{T_C}{T_H} \quad (7)$$

Finally, adding a 1 to both sides gives

$$1 - \frac{Q_C}{Q_H} \leq 1 - \frac{T_C}{T_H} \quad (8)$$

Comparing with Equation (2), we have

$$\eta \leq 1 - \frac{T_C}{T_H} \quad (9)$$

Therefore, the second law of thermodynamics sets a maximum efficiency for a heat engine that is given by

$$\eta_{\max} = 1 - \frac{T_C}{T_H} \quad (10)$$

which is only a function of the temperatures of the hot and cold regions, and is independent of the engine's design. We also mention that although we have obtained this maximum efficiency for converting heat into mechanical work, it applies to the conversion of heat to any other form of energy.

A hypothetical thermodynamic process that achieves the maximum thermodynamics efficiency is the Carnot cycle, in which an ideal gas undergoes four reversible processes: an isothermal expansion, an adiabatic expansion, an isothermal compression, and an adiabatic compression [6].

The objective of this article is to examine the validity of the current theories of hurricanes and tropical storms, and whether these systems are in fact Carnot cycles.

2. Hurricane as a Heat Engine

A tropical cyclone is a rotating system of clouds and thunderstorms with a low-pressure center that originates over warm tropical waters, typically when the water temperature is above 26°C - 27°C [7] [8]. Depending on where the tropical cyclone forms, the system has different names. For example, in the Northern Atlantic and Eastern Pacific regions, a tropical cyclone with wind speeds of over 120 km/h is called a hurricane, whereas in the Western Pacific or North Indian Oceans, it is called a typhoon. These systems, which are some of the most violent storms on Earth, are typically between 100 to 2000 km in diameter [8]. The highest hurricane wind speed ever recorded worldwide was 306 km/h (190 mph) during hurricane Camille when it struck the coast of Mississippi in 1969 [9].

Despite numerous articles that have been published over many years on the thermodynamics of hurricanes [10]-[24], some elementary and some advanced, a simple mathematical description is still lacking. Furthermore, despite enormous progress made in investigating hurricanes, many aspects of it still remain poorly understood [25].

A hurricane is essentially a heat engine operating between a warm and a cold region. In 1950, it was realized that the energy source, or the warm region, of a hurricane is the warm waters of tropical oceans [25] [26]. Warm air and moisture rise from the surface of tropical oceans, which results in a low-pressure region. The low-pressure region causes air from the surrounding high-pressure region to move in. Due to the rotation of Earth about its axis, the air that moves toward the low-pressure region experiences a Coriolis acceleration. An object of mass m , moving relative to the surface of Earth, which is a non-inertial frame of reference, experiences a Coriolis force given by [27] [28]

$$F_c = -2m\boldsymbol{\omega} \times \mathbf{v} \quad (11)$$

where $\boldsymbol{\omega}$ is the angular velocity of the rotating Earth, and \mathbf{v} is the velocity of the object relative to the Earth's surface. This force has a component normal to the Earth's surface and a component parallel to it. The normal component usually is very small compared to the weight of the object because the Coriolis force itself is much smaller than the weight of the object, since

$$\frac{F_c}{mg} = \frac{2m\omega v \sin \theta}{mg} \leq \frac{2\omega v}{g} \quad (12)$$

where $g = 9.80 \text{ m/s}^2$ is the acceleration due to gravity at the surface of Earth, and the angular velocity of the rotation of Earth is

$$\omega = \frac{2\pi \text{ rad}}{24 \times 3600 \text{ s}} = 7.272 \times 10^{-5} \frac{\text{rad}}{\text{s}} \quad (13)$$

Therefore, unless the speed of the object is of the order of 67,000 m/s (150,000 mph), the Coriolis force is much smaller than the weight of the object. As a result, the normal component of the Coriolis force either reduces the weight of the object slightly, or is balanced by the normal force from the Earth's surface.

The component of the Coriolis force that is parallel to the surface of Earth, on the other hand, is perpendicular to the velocity vector of the object, pushing the object to the right of its motion in the northern hemisphere, and to the left of its motion in the southern hemisphere. As a result, the air that is moving into the low-pressure region rotates counterclockwise in the northern hemisphere and clockwise in the southern hemisphere, as shown in **Figure 2** [29].

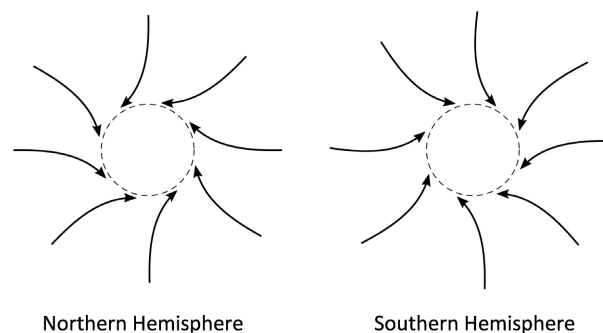


Figure 2. Rotation of a tropical cyclone in the northern and southern hemispheres.

Because the Coriolis force is perpendicular to the Earth's surface at the equator and has no horizontal component, hurricanes and tropical cyclones rarely form at the equator and within $\pm 5^\circ$ latitude [30]. This is also why these systems do not cross the equator [31].

During the formation of a hurricane, the humid air from warm tropical oceans rises to at least 15 km or so [32], which is well past the tropopause. This means that the air passes through temperatures as low as -55°C in the upper part of the troposphere [33]. Therefore, the upper region of the troposphere is the cold region of the hurricane heat engine, where some heat is delivered by the air. Finally, when the storm settles down and calm air replaces it, the cycle of the heat engine is completed.

3. Discussion and Conclusion

Hurricanes and tropical cyclones, in general, are heat engines operating between a warm and a cold region. The warm region is the warm tropical oceans [34] [35] [36] with temperatures of about 27°C (300 K), and the cold region is the upper part of the troposphere with temperatures of about -55°C (218 K). The working system or the engine itself, is the air. Based on these temperatures, the maximum possible thermodynamic efficiency from Equation (10) is about 27%, which is nearly the same as that of a heat engine operating between ice-cold water (273 K) and boiling water (373 K). The thermal energy from the warm ocean converted into mechanical energy becomes the kinetic energy of the air (hurricane wind).

In the theory of hurricanes suggested by Emanuel [35] [37] [38], it is suggested that a hurricane is a Carnot engine. Since a hurricane is not a reversible process, it cannot be a Carnot engine. Furthermore, since a reversible process must run infinitely slowly, hurricanes are not remotely Carnot engines. In fact, it has been shown that the thermodynamic efficiency of tropical cyclones is about 40% lower than the Carnot efficiency [39], or about 16%.

Furthermore, in their approach to the thermodynamics of hurricanes, Bister and Emanuel [21] have assumed that the mechanical work W generated during the process is added to the heat input Q_H . This assumption has been criticized by Makarieva *et al.* [40], who have argued that this assumption is in extreme violation of the first law of thermodynamics. They have also criticized the work of Emanuel on the theory of hurricanes [35], which summarizes much of the previous work, for violation of the second law of thermodynamics as well.

In conclusion, the validity of the current theories of hurricanes is still questionable and the phenomenon itself remains a geophysical enigma [40]. Consequently, the only simple theory that can be asserted with certainty is that a hurricane or tropical cyclone is a heat engine running between a warm and a cold region, in accord with the second law of thermodynamics. The warm region is the tropical ocean and the cold region is the upper part of the troposphere. The engine itself is the air, operating at efficiencies considerably below the maximum thermodynamic limit.

Acknowledgements

This work was supported in part by a URAP grant from the University of Wisconsin-Parkside.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Heat Engines. <https://aether.lbl.gov/www/classes/p10/heat-engine.html#:~:text=The%20first%20recorded%20heat%20engine,James%20Watt%20in%201765%2F1769>
- [2] James Watt. <https://www.britannica.com/biography/James-Watt>
- [3] Timeline of Heat Engine Technology. https://en.wikipedia.org/wiki/Timeline_of_heat_engine_technology\begin{verbatim}#:~:text=1816%20%2D%20Robert%20Stirling%20invented%20Stirling,the%20second%20law%20of%20thermodynamics
- [4] Munster, A. (1970) *Classical Thermodynamics*. Translated by Halberstadt, E.S., Wiley, New York, 16.
- [5] Pippard, A.B. (1966) *Elements of Classical Thermodynamics*. Cambridge University Press, Bentley House, London, 94.
- [6] Callen, H.B. (1985) *Thermodynamics and an Introduction to Thermostatistics*. Second Edition, Wiley, New York, 118-120.
- [7] What Is a Tropical Cyclone? <http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/understanding/tc-info>
- [8] Tropical Cyclone. https://en.wikipedia.org/wiki/Tropical_cyclone
- [9] What Was the Largest Hurricane to Hit the United States? <https://geology.com/hurricanes/largest-hurricane/#:~:text=Hurricane%20Camille%20of%201969%20had,the%20highest%20ever%20recorded%20worldwide>
- [10] Davies, T.V. (1948) Rotatory Flow on the Surface of the Earth—Part I. Cyclostrophic Motion. *Philosophical Magazine*, **39**, 482-491. <https://doi.org/10.1080/14786444808521699>
- [11] Bergeron, T. (1954) The Problem of Tropical Hurricanes. *Quarterly Journal of the Royal Meteorological Society*, **80**, 131-164. <https://doi.org/10.1002/qj.49708034402>
- [12] Ballenzweig, E.M. (1959) Relation of Long-Period Circulation Anomalies to Tropical Storm Formation and Motion. *Journal of Atmospheric Sciences*, **16**, 121-139. [https://doi.org/10.1175/1520-0469\(1959\)016<0121:ROLPCA>2.0.CO;2](https://doi.org/10.1175/1520-0469(1959)016<0121:ROLPCA>2.0.CO;2)
- [13] Kasahara, A. (1961) A Numerical Experiment on the Development of a Tropical Cyclone. *Journal of Meteorology*, **18**, 259-282. [https://doi.org/10.1175/1520-0469\(1961\)018<0259:ANEOTD>2.0.CO;2](https://doi.org/10.1175/1520-0469(1961)018<0259:ANEOTD>2.0.CO;2)
- [14] Abdullah, A.J. (1966) The Spiral Bands of a Hurricane: A Possible Dynamic Explanation. *Journal of Atmospheric Sciences*, **23**, 367-375. [https://doi.org/10.1175/1520-0469\(1966\)023<0367:TSBOAH>2.0.CO;2](https://doi.org/10.1175/1520-0469(1966)023<0367:TSBOAH>2.0.CO;2)
- [15] Anthes, R.A. (1971) A Numerical Model of the Slowly Varying Tropical Cyclone in Isentropic Coordinates. *Monthly Weather Review*, **99**, 617-635.

- [https://doi.org/10.1175/1520-0493\(1971\)099<0617:ANMOTS>2.3.CO;2](https://doi.org/10.1175/1520-0493(1971)099<0617:ANMOTS>2.3.CO;2)
- [16] Arakawa, A. and Schubert, W.H. (1974) Interaction of a Cumulus Cloud Ensemble with the Large-Scale Environment, Part I. *Journal of Atmospheric Sciences*, **31**, 674-701. [https://doi.org/10.1175/1520-0469\(1974\)031<0674:IOACCE>2.0.CO;2](https://doi.org/10.1175/1520-0469(1974)031<0674:IOACCE>2.0.CO;2)
- [17] Emanuel, K.A. (1986) An Air-Sea Interaction Theory for Tropical Cyclones. Part I. *Journal of Atmospheric Sciences*, **42**, 1062-1071. [https://doi.org/10.1175/1520-0469\(1985\)042<1062:FCITPO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1985)042<1062:FCITPO>2.0.CO;2)
- [18] Emanuel, K.A. (1987) The Dependence of Hurricane Intensity on Climate. *Nature*, **326**, 483-485. <https://doi.org/10.1038/326483a0>
- [19] Guinn, T.A. and Schubert, A.W.H. (1993) Hurricane Spiral Bands. *Journal of Atmospheric Sciences*, **50**, 380-3403. [https://doi.org/10.1175/1520-0469\(1993\)050<3380:HSB>2.0.CO;2](https://doi.org/10.1175/1520-0469(1993)050<3380:HSB>2.0.CO;2)
- [20] Bender, M.A., Ginis, I. and Kurihara, Y.Y. (1993) Numerical Simulations of Tropical Cyclone-Ocean Interaction with a High Resolution Coupled Model. *Journal of Geophysical Research*, **98**, 23245-23263. <https://doi.org/10.1029/93JD02370>
- [21] Bister, M. and Emanuel, K.A. (1998) Dissipative Heating and Hurricane Intensity. *Meteorology and Atmospheric Physics*, **50**, 233-240. <https://doi.org/10.1007/BF01030791>
- [22] Emanuel, K.A. (1999) Thermodynamic Control of Hurricane Intensity. *Nature*, **401**, 665-669. <https://doi.org/10.1038/44326>
- [23] Moller, J.D. and Montgomery, M.T. (2000) Tropical Cyclone Evolution via Potential Vorticity Anomalies in a Three-Dimensional Balance Model. *Journal of Atmospheric Sciences*, **57**, 3366-3387. [https://doi.org/10.1175/1520-0469\(2000\)057<3366:TCEVPV>2.0.CO;2](https://doi.org/10.1175/1520-0469(2000)057<3366:TCEVPV>2.0.CO;2)
- [24] Liu, C., Liu, Y., Luo, Z., Lei, X., Wang, D. and Zhou, X. (2011) Studies of the Hurricane Evolution Based on Modern Thermodynamics. https://publication/221912113_Studies_of_the_Hurricane_Evolution_Based_on_Modern_Thermodynamics
- [25] Emanuel, K. (2011) Hurricanes: A Century of Scientific Progress. <http://texmex.mit.edu/pub/emanuel/PAPERS/Simpson.pdf>
- [26] Riehl, H. (1950) A Model for Hurricane Formation. *Journal of Applied Physics*, **21**, 917-925. <https://doi.org/10.1063/1.1699784>
- [27] Fowles, G.R. and Cassiday, G.L. (1999) Analytical Mechanics. Sixth Edition, Saunders College Publishing, New York, 181-182.
- [28] Coriolis Force. https://en.wikipedia.org/wiki/Coriolis_force
- [29] Here's Why Hurricanes Spin Counterclockwise in the North. <https://www.cNBC.com/2016/10/07/heres-why-hurricanes-spin-counterclockwise-in-the-north.html>
- [30] Reply to Ask-an-Earthy-Scientist. <https://www.soest.hawaii.edu/GG/ASK/hurricanes.html#:~:text=Observations%20how%20that%20no%20hurricanes,can't%20get%20a%20storm>
- [31] Why Don't Hurricanes Cross the Equator. <https://lisbdnet.com/why-dont-hurricanes-cross-the-equator/#:~:text=Hurricanes%20and%20cyclones%20can't,storm%20to%20cross%20the%20equator>
- [32] How Does a Hurricane Form? <https://scijinks.gov/hurricane/#:~:text=When%20the%20wind%20speeds%20reach%2074%20mph%2C%20the%20storm%20is,5%20to%2030%20miles%20wide>
- [33] Temperature in the Atmosphere.

<https://www.cliffsnotes.com/study-guides/earth-science/weather/temperature-in-the-atmosphere>

- [34] Holland, G.J. (1997) The Maximum Potential Intensity of Tropical Cyclones. *Journal of Atmospheric Sciences*, **54**, 2519-2541. [https://doi.org/10.1175/1520-0469\(1997\)054<2519:TMPIOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1997)054<2519:TMPIOT>2.0.CO;2)
- [35] Emanuel, K.A. (1991) The Theory of Hurricanes. *Annual Review of Fluid Mechanics*, **23**, 179-196. <https://doi.org/10.1146/annurev.fl.23.010191.001143>
- [36] Emanuel, K.A. (2006) Hurricanes: Tempests in a Greenhouse. *Physics Today*, **59**, 74-75. <https://doi.org/10.1063/1.2349743>
- [37] Emanuel, K.A. Hurricane Physics. <https://www3.nd.edu/~its/Emanuel.pdf>
- [38] Emanuel, K.A. (1986) An Air-Sea Interaction Theory for Tropical Cyclones. Part I. *Journal of Atmospheric Sciences*, **43**, 585-604. [https://doi.org/10.1175/1520-0469\(1986\)043<0585:AASITF>2.0.CO;2](https://doi.org/10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2)
- [39] Ozawa, H. and Shimokawa, S. (2015) Thermodynamics of a Tropical Cyclone: Generation and Dissipation of Mechanical Energy in a Self-Driven Convection System. *Tellus A: Dynamic Meteorology and Oceanography*, **67**, Article No. 24216. <https://doi.org/10.3402/tellusa.v67.24216>
- [40] Makarieva, A.M., Gorshkov, V.G. and Li, B.-L. (2008) On the Validity of Representing Hurricanes as Carnot Heat Engine. *Atmospheric Chemistry and Physics, Discussions*, **8**, 17423-17437. <https://doi.org/10.5194/acpd-8-17423-2008>