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A Novel ”Positive” Approach/analysis for Enhanced Understanding of the ”Negative” Statement of the Second Law of Thermodynamics for Heat Pumps

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Abstract

According to the Clausius statement of the second law of Thermodynamics, "It is impossible to construct a device that will operate in a cycle and produce no effect other than the transfer of heat from a cooler body to a hotter body." Although this negative statement cannot be "proved", it is however accepted because no experiment has ever contradicted it. Thus, this statement is taken as an axiom which is then used to prove different theorems related to the efficiency of reversible heat engine and refrigerator cycles operating between two thermal reservoirs. A well-known example of such a theorem is the following important proposition regarding the efficiency of a reversible cycle: "It is impossible to construct a refrigerator or heat pump that operates between two given reservoirs and is more efficient than a reversible refrigerator/heat pump operating between the same two reservoirs."

Many engineering/engineering technology students taking Thermodynamics for the first time find it very difficult to appreciate the true meaning and profundity of this apparently simple statement. This is largely because the student needs to "accept" as true this negative statement right at the outset of his/her study of the second law, without being offered any "positive" explanations or supporting reasons. This might explain why many students end up considering the fascinating course of Thermodynamics, which is deeply philosophical as well as intensely pragmatic at once, as a "difficult" subject.

To alleviate this difficulty, we have taken a novel approach to enable the student to properly understand the negative statement related to heat pumps/refrigerators in a more "positive" manner. We commence the analysis by constructing several thermodynamic cycles using an ideal gas as the working substance and consisting of both reversible and irreversible processes. The working substance in all these cycles interacts with only two thermal reservoirs at two different temperatures, as required by the Clausius statement. It is then shown conclusively that not a single such cycle can be designed or constructed which will have the sole effect of transferring heat from the low temperature to the high temperature reservoir.

We wish to emphasize that this is by no means a "proof" of the negative Clausius statement of the second law. However, we believe and hope that the analysis presented in this article will offer an expedient tool for enabling the struggling student to properly understand the negative statement and comfortably transition to studying the subsequent theorems, corollaries, and practical applications of the second law of Thermodynamics.

1. **Introduction**

Thermodynamics is a core course for the majority of engineering majors - mechanical, chemical, civil and electrical, as well as for students majoring in engineering technology (ET), physics and chemistry, with varying coverage breadth and depth. In ET and engineering, students are exposed to thermodynamics relatively early in their study, and they often consider it a difficult course. Thermodynamics has been described as a gateway course [1] in mechanical engineering, which means that students' performance in thermodynamics correlates well with how students do in the rest of the courses in the curriculum. Thermodynamics is considered to be one of the most difficult and abstract disciplines of the physical sciences [2]. Several studies have reported that students' frustration and dissatisfaction with thermodynamics stemming from their lack of understanding are very common [3-5].

Thermodynamics is regarded by many undergraduate students as a difficult topic, packed as it is with abstract concepts and complicated equations. The traditional way of teaching the subject is heavily focused on mathematical deductions and does not promote deep understanding. As a result, thermodynamics students have largely settled for merely reproducing calculations to pass their exams [6]. Conceptual understanding must therefore be promoted to attain real academic success. Atarés et al. [6] presented a review in which they discussed difficulties experienced by undergraduate students in understanding the second law of thermodynamics (2LT) and entropy in introductory thermodynamics courses. They classified these difficulties into three groups: disregarding conceptual understanding, the inherent difficulties of the concepts, and the difficulties related to the student's previous knowledge. The authors proposed some guidelines on suitable teaching practices for instructors, including different sequencing of the introduction of concepts and addressing misconceptions for students to understand 2LT and entropy qualitatively.

Kesidou and Duit [7] conducted thirty-four clinical interviews with high school students (15- 16 years old) who had received four years of physics instruction. The results of the study revealed students' severe difficulties in learning concepts related to energy, the particle model, and the distinction between heat and temperature. Again, students' qualitative conceptions of and their explanations of irreversibility and 2LT showed significant lack of intuitive understanding. The authors observed that merely enlarging the traditional physics curriculum by adding ideas of 2LT would not be sufficient to familiarize students with these ideas. A totally new teaching approach to heat, temperature, and energy would be necessary. They also suggested that basic qualitative ideas related to 2LT should be a central and integral part of the instruction from early on.

Engineering students' difficulties in learning thermodynamics occur worldwide as indicated by the literature. Mulop et al. [8] reviewed and analyzed different approaches taken toward helping students learn Thermodynamics. They discussed efforts made to overcome the deficiencies as well as various teaching approaches meant to enhance students' learning of Thermodynamics. These approaches included blended learning, active learning techniques, computer-based instruction, and virtual lab – a web-based student learning tool for thermodynamic concepts related to multi-staging in compressors and turbines. TESTTM software used in design projects and laboratory was also briefly discussed. The authors used the characteristics of the learning systems, their effectiveness based on students' performance, student skills developed using the learning systems, and student feedback as their comparison criteria. Most of the methods reviewed used computer technology and multimedia to provide interactivity and visualization. Most of these methods were found to improve student performance and help develop their skills. Overall, student feedback and comments were positive and encouraging.

Engineering students often face difficulties comprehending the first and second laws (Meltzer [9]), particularly the concepts of heat, work, and cyclic processes. According to Meltzer, students are also largely unfamiliar and uncomfortable with the need to provide explanations and reasoning in problem solving. Homework and classroom problems typically require students to calculate numerical values and rarely ask students to connect their answers to conceptual understanding, or to reflect on their implications. Thus, being able to solve textbook problems may not necessarily indicate deep learning of the subject matter.

Senior high school students routinely confuse the concepts of quality and quantity of energy (Ben-Zvi [10]). "Concept inventories" have been widely used in gauging students' conceptual understanding in engineering education. In thermodynamics, concept inventories that focused on the properties and behavior of matter, work, heat and 1LT and 2LT were described by Midkiff et al. [11]. Real-life examples, hands-on experiments and projects have been used to help students in grasping abstract ideas in thermodynamics, and to connect them to physical hardware. Flotterud et al.[12] described a micro-combined heat and power system, sized for residential distributed power generation that was used in laboratory experiments to apply 1LT and 2LT. These real-life experiments were found to enhance students' learning of some thermodynamics principles. Mettes et al. [13] stressed the need for an orienting basis for students to be able to absorb new knowledge for the first time, and then to apply it in problem solving. Haber-Schaim [14] stressed the importance of establishing a practical need for a new term before the term is introduced. This way the terms would have an operational meaning, and would be better integrated with the student's natural vocabulary.

Dukhan [15] attempted to systematically describe and categorize learning difficulties experienced by engineering students taking a first course in thermodynamics. Two major root causes for these issues were identified: conceptual difficulties and the inability of students to recall and integrate relevant knowledge to solve thermodynamic problems. The literature and the related statistics pointed to the continued poor learning/performance of engineering students in thermodynamics. The author suggests that the summarized solutions [15], have either not worked, or have worked only partially. The lack of visible improvement in student comprehension (at the national level) implies that these solutions have not accounted for the nature and root causes of thermodynamic learning issues. This also suggests that without addressing these root causes, it would be difficult, if not impossible, to minimize these problems, as well as to guiding a didactic approach for curriculum and textbook design and new instructional strategies.

Mehendale [16] presented a hands-on assignment to help engineering/engineering technology students better understand the Kelvin-Planck (KP) statement of the second law of Thermodynamics.

To find out if this difficulty experienced in understanding the second law (in particular, the Clausius statement of the second law) is indeed common to many students or not, the present author conducted a survey. Both undergraduate and graduate students were surveyed. All of these students have already taken at least one course in undergraduate Thermodynamics. The survey in the form of a printout was shared with the undergraduate students in class, and collected later. The same survey was emailed to the graduate students, and their responses were emailed back to the author. The survey included the following text and questions:

Background:

According to the first law of thermodynamics for a cycle, the net heat absorbed in the cycle equals the net work produced by the cycle.

According to the Clausius statement of the second law of Thermodynamics, “It is **impossible** to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a cooler body to a warmer body.”

Thus, the first law is a **<u>positive</u>** statement, and the second law is a **<u>negative</u>** statement.

<u>Survey</u>:

1. In general, positive statements are inherently easier to understand compared to negative statements.

YES

NO

2. I think a hands-on assignment to help students understand that the second law is not violated will be very helpful in enhanced understanding of the second law.

YES

NO

The survey responses to these questions are summarized in Figure 1 below.

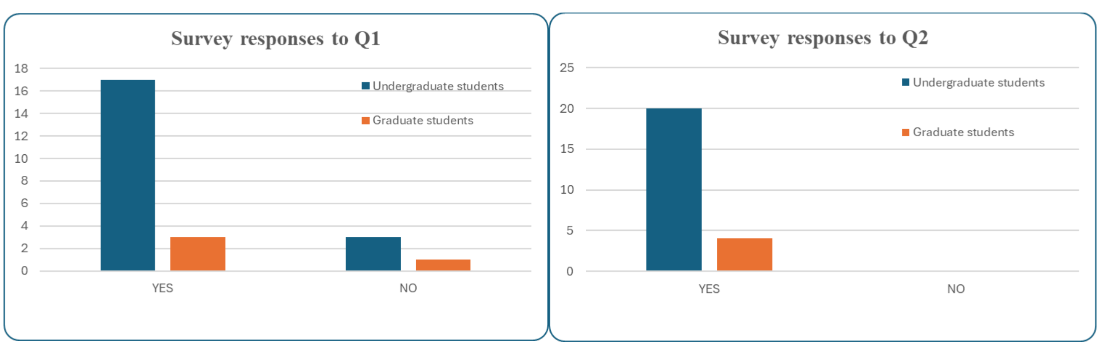


Figure 1 Summary of survey responses

It is seen that 85% of the surveyed undergraduate students and 75% of the surveyed graduate students responded YES to Q1, while 100% of the students responded YES to Q2. Thus, we are confident that the hands-on assignment created in this work will be helpful to students in achieving a deeper understanding of the second law of Thermodynamics, and particularly of the Clausius statement of the second law.

2. **Current Research**

The first law of Thermodynamics (1LT) is basically a statement of the conservation of energy. It states that when a system undergoes a cycle, the cyclic integral of the heat transfer equals the cyclic integral of the work. The first law, however, does not restrict the direction of heat and work flows in a cycle. Not only does it allow a cycle in which heat is transferred from the system and an equal amount of work is done on the system – it also permits a cycle in which heat is transferred to the system and an equal amount of work is done by the system.

However, experience teaches us that there is no guarantee that a proposed cycle that satisfies the first law will actually occur. This is where the second law of Thermodynamics (2LT) fills the gap, by pointing out that although heat and work are both forms of energy transfer, they are inherently different in quality or grade. The second law imposes directional limits on processes, and hence, cycles, which are composed of two or more processes. It acknowledges that processes can proceed only in a certain direction but not in the reverse manner. A common experience of this kind is that a hot cup of tea cools by transferring heat to its cooler surroundings, but the reverse process – the tea getting hotter by heat flowing into it from the surroundings – will not occur by itself. Many such familiar observations attest to the validity of 2LT. The ideas expressed in the second law not only offer deep insight into the way nature works, but also provide the foundation for understanding humanity's energy supply problems.

The Clausius statement of the second Law of Thermodynamics is a fundamental principle which imposes constraints on the direction of heat and work flow in the operation of while designing any thermodynamic cycle or device. As discussed earlier, Thermodynamics students often find it difficult to correctly understand the negative Clausius statement of the second law, because negative statements are inherently more difficult to grasp and apply as opposed to positive statements. The fact that this is a genuine difficulty has come up repeatedly during the author's conversations with both ME and MET students who are current as well as former students of Thermodynamics. Please see the above survey and the associated results reported above. Without any exception, when the author discussed the proposed hands-on activity with his students, they were highly enthusiastic about such a learning exercise being available to them. In their opinion, such a tool would go a long way in enabling a much clearer comprehension of the Clausius statement of the second law of Thermodynamics. As discussed above, a study of the relevant literature reveals that practically no strategies have been considered to help students understand the negative Clausius statement of the 2LT in a more "positive" manner.

3. Method: Hands-on Assignment/Learning Exercise:

To help students better understand the significance of the Clausius statement, the following "positive" hands-on activity/exercise is proposed. The hands-on exercise should be given as an in-class assignment directly after the Clausius statement has been discussed in class. One possible way the assignment could be presented is as follows:

Three thermodynamic cycles (only three cycles are shown here for illustrative purposes, but the instructor can provide more cycles in the assignment at their discretion) are constructed such that they exchange heat with only two isothermal energy reservoirs R_H and R_L at temperatures $T_H > T_L$, and T_L, respectively, as required by the Clausius statement. Furthermore, the system is taken to be 1 kg of an ideal gas operating in a piston-cylinder assembly.

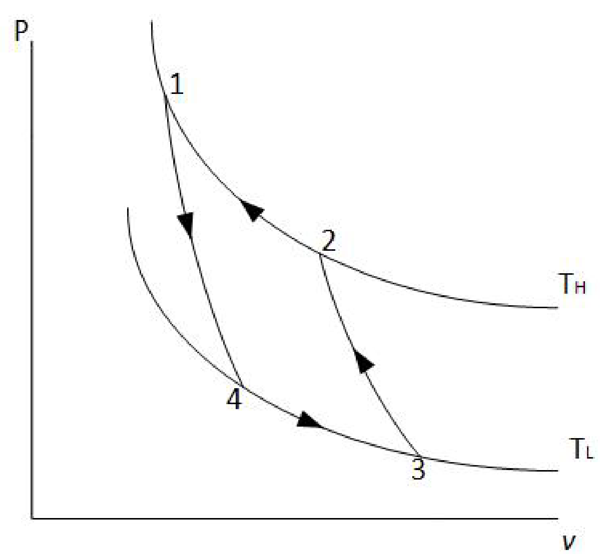
Analyze each cycle process-by-process to determine if (a) the cycle is even possible or not. (NOTE: If even a single process is not possible, the cycle will be impossible to design/construct.) (b) If all processes are possible, then the cycle is possible, and your next step is to assess whether the cycle violates the Clausius statement or not. (NOTE: The Clausius statement will be violated if the sole effect of the cycle is to transfer heat from R_L to R_H. The complete student assignment is available in Appendix 1.

4. Discussion:

As discussed in the following, this activity will of course ultimately be helpful for the students to properly understand the negative Clausius statement. Additionally, during the exercise, students will also have the opportunity to clarify/reinforce concepts which they have already been exposed to. These concepts include correctly applying the first law to processes, and calculating the associated heat, work, and internal energy changes. Students will also be challenged to apply their understanding to determine if a particular process must necessarily be reversible, or irreversible, or whether it can be of either type.

CYCLE 1:

As shown in Fig. 2, Cycle 1 (2-1-4-3-2-1) comprises four processes, which are analyzed below.



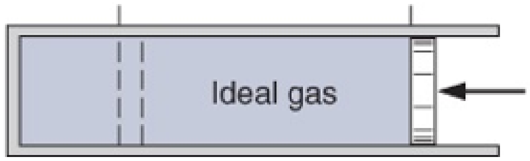


Figure 2 Cycle 1

Let us first consider Process 2→1: The ideal gas undergoes an isothermal compression from V_2 to V_1 during which the working substance rejects heat to reservoir R_H and absorbs work from the surroundings. Since the system must reject heat to R_H, it must be at a temperature $T_H + \Delta T$, where $\Delta T \geq 0$. This process can be performed reversibly or irreversibly. However, for simplicity, we consider this as a reversible process, which implies that $\Delta T \rightarrow 0$. Thus, this process is possible.

The first law of thermodynamics as applied to a closed system is $q_H = w_H + \Delta u$, where q (J/kg) is the heat transfer to or from the system, w (J/kg) is the work done by or on the system, and u (J/kg) represents the internal energy of the system. Since process 2→1 is isothermal, and for an ideal gas, $u = u(T), u_1 = u_2, i.e. \Delta u = 0$, and $q_H = w_H$. Since for a reversible isothermal process executed by an ideal gas, $w_H = RT_H ln\left(\frac{v_1}{v_2}\right) < 0$, where R represents the gas constant for the ideal gas (J.kg^{-1}.K^{-1}), we see that the heat transfer and the work in process 2→1 are both negative.

Process 1→4: The ideal gas undergoes an adiabatic expansion from V_1 to V_4 during which the working substance does work on the surroundings and cools down from T_H to T_L. Again, this process can be performed either reversibly or irreversibly. However, for simplicity, we consider this to be a reversible process. Thus, this process is possible, and $w_{1-4} = R\left(\frac{T_H - T_L}{k-1}\right)$, where $k = \frac{C_{p0}}{C_{v0}}$, the ratio of the specific heats of the ideal gas. It is thus seen that $w_{1-4} > 0$.

Process 4→3: The ideal gas undergoes an isothermal expansion from V_4 to V_3 during which the working substance absorbs heat from reservoir R_L and does work on the surroundings. Since the system must absorb heat from R_L, it must be at a temperature $T_L - \Delta T$, where $\Delta T \geq 0$. This process also can be performed either reversibly or irreversibly. However, for simplicity, we consider this as a reversible process, which implies that $\Delta T \rightarrow 0$. Thus, this process is possible.

The first law of thermodynamics as applied to a closed system is $q_L = w_L + \Delta u$. Since process 4→3 is isothermal, and for an ideal gas, $u = u(T), u_3 = u_4, i.e. \Delta u = 0$, and $q_L = w_L$. Since for a reversible isothermal process executed by an ideal gas, $w_L = RT_L ln\left(\frac{v_3}{v_4}\right) < 0$, we see that the heat transfer and the work in process 4→3 are both positive.

Process 3→2: The ideal gas undergoes an adiabatic compression from V_3 to V_2 during which the working substance absorbs work from the surroundings and heats up from T_L to T_H. Again, this process can be performed either reversibly or irreversibly, and we have considered this to be a reversible process. Thus, this process is possible, and $w_{3-2} = R\left(\frac{T_L - T_H}{k-1}\right)$, where k is the ratio of the specific heats of the ideal gas. It is thus seen that $w_{3-2} < 0$.

Overall analysis of cycle 1:

From the above equations, it is clear that $w_{3-2} = -w_{1-4}$. Thus, the net work of this cycle is $w_{net} = w_{2-1} + w_{4-3} = RT_H ln\left(\frac{v_1}{v_2}\right) + RT_L ln\left(\frac{v_3}{v_4}\right)$. It can also be shown that $\frac{v_3}{v_4} = \frac{v_2}{v_1}$. Hence, $w_{net} = RT_H ln\left(\frac{v_1}{v_2}\right) + RT_L ln\left(\frac{v_2}{v_1}\right) = R(T_L - T_H)ln\left(\frac{v_2}{v_1}\right) < 0$. In other words, a net absorption of work is required to transfer heat from reservoir R_L to reservoir R_H.

This can also be seen to be the net area (negative) enclosed by the cycle. (this is the "other" effect referred to in the Clausius statement!)

Thus, not only is each process possible (and hence, the whole cycle is possible), it also does not violate the Clausius statement of 2LT!

CYCLE 2:

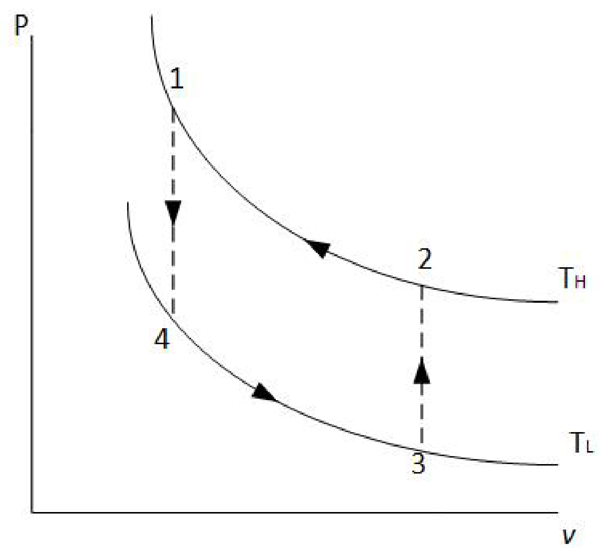


Figure 3 Cycle 2

As shown in Fig. 3, Cycle 2 (2-1-4-3-2-1) consists of four processes, which are analyzed below.

<u>Process 2→1</u>: Similar to Cycle 1, the ideal gas undergoes an isothermal compression from V_2 to V_1 during which the working substance rejects heat to reservoir R_H and absorbs work from the surroundings. Following the same logic as for process 2→1 in cycle 1, process 2→1 in cycle 2 can be reversible or irreversible. However, for simplicity, we again consider this to be a reversible process, which implies that $\Delta T \rightarrow 0$. Thus, this process is possible.

The first law of thermodynamics as applied to a closed system is $q_H = w_H + \Delta u$. Since process 2→1 is isothermal, and for an ideal gas, $u = u(T), u_1 = u_2, i.e. \Delta u = 0$, and $q_H = w_H$. Since for a reversible isothermal process executed by an ideal gas, $w_H = RT_H ln\left(\frac{v_1}{v_2}\right) < 0$, we see that the heat transfer and the work in process <u>2→1 are both negative</u>.

Process 1→4: The ideal gas undergoes isochoric (constant volume) cooling from V_1 to V_4 during which the gas cools down from T_H to T_L by rejecting heat to R_L, and no work is done since the process is at constant volume. It is essential to notice that this process is necessarily irreversible, as the ideal gas loses heat at temperatures ranging from T_H to T_L, and the heat transfer thus occurs through a finite temperature difference. In this process, $q_{1-4} = u_4 - u_1 = C_{v0}(T_L - T_H)$. Thus, this process is possible.

Process 4→3: The ideal gas undergoes an isothermal expansion from V_4 to V_3 during which the working substance absorbs heat from reservoir R_L and does work on the surroundings. Since the system must absorb heat from R_L, it must be at a temperature $T_L - \Delta T$, where $\Delta T \geq 0$. This process also can be performed either reversibly or irreversibly. However, for simplicity, we consider this as a reversible process, which implies that $\Delta T \to 0$. Thus, this process is possible.

The first law of thermodynamics as applied to a closed system is $q_L = w_L + \Delta u$. Since process 4→3 is isothermal, and for an ideal gas, $u = u(T)$, $u_3 = u_4, i.e. \Delta u = 0$, and $q_L = w_L$. Since for a reversible isothermal process executed by an ideal gas, $w_L = RT_L ln\left(\frac{v_3}{v_4}\right) < 0$, we have additional confirmation that the heat transfer and the work in process 4→3 are both positive.

Process 3→2: The ideal gas undergoes isochoric heating from V_3 to V_2 during which the gas heats up from T_L to T_H by absorbing heat from R_H, and no work is done since the process is a constant volume one. It is essential to notice that this process is necessarily irreversible, as the ideal gas absorbs heat at temperatures ranging from T_L to T_H, and the heat transfer thus occurs through a finite temperature difference. This is why process 3→2 as well as process 1→4 are shown by dashed lines. In this process, $q_{3-2} = u_2 - u_3 = C_{v0}(T_H - T_L)$. Thus, this process is possible.

Overall analysis of cycle 2:

From the above equations, it is clear that the net work of this cycle is $w_{net} = w_{2-1} + w_{4-3} = RT_H ln\left(\frac{v_1}{v_2}\right) + RT_L ln\left(\frac{v_3}{v_4}\right)$. It is also clear from the *P*-*v* diagram that $\frac{v_3}{v_4} = \frac{v_2}{v_1}$. Hence,

$$w_{net} = RT_H ln\left(\frac{v_1}{v_2}\right) + RT_L ln\left(\frac{v_2}{v_1}\right) = R(T_L - T_H) ln\left(\frac{v_2}{v_1}\right) < 0$$

In other words, a net absorption of external work is required to transfer heat from reservoir R_L to reservoir R_H. It is important to notice that this net work is also represented by the net area (negative) enclosed by the cycle, even though processes 1→4 and 3→2 are both irreversible. (this is the "other" effect referred to in the Clausius statement of the second law of Thermodynamics!). Thus, not only is each process in this cycle possible (thus making the whole cycle possible), but it also does not violate the Clausius statement of 2LT!

CYCLE 3:

As shown in Fig. 4, Cycle 3 (2-1-4-3-2-1) comprises four processes, which are analyzed below.

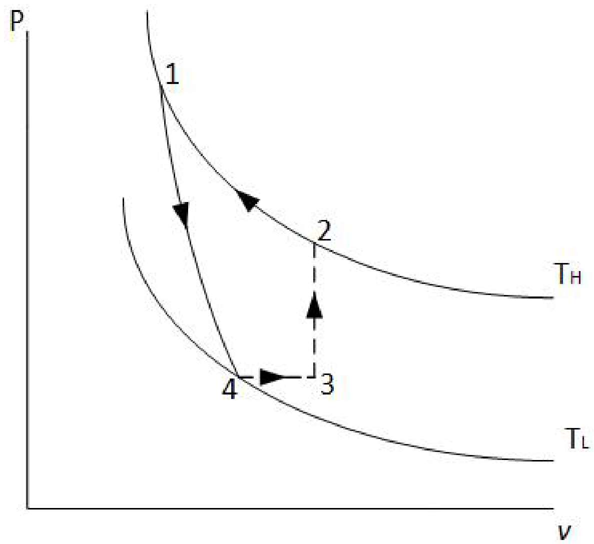


Figure 4 Cycle 3

Process 2→1: Similar to Cycles 1 and 2, the ideal gas undergoes an isothermal compression from V_2 to V_1 during which the working substance rejects heat to reservoir R_H and absorbs work from the surroundings. Following the same logic as for process 2→1 in cycles 1 and 2, process 2→1 in cycle 3 can be either reversible or irreversible. However, for simplicity, we again consider this to be a reversible process, which implies that $\Delta T \to 0$. Thus, this process is possible.

The first law of thermodynamics as applied to a closed system is $q_H = w_H + \Delta u$. Since process 2→1 is isothermal, and for an ideal gas, $u = u(T)$, $u_1 = u_2, i.e. \Delta u = 0$, and $q_H = w_H$. Since for a reversible isothermal process executed by an ideal gas, $w_H = RT_H ln\left(\frac{v_1}{v_2}\right) < 0$, we see that the heat transfer and the work in process 2→1 are both negative.

Process 1→4: The ideal gas undergoes an adiabatic expansion from V_1 to V_4 during which the working substance does work on the surroundings and cools down from T_H to T_L. Again, this process can be performed either reversibly or irreversibly. However, for simplicity, we consider this to be a reversible process. Thus, this process is possible, and $w_{1-4} = R\left(\frac{T_H - T_L}{k-1}\right)$, where $k = \frac{C_{p0}}{C_{v0}}$, the ratio of the specific heats of the ideal gas. It is thus seen that $w_{1-4} > 0$.

Process 4→3: Constant pressure heat absorption/isobaric heating

In this process, the ideal gas is heated from $T_4 = T_L$ to T_3 by absorbing heat at constant pressure. Since the gas needs to absorb heat in this process, it must necessarily interact only with the reservoir R_H in this process. Since this process thus involves heat transfer driven by a finite temperature difference, process 4→3 must be irreversible, and this is indicated by showing the process by a dashed line in Figure 4. This also means that although $P_3 = P_4$, since process 4→3 is irreversible, we really do cannot say that the pressure of the ideal gas at every intermediate state between 4 and 3 is equal to $P_3 = P_4$. Hence, we cannot calculate the actual work w_{4-3} done in this irreversible process. However, for a reversible isobaric process from 4 to 3, since the work of a reversible expansion between two states will always exceed that of an irreversible expansion between the same to states, we can write: $w_{4-3,max} = R(T_3 - T_L)$, and $\Delta u_{4-3} = C_{v0}(T_3 - T_L)$. The first law of thermodynamics as applied to this closed system process then gives $q_{4-3,max} = w_{4-3,max} + \Delta u_{4-3} = R(T_3 - T_L) + C_{v0}(T_3 - T_L) = C_{p0}(T_3 - T_L)$. Thus, we see that the maximum (reversible) heat transfer and the maximum (reversible) work in process 4→3 are both positive, as expected.

Process 3→2: Isochoric heating

During this process, the working substance undergoes a constant volume heat absorption, therefore making it necessary that the system exchange heat only with reservoir R_H. Since this process involves heat transfer driven by a finite temperature difference, it must be irreversible, which is indicated by a dashed line in Figure 4. Since the volume remains constant in the proves, the work is zero, and $\Delta u_{3-2} = C_{v0}(T_H - T_3)$. Hence, from the first law of Thermodynamics applied to process 3→2, $q_{4-3} = \Delta u_{3-2} = C_{v0}(T_H - T_3)$.

Overall analysis of cycle 3:

From the above equations, the net work of this cycle (i.e., the net work produced by the cycle) is $w_{net} = w_{1-4} + w_{4-3} + w_{2-1}$. Hence, considering the above discussion in connection with the reversibility of process 4→3, we can write $w_{net,max} = w_{1-4} + w_{4-3,max} + w_{2-1} = R\left(\frac{T_H - T_L}{k-1}\right) + R(T_3 - T_L) + RT_H ln\left(\frac{v_1}{v_2}\right)$. The above expression for the maximum possible cycle work $w_{net,max}$, it is not very obvious whether this quantity is positive or negative. However, this becomes very clear by relating the various work terms in the equation to areas on the $P - v$ diagram of cycle 3 shown below in Fig. 5.

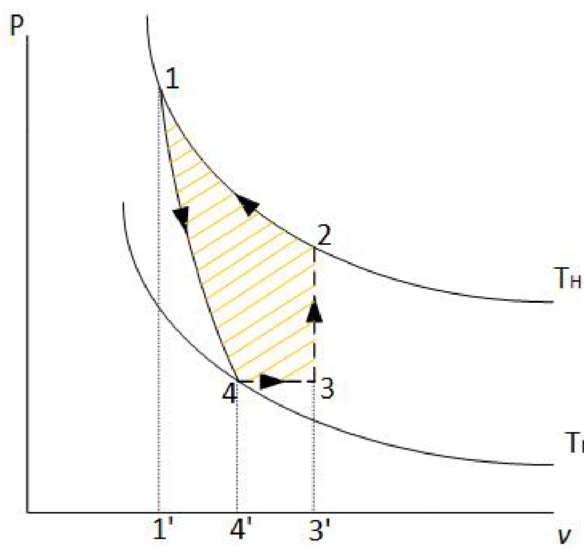


Figure 5 Net work of cycle 3

$$w_{net,max} = w_{1-4} + w_{4-3,max} + w_{2-1}$$

Since process 1→4 is reversible, w_{1-4} is represented by area 1-1´-4´-4-1 in Figure 5. This area is positive. $w_{4-3,max}$ is represented by area 4-4´-3´-3-4, and this area is also positive. w_{2-1} corresponds to area 2-1-1´-3´-2, and it is important to note that this area is negative. Thus, $w_{net,max}$ is depicted by area 1-1´-4´-4-1+4-4´-3´-3-4-2-1-1´-3´-2 = area 2-1-4-3-2, which is negative, and thus the net work of the cycle, even when process 4→3 is reversible, is negative! In an actual cycle, where process 4→3 is irreversible, w_{net} will have an even smaller magnitude than $w_{net,max}$. (this is the "other" effect referred to in the Clausius statement!)

Thus, not only is each process possible (and hence, the whole cycle 3 is possible), it also does not violate the Clausius statement of 2LT!

5. Conclusion:

A study of the literature reveals that engineering/engineering technology students of Thermodynamics find it extremely difficult to appreciate the significance of the negative Clausius statement of the second law of Thermodynamics. This is because students must "accept" this negative statement as true right at the beginning of their study of the subject, without being offered any "positive" explanations or supporting reasons. This leads to the unfortunate situation where many students end up concluding that Thermodynamics, is a very "difficult" subject.

To alleviate this difficulty, a novel approach in the form of a hands-on exercise assignment is suggested to enable students to properly understand the negative statement in a more "positive" manner. It should be pointed out that the author has not yet had an opportunity to use the tool developed in this paper in an actual Thermodynamics class. However, we hope that this exercise can be implemented in an upcoming Thermodynamics class, and that any resulting student performance improvements can be properly assessed and published in a follow-on article.

The analysis begins by constructing three thermodynamic cycles using an ideal gas as the working substance and consisting of both reversible and irreversible processes. The working substance in all these cycles interacts with only two thermal reservoirs at two distinct temperatures, as required by the Clausius statement. It is then shown conclusively that although these cycles are realizable, their sole effect will be not just to transfer heat from the low temperature reservoir to the high temperature reservoir. Additionally, the working substance will absorb net work from the surroundings. Thus, none of these cycles will violate the Clausius statement of the second law of Thermodynamics.

We believe and hope that the hands-on activity/analysis presented in this article will offer an expedient tool for enabling the struggling student to properly understand the negative Clausius statement and comfortably transition to studying the subsequent theorems, corollaries, and practical applications of the second law of Thermodynamics.

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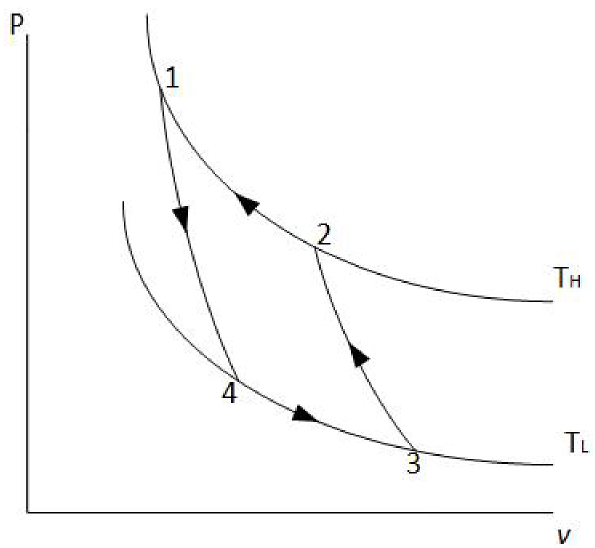
Appendix 1: Student Assignment

Three thermodynamic cycles (see figures below) are constructed such that they exchange heat with only two isothermal energy reservoirs, R_H at temperature T_H, and R_L at temperature T_L, where $T_H > T_L$, as required by the Clausius statement of the second law of Thermodynamics. Furthermore, the system is taken to be 1 kg of an ideal gas operating in a piston-cylinder assembly.

Analyze each cycle process-by-process to determine if (a) it is even possible or not. (NOTE: If even a single process is not possible, the cycle will be impossible to design/construct.) (b) If all processes are possible, then the cycle is possible, and your next step is to assess whether the cycle violates the Clausius statement or not. (NOTE: The Clausius statement will be violated if the sole effect of the cycle is to transfer heat from reservoir R_L at temperature T_L to reservoir R_H at temperature T_H, **while producing no other change either in the system, or in the surroundings**.



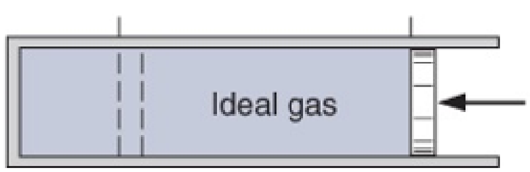


Figure 6 Cycle 1

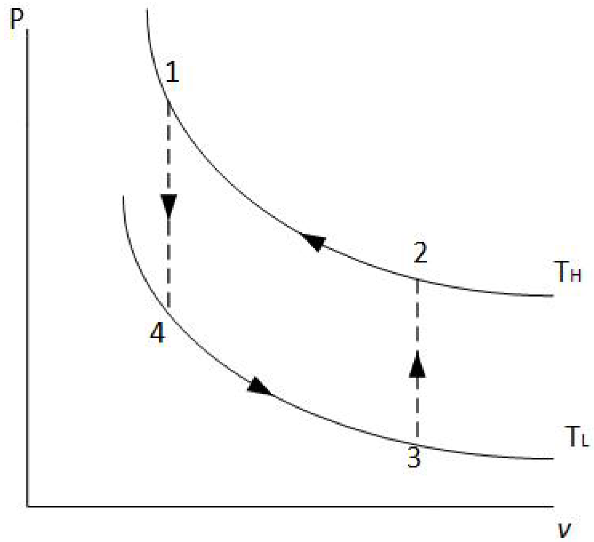


Figure 7 Cycle 2

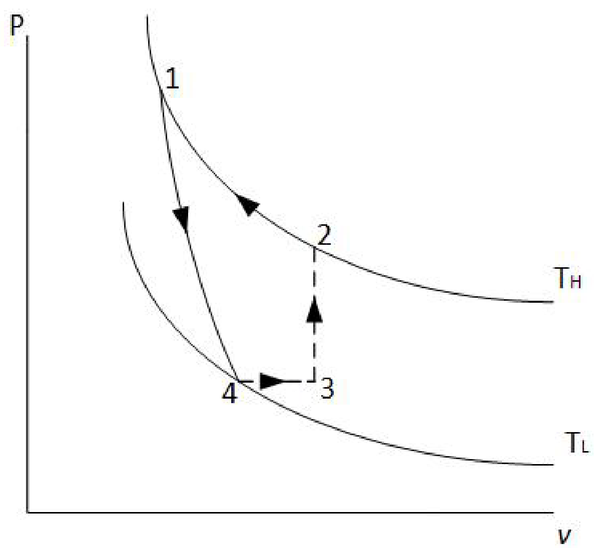


Figure 8 Cycle 3