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

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Abstract

According to the Kelvin–Planck (K-P) 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 raising of a weight and the exchange of heat with a single reservoir." Although it is impossible to prove this negative statement, it is however accepted because it rests on the fact that no experiment has ever contradicted it. Thus, this statement is accepted 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 an engine that operates between two given reservoirs and is more efficient than a reversible engine operating between the same two reservoirs."

Many engineering/engineering technology students of Thermodynamics for the first time find it very difficult to appreciate the true meaning and profundity of this apparently simple K-P statement. This is largely due to the fact that 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 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 one thermal reservoir at a single temperature, as required by the K-P statement. It is then shown conclusively that not a single such cycle can be designed or constructed which will have the sole effect of doing positive work on the surroundings.

We recognize that this is by no means a "proof" of the negative K-P 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 K-P 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.

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 Kelvin-Planck 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 K-P 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. 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 K-P 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 K-P statement of the 2LT in a more "positive" manner.

3. Method: Hands-on Learning Exercise:

To help students better understand the significance of the K-P 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 K-P statement has been discussed in class. One possible way the assignment could be presented is as follows:

Four (only four cycles are shown here for illustrative purposes, but the instructor can provide more cycles in the assignment at their discretion) thermodynamic cycles are constructed such that they exchange heat with only one isothermal energy reservoir R at a temperature T, as required by the K-P 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 <u>(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 K-P statement or not. (NOTE: The K-P statement will be violated if the sole effect of</u>

the cycle is to produce a net positive work output, while exchanging heat only with R.) The complete student assignment is available in Appendix 1.

4. Discussions:

As discussed in the following, this activity will of course ultimately be helpful for the students to properly understand the negative K-P 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, for instance, 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, irreversible, or can be of either type.

CYCLE 1:

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

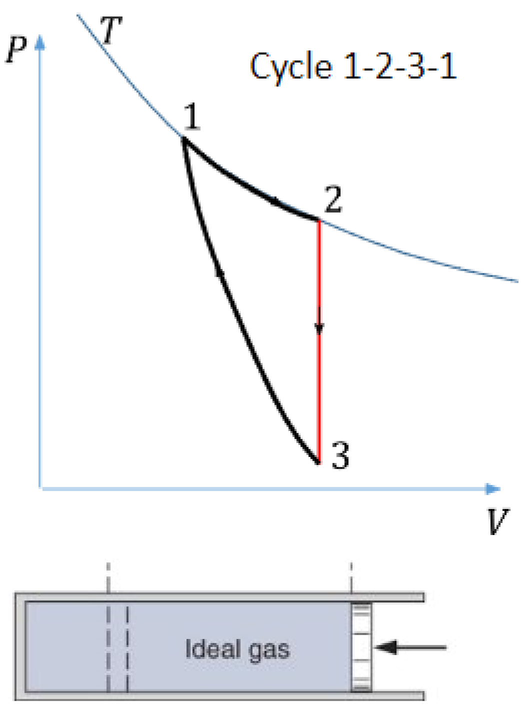

Figure 1 Cycle 1

Let us consider Process 1→2: The ideal gas undergoes an isothermal expansion from V_1 to V_2 during which the working substance absorbs heat from the reservoir and performs work on the surroundings. Since the system must absorb heat from R, it must be at a temperature $T - \Delta T$, 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 $\Delta T \to 0$. Thus, this process is possible.

The first law of thermodynamics as applied to a closed system is $q = w + \Delta u$. Since the process 1→2 is isothermal, and for an ideal gas, $u = u(T)$, $u_1 = u_2, i.e. \Delta u = 0$. Since for a reversible isothermal process executed by an ideal gas, $w = RTln(v_2/v_1)$, the heat transfer is also given as $q = RTln(v_2/v_1)$.

<u>Process 2→3</u>: Constant volume heat rejection/isochoric cooling

In this process, the ideal gas rejects heat at constant volume and the temperature decreases from T to T_3. The gas needs to reject heat to the reservoir in order to cool down. However, this will involve a heat transfer from a lower temperature (lower than T) to the reservoir at T. Hence, process 2→3 is impossible. To show that it is impossible for this process to occur, it has been shown in orange color in Figure 1.

Now, as discussed above, this cycle is impossible because process 2→3 is impossible. Yet, for the sake of completeness, we discuss the remaining process 3→1.

<u>Process 3→1</u>: Adiabatic compression

During this process, the working substance undergoes adiabatic compression, returning to the initial temperature T. This process can be performed either reversibly or irreversibly. Again, for simplicity, we consider this to be a reversible process. As the process is adiabatic, there is no heat transfer between the ideal gas and the reservoir. Therefore, $\Delta u = -w = \frac{R(T-T_3)}{k-1}$.

This, the cycle 1-2-3-1, as depicted in Fig. 1 is not possible, and therefore the question of whether it violates the K-P statement or not does not arise.

CYCLE 2:

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

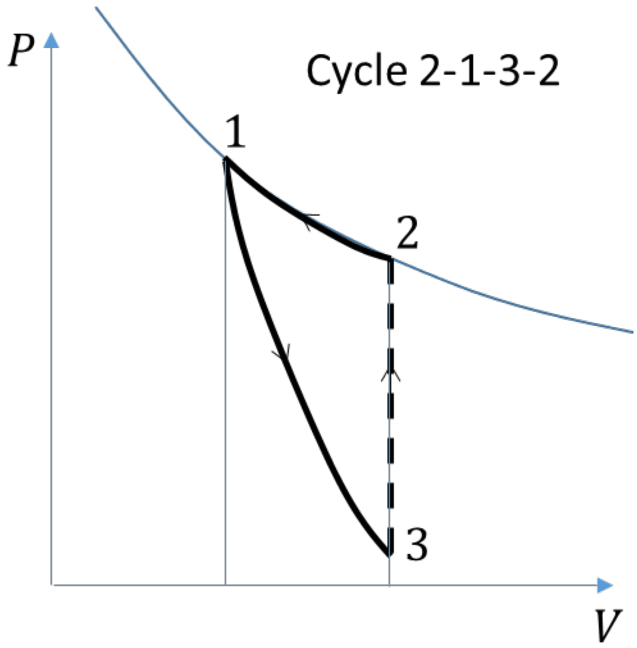

Figure 2 Cycle 2

<u>Process 2→1</u>: The ideal gas undergoes an isothermal compression from V_2 to V_1 during which it rejects heat to the reservoir and needs work from the surroundings. Since the system must reject heat to R, it must be at a temperature $T + \Delta T$, where $\Delta T \geq 0$. This process can be performed reversibly or irreversibly. However, for simplicity, we 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 $q = w + \Delta u$. Since the process 2→1 is isothermal, and for an ideal gas, $u = u(T)$, $u_1 = u_2, i.e. \Delta u = 0$. Since for a reversible isothermal process executed by an ideal gas, $w = RTln(v_1/v_2)$, the heat transfer is also $q = RTln(v_1/v_2)$. Thus the work and heat are both negative for this process.

<u>Process 1→3</u>: Adiabatic expansion

During this process, the working substance undergoes adiabatic expansion. This process can be performed either reversibly or irreversibly. Again, for simplicity, we consider this to be a reversible process. As the process is adiabatic, there is no heat transfer between the ideal gas and the reservoir. Therefore, $\Delta u = -w = \frac{R(T_3 - T)}{k-1}$. Thus, the process 1→3 is also possible, and moreover, the work is positive for this process.

<u>Process 3→2</u>: Constant volume /isochoric heating

In this process, the ideal gas absorbs heat at constant volume as its temperature increases from T_3 to T. Since the heat transfer is always from a higher temperature (T) to a temperature lower than T, this process is possible.

However, since the work done in a reversible process is the area under the process curve on a $P-v$ diagram, as seen from Fig. 2, the work done in process 2→1 exceeds the work done in process 1→3. In other words, the net work of cycle 2-1-3-2 is negative, i.e., it is equivalent to lowering a weight, not raising it. Thus, this cycle does not violate the K-P statement of 2LT.

CYCLE 3:

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

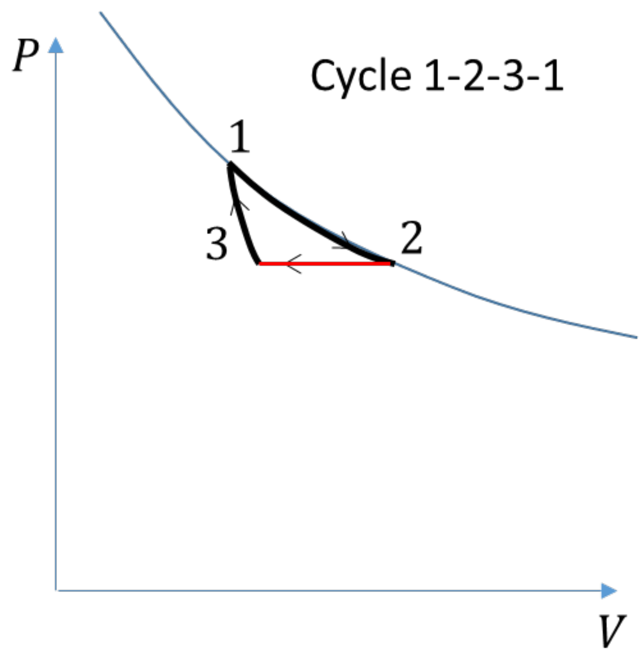

Figure 3 Cycle 3

<u>Process 1→2</u>: The ideal gas undergoes an isothermal expansion from V_1 to V_2 during which the working substance absorbs heat from the reservoir and performs work on the surroundings. Since the system must absorb heat from R, it must be at a temperature $T-\Delta T$, 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.

As shown in the discussion related to Cycle 1, $w = RTln(v_2/v_1)$, and the heat transfer is also given as $q = RTln(v_2/v_1)$ for this process.

<u>Process 2→3</u>: Constant pressure heat rejection/isobaric cooling

In this process, the ideal gas rejects heat at constant pressure and its temperature decreases from T_2 to T_3. The gas needs to reject heat to the reservoir in order to cool down. However, this will involve a heat transfer from a lower temperature (lower than T) to the reservoir at T. Hence, process 2→3 is impossible. To show that it is impossible for this process to occur, it has been shown in orange color in Figure 3.

Now, as discussed above, this cycle is impossible because process 2→3 is impossible. Yet, for the sake of completeness, we discuss the remaining process 3→1.

<u>Process 3→1</u>: Adiabatic compression

During this process, the working substance undergoes adiabatic compression, returning to the initial temperature T. This process can be performed either reversibly or irreversibly. Again, for simplicity, we consider this to be a reversible process. As the process is adiabatic, there is no heat transfer between the ideal gas and the reservoir. Therefore, $\Delta u = -w = \frac{R(T-T_3)}{k-1}$.

Thus, the cycle 1-2-3-1, as depicted in Fig. 3 is not possible, and therefore the question of whether it violates the K-P statement or not does not arise.

CYCLE 4:

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

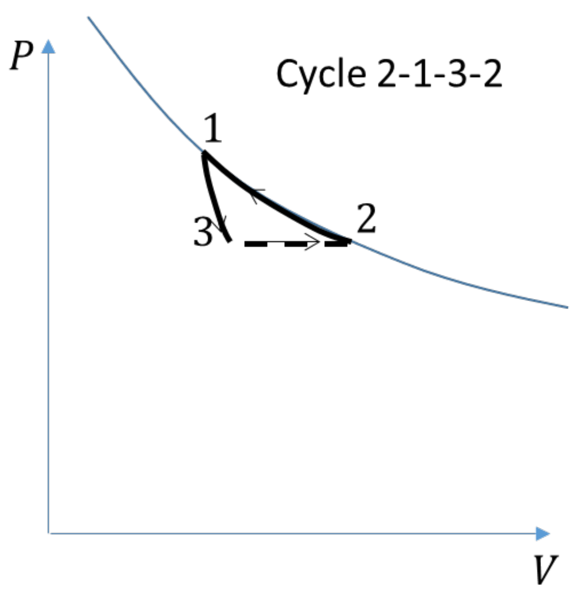

Figure 4 Cycle 4

<u>Process 2→1</u>: The ideal gas undergoes an isothermal compression from V_2 to V_1 during which it rejects heat to the reservoir and needs work from the surroundings. Since the system must reject heat to R, it must be at a temperature $T + \Delta T$, where $\Delta T \geq 0$. This process can be performed reversibly or irreversibly. However, for simplicity, we consider this to be a reversible process, which implies that $\Delta T \to 0$. Thus, this process is possible.

As shown in connection with Cycle 2, $w = RTln(v_1/v_2)$, and the heat transfer is also $q = RTln(v_1/v_2)$ for this process. Thus the work and heat are both negative for this process.

<u>Process 1→3</u>: Adiabatic expansion

During this process, the working substance undergoes adiabatic expansion. This process can be performed either reversibly or irreversibly. Again, for simplicity, we consider this to be a reversible process. As the process is adiabatic, there is no heat transfer between the ideal gas and the reservoir. Therefore, $\Delta u = -w = \frac{R(T_3 - T)}{k-1}$. Thus, the process 1→3 is also possible, and moreover, the work is positive for this process.

Process 3→2: Constant pressure /isobaric heating

In this process, the ideal gas absorbs heat at constant pressure as its temperature increases from T_3 to T. Since the heat transfer is always from a higher temperature (T) to a temperature lower than T, this process is possible.

However, since the work done in a reversible process is the area under the process curve on a $P - v$ diagram, as seen from Fig. 4, the work done in process 2→1 exceeds the work done in process 1→3. In other words, the net work of cycle 2-1-3-2 is negative, i.e., it is equivalent to lowering a weight, not raising it. Thus, this cycle does not violate the K-P 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 K-P statement of the second law of Thermodynamics. This is because students have to "accept" this negative statement as true right, 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 is begun by constructing four 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 one thermal reservoir at a single temperature, as required by the K-P statement. It is then shown conclusively that these cycles are either impossible to realize or, if they are realizable, their sole effect will be to lower a weight (i.e., they will absorb net work from the surroundings). Thus, they do not violate the K-P 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 K-P statement and comfortably transition to studying the subsequent theorems, corollaries, and practical applications of the second law of Thermodynamics.

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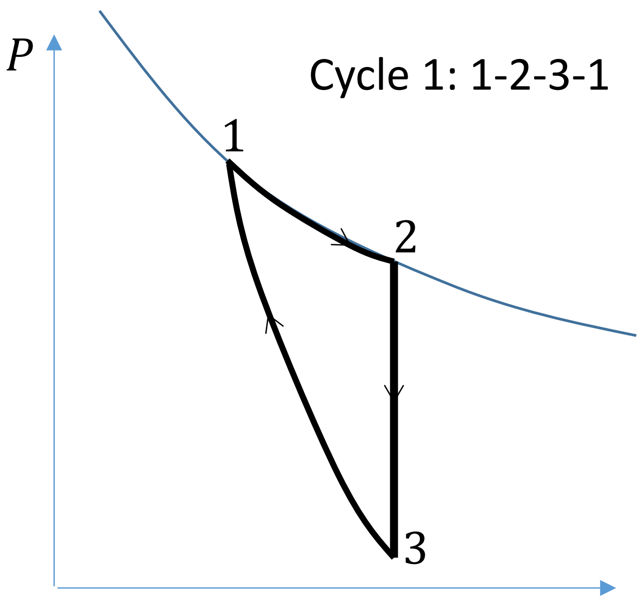
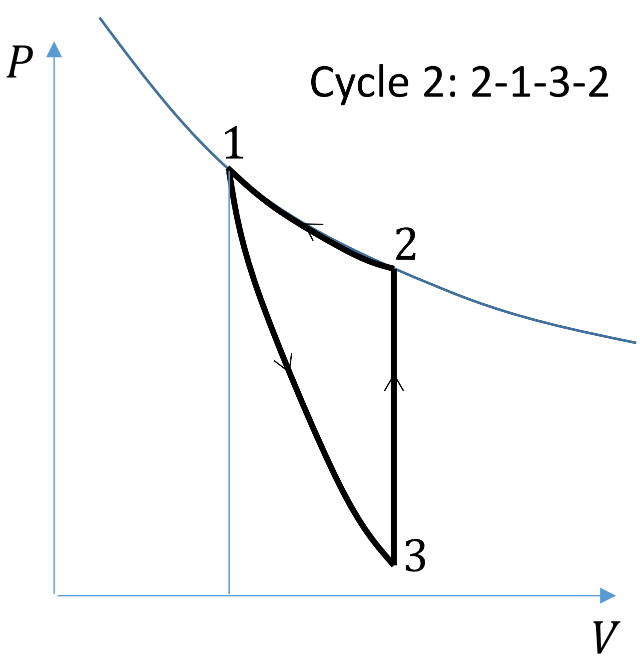
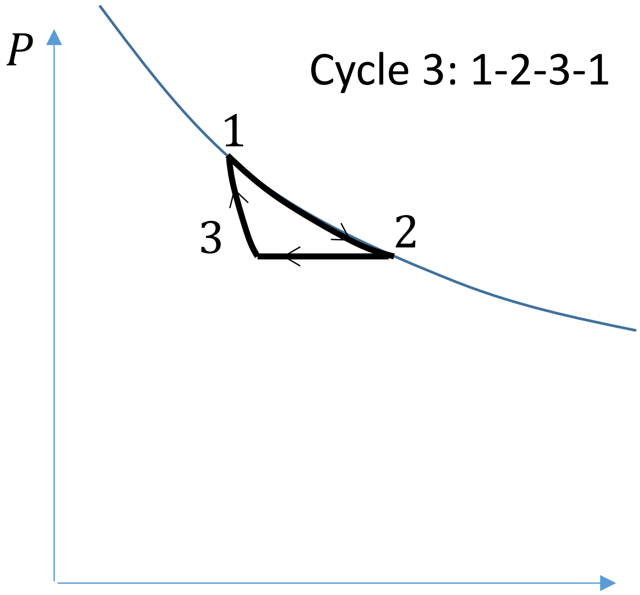
Appendix 1: Student Assignment

Four thermodynamic cycles (see figures below) are constructed such that they exchange heat with only one isothermal energy reservoir R at a temperature T, as required by the K-P statement. Furthermore, the system is taken to be 1 kg of an ideal gas operating in a piston-cylinder assembly.

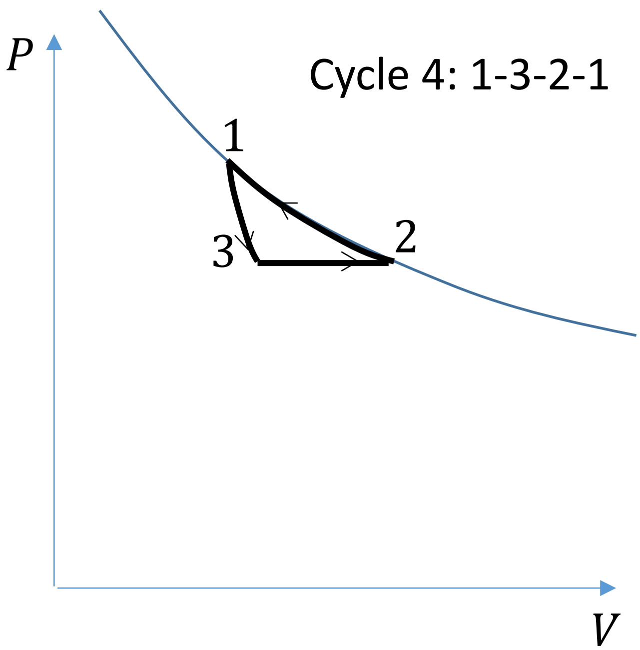
Analyze each cycle process-by-process to determine if <u>(a) it is even possible or not. (NOTE: If even a single process is not possible, the cycle will be impossible to design/construct.) (b) If all processes are possible, then the cycle is possible, and your next step is to assess whether the cycle violates the K-P statement or not. (NOTE: The K-P statement will be violated if the sole effect of the cycle is to produce a net positive work output, while exchanging heat only with R.) The complete student assignment is available in Appendix 1.</u>







P
Cycle 3: 1-2-3-1
1
2
3



P
Cycle 4: 1-3-2-1
1
2
3
V