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Class 2 heating cycles: A new class of thermodynamic cycles

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Abstract

Considering the significance of thermodynamic cycles in the global energy system, it is necessary to develop new general classes of thermodynamic cycles to relieve current energy and environmental problems. Inspired by the relationship between power cycles and refrigeration cycles, we realize that general classes of thermodynamic cycles should occur in pairs with opposite functions. Here we reverse class 1 heating cycles to obtain another new general class of thermodynamic cycles named class 2 heating cycles (HC-2s). HC-2s have two basic forms, and each contains six thermodynamic processes. HC-2s present the simplest and most general approach to utilizing the temperature difference between a medium-temperature heat source and a low-temperature heat sink to achieve efficient high-temperature heating. HC-2s fill the gaps that have existed since the origin of thermal science, and they will play significant roles in the global sustainable energy system.

Keywords

heating cycles; thermodynamic cycles; thermodynamics; temperature difference utilization; heating; cold energy utilization; sustainable energy; cogeneration; thermal science

Highlights

· A new general class of thermodynamic cycles are constructed.

· Their nature, functions, characteristics and advantages are generally analyzed.

· A novel, efficient, coordinating, simple and general approach to heating.

· Efficiently exploit medium-temperature heat and low-temperature cold resources.

· Only need six processes to achieve heat-driven heating and cold-driven heating.

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Main Text

1. Introduction

Each general class of thermodynamic cycles present a simple and general approach to energy conversion and utilization. At present, there are three general classes of thermodynamic cycles: power cycles, refrigeration cycles (also called heat pump cycles) [1], and the one we have just proposed—class 1 heating cycles (HC-1s) [2]. Power cycles covert part of heat into power; refrigeration cycles utilize power to lift heat; HC-1s move high-temperature heat and low-temperature heat together to the medium temperature, and they can also produce or utilize power. Considering the important roles of thermodynamic cycles in the global energy system, as well as a series of energy problems humans are facing, it is necessary to explore new general classes of thermodynamic cycles.

It's worth noting that power cycles and refrigeration cycles are the reverse of each other with the functions of the two being opposite. In 1824, Sadi Carnot [3] raised the concept of a power cycle as a generalization of actual heat engines, then he reversed the power cycle to get a refrigeration cycle; in 1852, William Thomson (Lord Kelvin) [4] demonstrated that the refrigeration cycle can also be used for efficient heating. These facts inspire us to realize that general classes of thermodynamic cycles should occur in pairs with opposite functions. Therefore, in this study we reverse HC-1s [2] to obtain a new general class of thermodynamic cycles—class 2 heating cycles (HC-2s). HC-2s present the simplest and most general approach to utilizing the temperature difference between a medium-temperature heat source and a low-temperature heat sink to achieve efficient high-temperature heating. Without loss of generality, we mainly introduce and discuss HC-2s on the basis of the mechanical

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compression system, while the conclusions are applicable to various types of systems.

2. Construction

HC-1s operate among a high-temperature heat source, a medium-temperature heat sink, and a low-temperature heat source; their core function is to move high-temperature heat and low-temperature heat together to the medium temperature, and they can also produce or utilize power; HC-1s have two basic forms, and each contains six essential thermodynamic processes [2]. Correspondingly, HC-2s operate among a high-temperature heat sink, a medium-temperature heat source, and a low-temperature heat sink; their core function is to move one part of medium-temperature heat to the low temperature and the other part of the medium-temperature heat to the high temperature, and they can also utilize or produce power; HC-2s have two basic forms, and each contains six essential thermodynamic processes:

The basic form A of HC-2s (HC-2A, Figure 1a) consists of the following six processes: pressurization 1-2, medium-temperature heat absorption 2-3, pressurization 3-4, high-temperature heat rejection 4-5, depressurization 5-6, and low-temperature heat rejection 6-1.

The basic form B of HC-2s (HC-2B, Figure 1b) consists of the following six processes: pressurization 1-2, high-temperature heat rejection 2-3, depressurization 3-4, medium-temperature heat absorption 4-5, depressurization 5-6, and low-temperature heat rejection 6-1.

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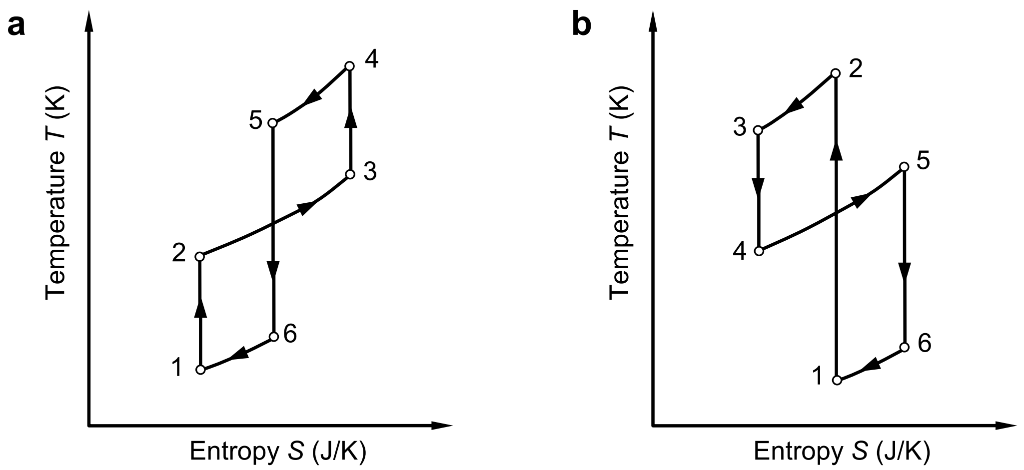

Figure 1. The basic forms of class 2 heating cycles (HC-2s). (a) An HC-2A consists of six processes: pressurization 1-2, medium-temperature heat absorption 2-3, pressurization 3-4, high-temperature heat rejection 4-5, depressurization 5-6, and low-temperature heat rejection 6-1. Although process 2-3 and process 5-6 seem to intersect in the temperature-entropy (*T*-*S*) diagram, they are independent of each other. (b) An HC-2B consists of six processes: pressurization 1-2, high-temperature heat rejection 2-3, depressurization 3-4, medium-temperature heat absorption 4-5, depressurization 5-6, and low-temperature heat rejection 6-1. Process 1-2 and process 4-5 are also independent of each other.

If needed, adjustments or improvements can be applied to these basic forms to obtain diverse cycle structures, and thus better performance can be achieved without losing simplicity. Therefore, although we only show their two basic forms, HC-2s are actually a huge family of thermodynamic cycles, just like power cycles, refrigeration cycles and HC-1s.

3. Analysis

Next, we analyze the functions, characteristics and advantages of HC-2s based on their basic forms.

3.1. The basic functions of HC-2s

According to the law of conservation of energy, we have

$$W_{\mathrm{net}} = Q_{\mathrm{in}} - Q_{\mathrm{out,\,H}} - Q_{\mathrm{out,\,L}} \tag{1}$$

where W_{net} is the net work output of an HC-2, Q_{in} is the amount of heat absorbed from the medium-temperature heat source by the cycle, $Q_{\mathrm{out,\,H}}$ is the amount of heat rejected to the high-temperature heat sink by the cycle, and $Q_{\mathrm{out,\,L}}$ is the amount of heat rejected to the low-temperature heat sink by the cycle.

For an HC-2 with $W_{\mathrm{net}} = 0$, Eq. (1) can be written as $Q_{\mathrm{out,\,H}} = Q_{\mathrm{in}} - Q_{\mathrm{out,\,L}}$. The cycle utilizes the temperature difference between the medium-temperature heat source and the low-temperature heat sink, to efficiently supply high-temperature heat $Q_{\mathrm{out,\,H}}$.

For an HC-2 with $W_{\mathrm{net}} > 0$, Eq. (1) can be written as $Q_{\mathrm{out,\,H}} + W_{\mathrm{net}} = Q_{\mathrm{in}} - Q_{\mathrm{out,\,L}}$. The cycle utilizes the above-mentioned temperature difference to efficiently supply both high-temperature heat $Q_{\mathrm{out,\,H}}$ and power W_{net}.

For an HC-2 with $W_{\mathrm{net}} < 0$, Eq. (1) can be written as $Q_{\mathrm{out,\,H}} = Q_{\mathrm{in}} - Q_{\mathrm{out,\,L}} + |W_{\mathrm{net}}|$. The cycle utilizes the above-mentioned temperature difference, as well as the grade difference between power and high-temperature heat, to efficiently supply high-temperature heat $Q_{\mathrm{out,\,H}}$.

Same as the circumstance in an internally reversible HC-1 [2], for an internally reversible HC-2 with $W_{\mathrm{net}} = 0$, $W_{\mathrm{net}} > 0$, or $W_{\mathrm{net}} < 0$, the area enclosed by the cycle's

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clockwise part is equal to, larger than, or smaller than that enclosed by the anticlockwise part in the *T*-*S* diagram, respectively. This conclusion provides a visual guidance for designing the shapes and parameters of HC-2s to meet diverse energy supplies and demands.

3.2. Typical application scenario: Upgrading medium-temperature heat resources

HC-2s will play significant roles in the global sustainable energy system. HC-2s can resolve a common conflict between energy supply and demand—the temperature of heat supply being lower than that of heat demand. This conflict has severely limited the effective utilization of many sustainable energy resources, especially waste heat, solar energy and geothermal energy, because these resources are often at medium temperatures and thus cannot directly satisfy widespread high-temperature heat demands. Previous studies have mainly focused on utilizing the temperature difference between these medium-temperature heat resources and the environment to generate power [5-11]; in contrast, HC-2s present a simple and general approach to utilizing this temperature difference to achieve high-temperature heating. In this case, the environment serves as the above-mentioned low-temperature heat sink, a medium-temperature heat resource serves as the above-mentioned medium-temperature heat source, and a heat consumer serves as the above-mentioned high-temperature heat sink. By degrading one part of the medium-temperature heat resource and rejecting it to the environment, an HC-2 with $W_{net} = 0$ can upgrade the other part of the medium-temperature heat resource to satisfy the high-temperature heat demand. In addition, if there also exists a power demand or a power supply, an HC-2 with $W_{net} > 0$ or $W_{net} < 0$ can be applied to match energy supplies with demands.

3.3. Typical application scenario: Utilizing cold energy for heating

HC-2s also provide a new perspective for exploiting low-temperature cold energy. This is because the environment can serve as the medium-temperature heat source if there exists a colder object to serve as the low-temperature heat sink; a heat consumer hotter than the environment serves as the high-temperature heat sink. The recovery processes of liquefied gas fuels and compressed gas fuels are typical cold energy resources. Liquefied natural gas and compressed natural gas have been widely used as clean fuels, and liquefied hydrogen and compressed hydrogen are expected to play important roles in the next-generation energy system. On the one hand, liquefying or compression makes it easier for people to store and transport gas fuels, but these two processes consume power and thus lead to extra cost [12, 13]. On the other hand, the fuels need to be regasified or decompressed before being used. Liquefied gas fuels are at normal pressure but extremely low temperatures; they need to firstly absorb latent heat then sensible heat to reach the normal state. Compressed gas fuels are at normal temperature but extremely high pressures; they will expand and chill during decompression, and thus their pressure energy will be converted into power and cold energy. The utilization of the cold energy (or both the power and cold energy) associated with these clean fuels can recover part of the cost of liquefying or compression and thus promote the application of these fuels. To the best of our knowledge, previous studies have usually used such cold energy for cooling [14-16], or utilized the temperature difference between the environment and the cold energy resources to generate power [15-18]; in contrast, we propose for the first time a simple and general approach to utilizing this temperature difference to supply heat. A considerable proportion of these fuels are exactly used to supply heat, in this case the application of HC-2s can bring significant benefits—consuming equal fuel to supply more heat, or consuming less fuel to supply equal heat. For liquefied fuels, an HC-2 with $W_{net} = 0$ can be applied to utilize the cold energy to supply heat; for compressed fuels, an HC-2 with $W_{net} < 0$ can be applied to utilize both the power and cold energy to supply heat. In addition, if a heat resource described in the last paragraph and a cold energy resource described in this paragraph coexist, they can both be utilized by an HC-2, serving as the medium-temperature heat source and the low-temperature heat sink respectively.

3.4. Simplicity: HC-2s *vs* the combination of a power cycle and a refrigeration cycle

As mentioned above, the core function of HC-2s is to move one part of medium-temperature heat to the low temperature and the other part to the high temperature. This goal cannot be achieved by a power cycle or a refrigeration cycle alone, but only by the combination of both. The power cycle operates between the above-mentioned medium-temperature heat source and low-temperature heat sink (Figure 2b, cycle 1-2-3-4-1), and the refrigeration cycle operates between the above-mentioned high-temperature heat sink and medium-temperature heat source (Figure 2b, cycle 5-6-7-8-5); the power cycle drives the refrigeration cycle. Similar to the circumstance in the former article [2], since a basic power cycle and a basic refrigeration cycle each contain four thermodynamic processes, the combination of both requires eight thermodynamic processes and a power transmission process between two cycles. In contrast, a basic HC-2 only needs six thermodynamic processes, and it also avoids the transmission loss between two cycles. Moreover, HC-2s can be further simplified in special cases. For example, when heating up a gas which is suitable to be the cycle's working medium, we can employ it to directly conduct an open cycle, i.e., 5-6-1-2-3-4 in Figure 1a, or 3-4-5-6-1-2 in Figure 1b. We can get the heated gas at the exit of the open cycle with no need for the process of high-temperature heat rejection and the corresponding heat exchanger.

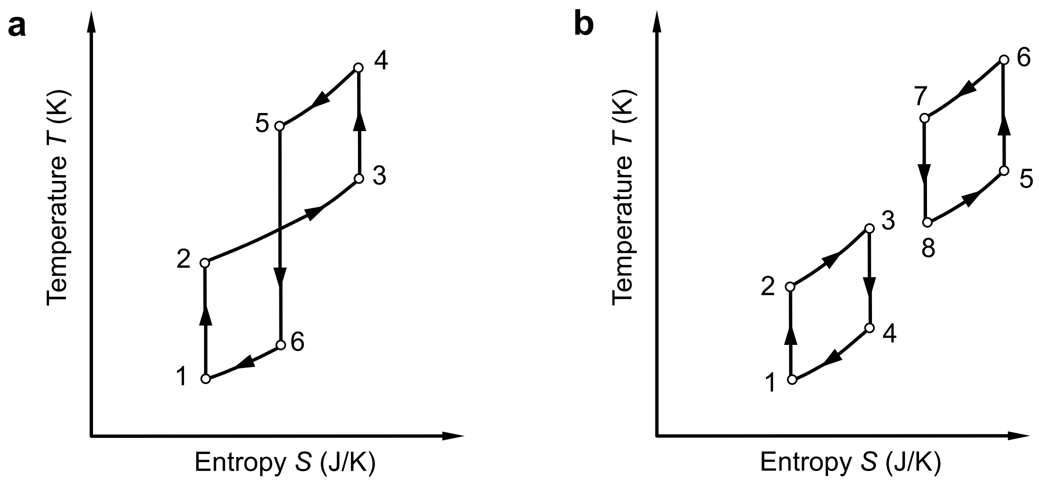

Figure 2. The comparison between an HC-2 and the combination of a power cycle and a refrigeration cycle. (a) A basic HC-2 only requires one cycle with six thermodynamic processes. (b) The combination of a basic power cycle and a basic refrigeration cycle requires two cycles with eight thermodynamic processes (and a power transmission process between two cycles) in total. The power cycle 1-2-3-4-1 operates between the medium-temperature heat source and the low-temperature heat sink; the refrigeration cycle 5-6-7-8-5 operates between the high-temperature heat sink and the medium-temperature heat source; the power cycle drives the refrigeration cycle.

3.5. Generality: HC-2s *vs* absorption heat transformers

It should be noted that, apart from being obtained through the method described in this article (i.e., reversing an existing general class of thermodynamic cycles to obtain a new one), HC-2s can also be obtained in the similar way as constructing HC-1s [2]: first, determine the cycles' core task and find available heat sources and sinks; second, explore the minimum number of processes required to achieve the task; finally, connect these processes in the proper order and form a thermodynamic cycle. Either way, we only use the fundamentals of thermodynamics to construct HC-2s without involving characteristics of any specific working medium. Therefore, HC-2s are of great generality; they can be performed by various working media and devices, and on a wide range of temperatures and scales. Although we mainly describe HC-2s on the basis of the mechanical compression system, they are also expected to be performed by other types of systems with their functions and advantages remained; to this end, researchers should replace the processes of pressurization and depressurization described above with the corresponding transition processes in each system. In contrast, although absorption heat transformers[19] also can realize HC-2s' core function (i.e., to move one part of medium-temperature heat to the low temperature and the other part to the high temperature) in limited cases, they have to operate on the concentration change of a solution. Therefore, they face restrictions in many aspects, including the choice of their working media and materials, as well as the range of their operating temperatures and sizes; besides, their working mechanism lacks generality and thus is hard be transferred to other types of systems.

4. Examples

Here we show three typical examples of HC-2s (without loss of generality, they are all in basic form A); they each possess clear theoretical significance or

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practical value. We also present their coefficients of performance (COPs, the ratio of the cycle's output to input) for high-temperature heating when $W_{net} = 0$; the derivation is included in the Supplementary Information.

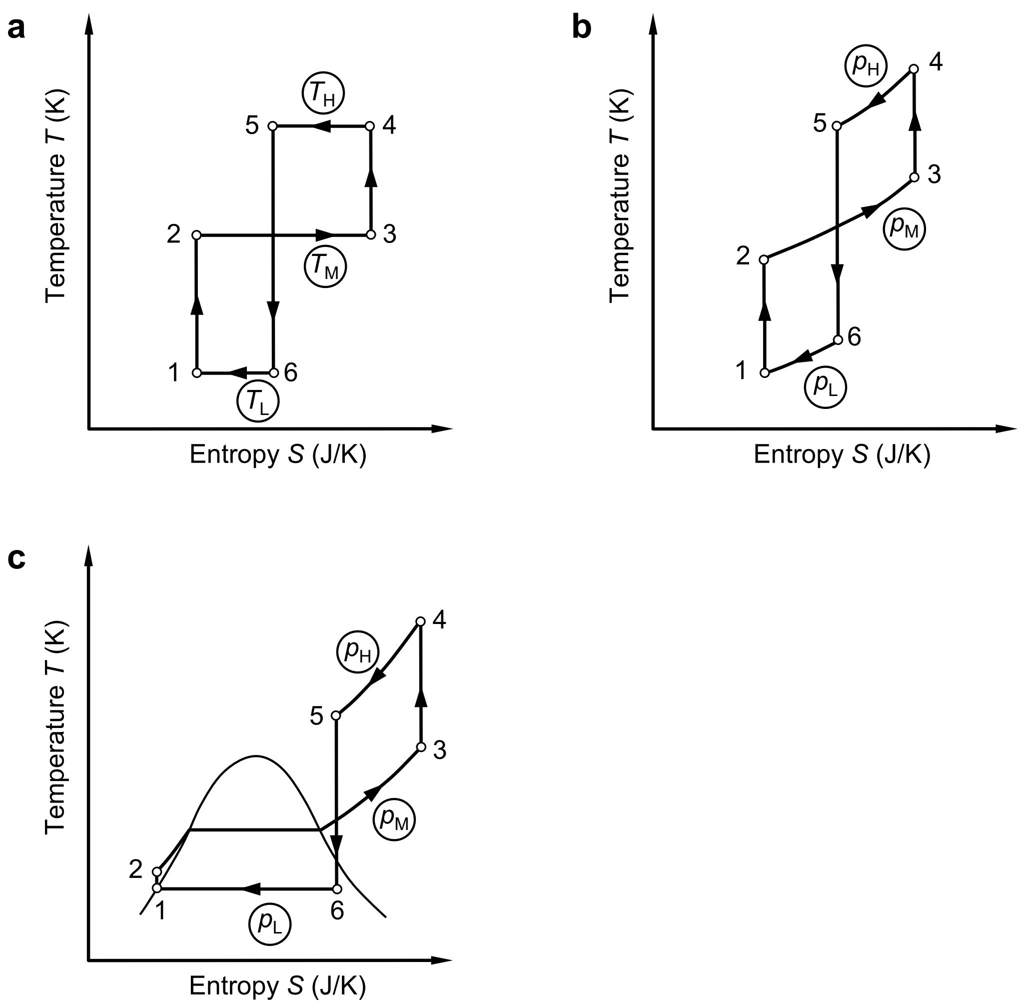

Figure 3. Three typical examples of HC-2s. (a) An HC-2A with isothermal heat transfer processes. T_H, T_M and T_L are the working medium's thermodynamic temperatures during high-temperature heat rejection, medium-temperature heat absorption, and low-temperature heat rejection, respectively. (b) An HC-2A with isobaric heat transfer processes, employing an ideal gas as its working medium. (c) An HC-2A with isobaric heat transfer processes, employing a phase-change working medium. In (b) and (c), p_H, p_M and p_L are the working

medium's pressures during high-temperature heat rejection, medium-temperature heat absorption, and low-temperature heat rejection, respectively.

4.1. The HC-2A with isothermal heat transfer processes

The first example (Figure 3a) has isothermal heat transfer processes so it can clearly reveal the proportional relationships during moving heat among three different temperatures. Regarding the cycle as internally reversible [1], we can express its COPs as

$$\mathrm{COP_{HD}} = \frac{Q_{\mathrm{out,\,H}}}{Q_{\mathrm{in}}} = \frac{T_{\mathrm{H}}(T_{\mathrm{M}} - T_{\mathrm{L}})}{T_{\mathrm{M}}(T_{\mathrm{H}} - T_{\mathrm{L}})} \quad (2)$$

$$\mathrm{COP_{CD}} = \frac{Q_{\mathrm{out,\,H}}}{Q_{\mathrm{out,\,L}}} = \frac{T_{\mathrm{H}}(T_{\mathrm{M}} - T_{\mathrm{L}})}{T_{\mathrm{L}}(T_{\mathrm{H}} - T_{\mathrm{M}})} \quad (3)$$

where $\mathrm{COP_{HD}}$ and $\mathrm{COP_{CD}}$ are the COPs when the cycle is driven by medium-temperature heat and by low-temperature cold energy respectively.

4.2. The HC-2A with isobaric heat transfer processes, employing an ideal gas as its working medium

The other two are not hard to be realized on the basis of current technologies. The second example (Figure 3b) has isobaric heat transfer processes and employs an ideal gas as its working medium. Regarding the cycle as internally reversible, and the ideal gas's isobaric specific heat as constant [1], we can express the cycle's COPs as

$$\mathrm{COP_{HD}} = \frac{Q_{\mathrm{out,\,H}}}{Q_{\mathrm{in}}} = \frac{p_{\mathrm{H}}^{\frac{k-1}{k}}\left(p_{\mathrm{M}}^{\frac{k-1}{k}} - p_{\mathrm{L}}^{\frac{k-1}{k}}\right)}{p_{\mathrm{M}}^{\frac{k-1}{k}}\left(p_{\mathrm{H}}^{\frac{k-1}{k}} - p_{\mathrm{L}}^{\frac{k-1}{k}}\right)} \quad (4)$$

$$\mathrm{COP_{CD}} = \frac{Q_{\text{out, H}}}{Q_{\text{out, L}}} = \frac{p_{\mathrm{H}}^{\frac{k-1}{k}}\left(p_{\mathrm{M}}^{\frac{k-1}{k}} - p_{\mathrm{L}}^{\frac{k-1}{k}}\right)}{p_{\mathrm{L}}^{\frac{k-1}{k}}\left(p_{\mathrm{H}}^{\frac{k-1}{k}} - p_{\mathrm{M}}^{\frac{k-1}{k}}\right)} \quad (5)$$

where k is the ideal gas's specific heat ratio.

4.3. The HC-2A with isobaric heat transfer processes, employing a phase-change working medium

The third example (Figure 3c) has isobaric heat transfer processes and employs a phase-change working medium. The cycle's COP can be expressed as

$$\mathrm{COP_{HD}} = \frac{Q_{\text{out, H}}}{Q_{\text{in}}} = \frac{h_4 - h_5}{h_3 - h_2} \quad (6)$$

$$\mathrm{COP_{CD}} = \frac{Q_{\text{out, H}}}{Q_{\text{out, L}}} = \frac{h_4 - h_5}{h_6 - h_1} \quad (7)$$

where h is the working medium's enthalpy per unit of mass at each state point.

5. Conclusions

Each thermodynamic process of HC-2s has been widely used in practice and exists in every current power cycle and refrigeration cycle; besides, all the functions, characteristics and advantages of HC-2s are demonstrated by analysis on the basis of the basic principles of thermodynamics. Therefore, the conclusions of this article can be reached with no need for numerical or experimental case studies (but they can be future research contents). Theoretically, HC-2s are in equal status with power cycles, refrigeration cycles and HC-1s, and they fill the gaps that have existed since the origin of thermal science. Practically, HC-2s provide a novel, efficient, coordinating, simple and general approach to utilizing medium-temperature heat and low-temperature cold energy resources, and they will play significant roles in the global sustainable energy system.

Up to this point, we have completed the construction and analysis of two classes of heating cycles, and increased the number of general classes of thermodynamic cycles to four. Power cycles, refrigeration cycles, HC-1s and HC-2s are not only the cornerstones of thermal science, but also essential parts of the global energy system. Simply speaking, power cycles and refrigeration cycles are better at handling power-centered energy issues, while HC-1s and HC-2s are better at handling heat-centered energy issues. Considering the significant roles of heat in both the global primary energy utilization and final energy consumption, the importance of these two new general classes of thermodynamic cycles is beyond question.

In general, HC-1s and HC-2s possess good compatibility with diverse advanced technologies currently applied to thermodynamic cycles; however, given that the structures and characteristics of HC-1s and HC-2s are obviously different from those of power cycles and refrigeration cycles, researchers still need to explore dedicated principles and methods to improve their performance. In addition, the construction methods of HC-1s and HC-2s can inspire scientists to further develop more new general classes of thermodynamic cycles.

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Competing interests

H.-Y.L. is the inventor and applicant of the following patents on HC-2s: CN ZL201610243934.7; CN ZL201610243616.0; CN ZL201610240650.2; CN ZL201610240687.5; all the patents have been authorized. H.-Y.L. is the main founder of two energy technology companies.

Author contributions

H.-Y.L. proposed the initial concept. H.-R.L. and H.-Y.L. performed the analysis. H.-R.L. and H.-Y.L. wrote the manuscript. H.-R.L. drew the figures and derived the formulae.

Supplementary Information

Supplementary Information is available for this paper.

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