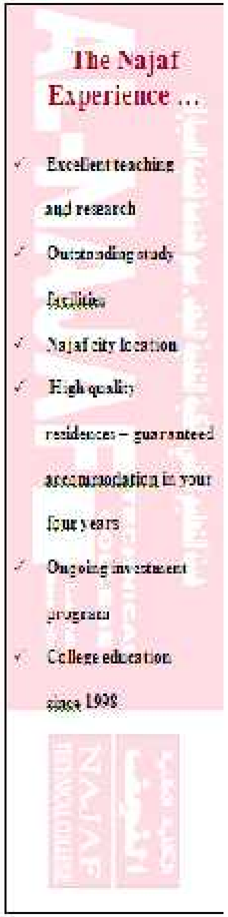


Thermodynamics

الديناميكا الحرارية

اعداد الدكتور
علي شاكر باقر الجابري

Thermodynamics الديناميكا الحرارية

CHAPTER FIVE The Second Law of Thermodynamics

The classical presentation of the second law of thermodynamics starts with the concept of heat engines and refrigerators. A heat engine produces work from a heat transfer obtained from a thermal reservoir, and its operation is limited by the Kelvin–Planck statement. Refrigerators are functionally the same as heat pumps, and they drive energy by heat transfer from a colder environment to a hotter environment, something that will not happen by itself. The Clausius statement says in effect that the refrigerator or heat pump does need work input to accomplish the task. To approach the limit of these cyclic devices, the idea of reversible processes is discussed and further explained by the opposite, namely, irreversible processes and impossible machines. A perpetual motion machine of the first kind violates the first law (energy equation), and a perpetual machine of the second kind violates the second law of thermodynamics.

The limitations for the performance of heat engines (thermal efficiency) and heat pumps or refrigerators (coefficient of performance or COP) are expressed by the corresponding Carnot-cycle device. Two propositions about the Carnot cycle device are another way of expressing the second law of thermodynamics instead of the statements of Kelvin–Planck or Clausius. These propositions lead to the establishment of the thermodynamic absolute temperature, done by Lord Kelvin, and the Carnot-cycle efficiency. We show this temperature to be the same as the ideal-gas temperature introduced in Chapter 3.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Understand the concepts of heat engines, heat pumps, and refrigerators.
- Have an idea about reversible processes.
- Know a number of irreversible processes and recognize them.
- Know what a Carnot-cycle is.
- Understand the definition of thermal efficiency of a heat engine.
- Understand the definition of coefficient of performance of a heat pump.
- Know the difference between the absolute and relative temperature.
- Know the limits of thermal efficiency as dictated by the thermal reservoirs and the Carnot-cycle device.
- Have an idea about the thermal efficiency of real heat engines.
- Know the limits of coefficient of performance as dictated by the thermal reservoirs and the Carnot-cycle device.
- Have an idea about the coefficient of performance of real refrigerators.

The inequality of Clausius and the property entropy (s) are modern statements of the second law. The final statement of the second law is the entropy balance equation that includes generation of entropy. All the results that were derived from the classical formulation of the second law in Chapter 7 can be re-derived with the entropy balance equation applied to the cyclic devices. For all reversible processes, entropy generation is zero and all real (irreversible) processes have a positive entropy generation. How large the entropy generation is depends on the actual process.

Thermodynamic property relations for s are derived from consideration of a reversible process and leads to Gibbs relations. Changes in the property s are covered through general tables, approximations for liquids and solids, as well as ideal gases. Changes of entropy in various processes are examined in general together with special cases of polytropic processes. Just as a reversible specific boundary work is the area below the process curve in a P–v diagram, the reversible heat transfer is the area below the process curve in a T–s diagram.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Know that Clausius inequality is an alternative statement of the second law.
- Know the relation between the entropy and the reversible heat transfer.
- Locate states in the tables involving entropy.
- Understand how a Carnot cycle looks in a T–s diagram.
- Know how different simple process curves look in a T–s diagram.
- Understand how to apply the entropy balance equation for a control mass.
- Recognize processes that generate entropy and where the entropy is made.
- Evaluate changes in s for liquids, solids, and ideal gases.
- Know the various property relations for a polytropic process in an ideal gas.
- Know the application of the unsteady entropy equation and what a flux of s is.

أنت تعلم بأن قانون ثبات الطاقة ينص على أن الطاقة لا تفنى ولا تستحدث من العدم، وإنما تتحول من صورة إلى أخرى، وقد يجعلك ذلك تتساءل، إذا كان لدينا كمية من الوقود تحتوي على طاقة كامنة، وقمنا بوضع هذا الوقود في خزان السيارة وشغلنا محرك السيارة وقدناها لمسافة ما، فإن الوقود سينفذ، فأين ذهبت تلك الطاقة التي كانت في الوقود؟ والإجابة هي أن هذه الطاقة لم تفنى، وإنما تحولت إلى صورة أخرى هي الطاقة الحرارية، بعضها في محرك السيارة، وبعضها في الكابح لإيقاف السيارة، وبعضها أثناء احتكاك أجزاء السيارة بجزيئات الهواء والاسفلت المحيطة بها، كل هذه الطاقة الحرارية خرجت من السيارة إلى الوسط المحيط الذي هو الهواء، والمفترض بناءا على قوانين الاتزان الحراري أن هذه الطاقة ستنتقل من المكان الأعلى حرارة إلى المكان الأقل حرارة إلى أن تتوزع الحرارة بالكامل.

هذه الطاقة، على الرغم من أنها لم تفنى، إلا أنها تحولت إلى طاقة غير متوفرة لنا، ولا توجد طريقة لاسترجاع هذه الطاقة وإعادة استخدامها، فليست هنالك أية قوانين فيزيائية تحقق العكس، أي عودة الطاقة الحرارية التي تبددت في أرجاء الكون وجمعها في مكان واحد للاستفادة منها مرة أخرى، ولذلك فإن هذا هو *مآل الطاقة التي في الكون كلّها، طال الزمن أو قصر، وهو أن تتحول من طاقة متوفرة ومفيدة إلى طاقة مبعثرة أو منعدمة النظام*، وهذا هو المقصود من قانون الثاني للديناميكا الحرارية (The Second Law of Thermodynamics) الذي ينص على أن المسارات في النظام المغلق تسير في محصلتها باتجاه العشوائية وانعدام النظام.

إذا كان هنالك شيء حار وشيء بارد فإن الحرارة ستنتقل من الحار إلى البارد إلى أن يصبحان متساويان في درجة الحرارة، وعندما يصلان إلى درجة الحرارة نفسها فإن انتقال الطاقة سيتوقف ولن يحدث أي شيء، وهنا يقال عن النظام بأنه ميت حراريًا، وهذا هو ما سيحدث للكون كله، وعندها يتوقف كل شيء عن العمل، هذه حقيقة علمية.

The Second Law of Thermodynamics

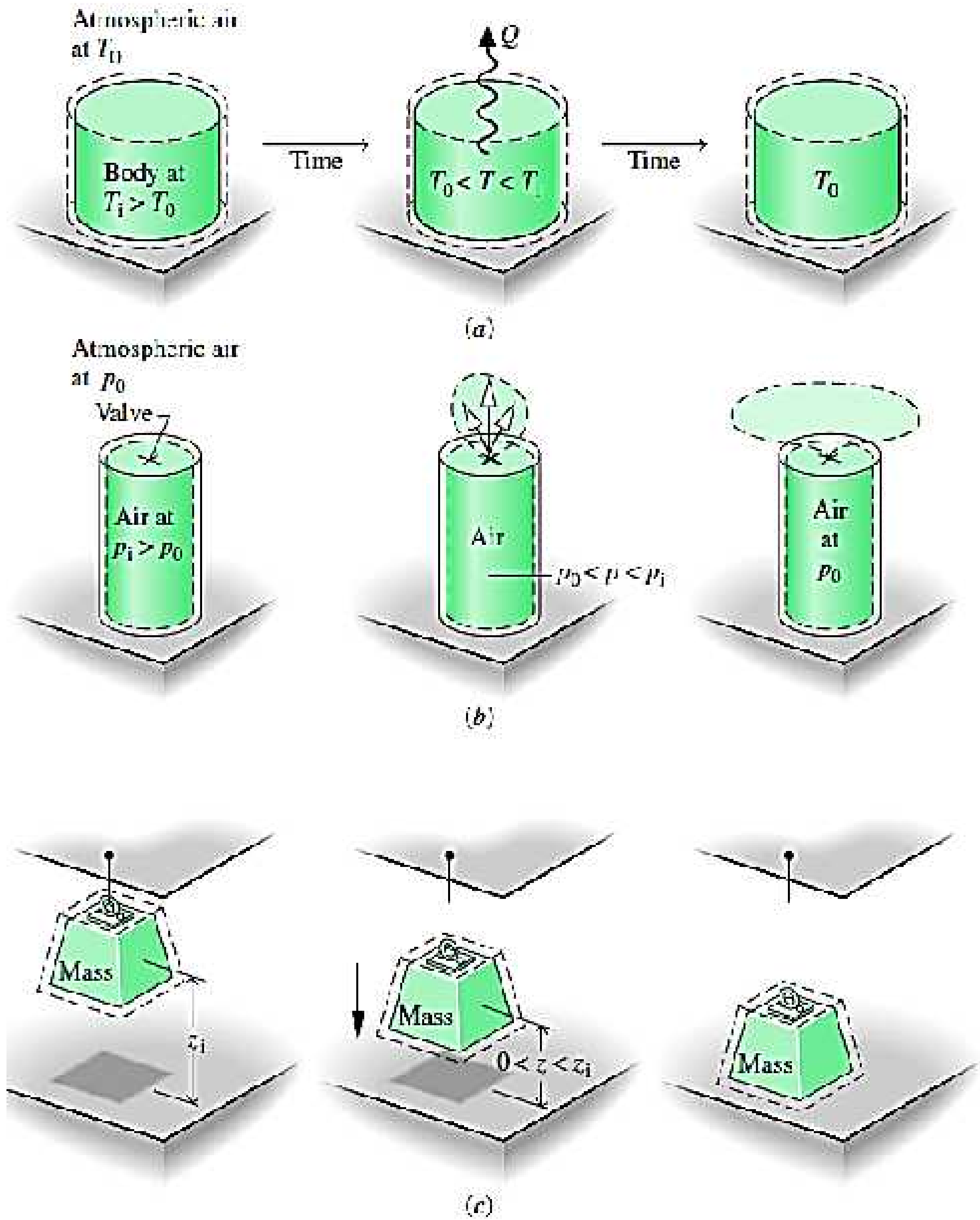
Water flows down a hill, heat flows from a hot body to a cold one, rubber bands unwind, fluid flows from a high-pressure region to a low-pressure region, and we all get old! Our Experiences in life suggest that processes have a definite direction. The first law of thermodynamics relates the several variables involved in a physical process, but does not give any information as to the direction of the process. It is the second law of thermodynamics that helps us establish the direction of a particular process.

Consider, for example, the work done by a falling weight as it turns a paddle wheel thereby increasing the internal energy of air contained in a fixed volume. It would not be a violation of the first law if we postulated that an internal energy decrease of the air can turn the paddle and raise the weight. This, however, would be a violation of the second law and would thus be impossible.

In the first part of this chapter, we will state the second law as it applies to a cycle. It will then be applied to a process and finally a control volume; we will treat the second law in the same way we treated the first law.

Motivating the Second Law

تحفيز القانون الثاني



▲ **Figure 5.1** Illustrations of spontaneous processes and the eventual attainment of equilibrium with the surroundings. (*a*) Spontaneous heat transfer. (*b*) Spontaneous expansion. (*c*) Falling mass.

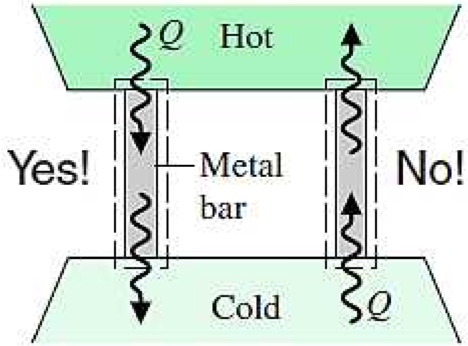
Statements of the Second Law

CLAUSIUS STATEMENT OF THE SECOND LAW

The Clausius statement of the second law asserts that: It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body.

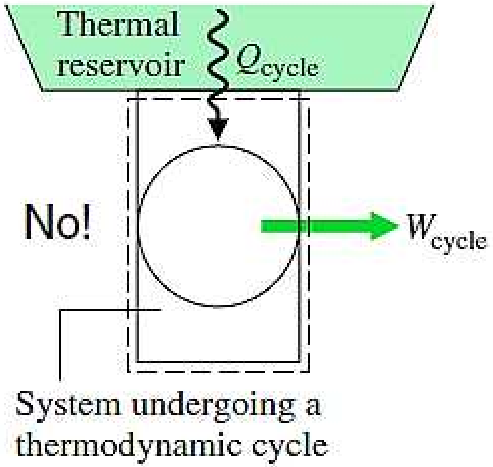
لا يمكن بأي حل من الاحول تحويل كمية من الحرارة الى شغل ميكانيكي دون ان يتم نقل كمية الحرارة من جسم ساخن الى جسم اخر بارد

من المستحيل ان تكون هناك عملية تكون نتيجتها الجوهرية الوحيدة هي انتقل حرارة من جسم بارد الى جسم ساخن“



KELVIN–PLANCK STATEMENT OF THE SECOND LAW

It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surroundings while receiving energy by heat transfer from a single thermal reservoir



-مماسبق يمكننا وضع الحقائق التالية
١- يمكن يضيع الشغل ويتحول بكاملة الى حرارة لكن العكس غير ممكن
٢- الحرارة تتدفق تلقائيا من الجسم الساخن الى الجسم البارددون مساعدة
٣- تتدفق الغازات المحجوزة تحت ضغط عالي عبر ثقب يؤدي الى منطقة ضغطها منخفض
ولا يحدث العكس
٤- تختلط الغازات المختلفة (اوسؤائل مختلف) بعضها ببعض تلقائيا اذا ما تركت حرة متجاورة
ولكن لا يمكن ان ينفصل غازان (اوسائلان) عن بعضها بدون اجراء عملية (بذل شغل خارجي)
من نوع معين----
قانون الديناميكا الأول هو حالة خاصة لقانون الطبيعة العام (قانون حفظ الطاقة) الذي يؤكد أن الحرارة قادرة على التحول إلى شغل وبالعكس ، دون أن يُشير إلى الشروط
التي تحصل فيها هذه التحولات وبما أن القانون الأول لا يبحث مطلقاً في اتجاه العملية الحرارية ، لذا لا يمكن تعيين طبيعتها ونتائجها منه فمثلاً لا يُجيب القانون الأول على السؤل التالي :
هل يتم انتقال الحرارة من الجسم الساخن إلى البارد أم العكس ؟
بينما يُبين الواقع أن الحرارة تنتقل تلقائياً فقط من الجسم الساخن إلى الوسط الأكثر برودة ويبقى الانتقال مستمراً بينهما حتى يحل التوازن الحراري التام .
أما تغيير اتجاه حركة الحرارة فيتم ببذل شُغل ما لأن الشغل كغيره من أنواع الطاقة المشاركة في عملية ما ، يتحول كلياً إلى بسهولة إلى حرارة .
ولقد عرف الانسان منذ عهود قديمة تحول الشغل كله إلى حرارة فكان يحصل على النار بالاحتكاك وغير ذلك وكذلك في الطبيعة تجري عمليات تحول الشغل إلى حرارة بشكل مستمر ومثل ذلك : الاحتكاك - الاصطدام - الكبح ...
أما بالنسبة لتحول الحرارة إلى شغل فيختلف الأمر تماماً فمثلاً يحدث هذا التحول في الآلات الحرارية فقط بوجود فرق في درجتي حرارة مصدر الحرارة ومُستقبلها ، علماً أنه
عندئذ لا يمكن أن تتحول كل الحرارة إلى شغل ، وينتج مما تقدم أن ثمة فرق كبير بين تحول الحرارة إلى شغل وبالعكس .

5.1 Heat Engines, Heat Pumps, and Refrigerators

We refer to a device operating on a cycle as a heat engine, a heat pump, or a refrigerator, depending on the objective of the particular device. If the objective of the device is to perform work it is a *heat engine;* if its objective is to transfer heat to a body it is a *heat pump;* if its objective is to transfer heat from a body, it is a *refrigerator.*

Generically, a heat pump and a refrigerator are collectively referred to as a refrigerator. A schematic diagram of a simple heat engine is shown in Fig. 5.1. An engine or a refrigerator operates between two *thermal energy reservoirs,* entities that are capable of providing or accepting heat without changing temperatures. The atmosphere and lakes serve as *heat sinks;* furnaces, solar collectors, and burners serve as *heat sources.* Temperatures *TH* and *TL* identify the respective temperatures of a source and a sink. The net work *W* produced by the engine of Fig. 5.1 in one cycle would be equal to the net heat transfer, a consequence of the first law :

$$W = Q_H - Q_L$$

where *QH* is the heat transfer to or from the high-temperature reservoir, and *QL* is the heat transfer to or from the low-temperature reservoir.

If the cycle of Fig. 5.1 were reversed, a net work input would be required, as shown in Fig. 5.2. A heat pump would provide energy as heat *QH* to the warmer body (e.g., a house), and a refrigerator would extract energy as heat *QL* from the cooler body (e.g., a freezer). The work would also be given by above equation , where we use magnitudes only.

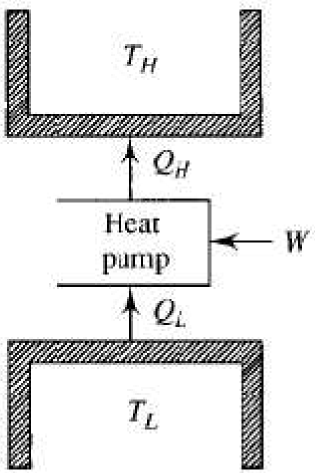


Figure 5.2 A refrigerator.

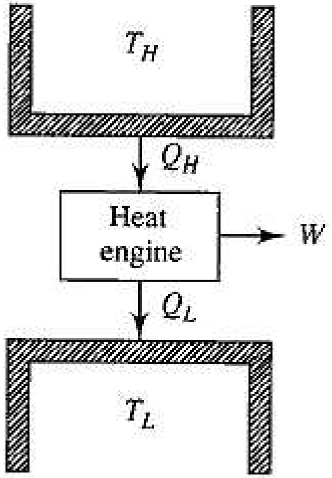


Figure 5.1 A heat engine.

The *thermal efficiency* of the heat engine and the *coefficients of performance* (abbreviated COP) of the refrigerator and the heat pump are defined as follows:

$$\eta = \frac{W}{Q_H} \qquad COP_{refrig} = \frac{Q_L}{W} \qquad COP_{h.p.} = \frac{Q_H}{W} \qquad COP = \frac{Q_L}{W} = \frac{T_L}{T_H - T_L}$$

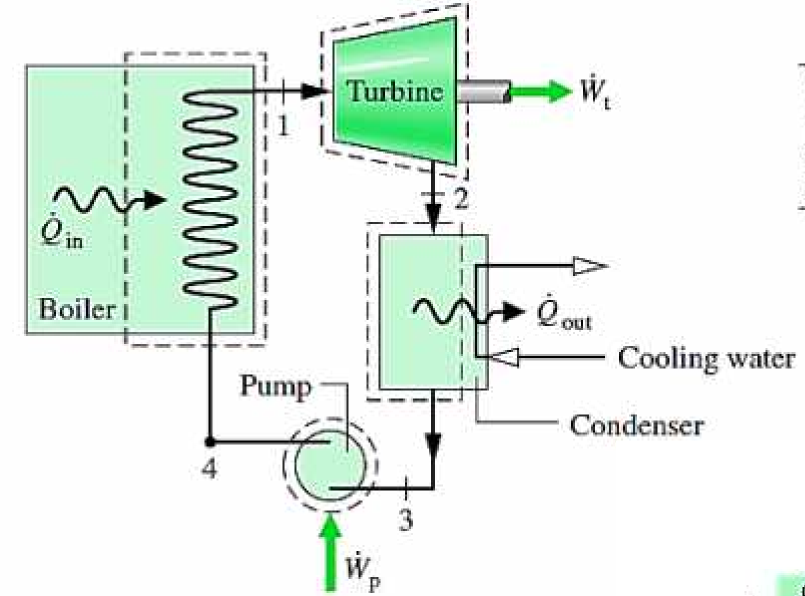
$$\eta = \frac{\dot{W}}{\dot{Q}_H} = 1 - \frac{T_L}{T_H} \qquad \eta_{thermal} = \frac{W(\text{energy sought})}{Q_H(\text{energy that costs})} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

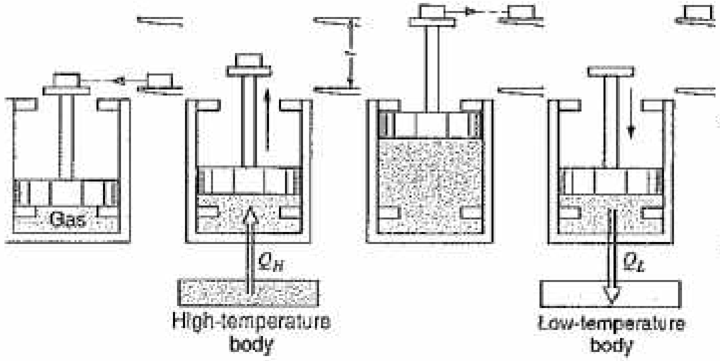
where W is the net work output of the engine or the work input to the refrigerator.
Each of the performance measures represents the desired output divided by the input (energy that is purchased).
The second law of thermodynamics will place limits on the above measures of performance. The first law would allow a maximum of unity for the thermal efficiency and an infinite coefficient of performance. The second law, however, establishes limits that are surprisingly low, limits that cannot be exceeded regardless of the cleverness of proposed designs.
One additional note: There are devices that we will refer to as heat engines that do not strictly meet our definition; they do not operate on a thermodynamic cycle but instead exhaust the working fluid and then intake new fluid. The internal combustion engine is an example. Thermal efficiency, as defined above, remains a quantity of interest for such engines.

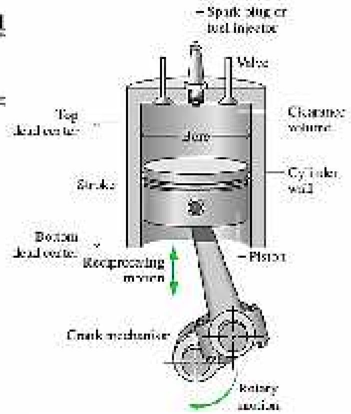
Heat engines vary greatly in size and shape, from large steam engines, gas turbines, or jet engines, to gasoline engines for cars and diesel engines for trucks or cars, to much smaller engines for lawn mowers or hand-held devices such as chain saws or trimmers. Typical values for the thermal efficiency of real engines are about 35–50% for large power plants, 30–35% for gasoline engines, and 35–40% for diesel engines. Smaller utility-type engines may have only about 20% efficiency, owing to their simple carburetion and controls and to the fact that some losses scale differently with size and therefore represent a larger fraction for smaller machines.

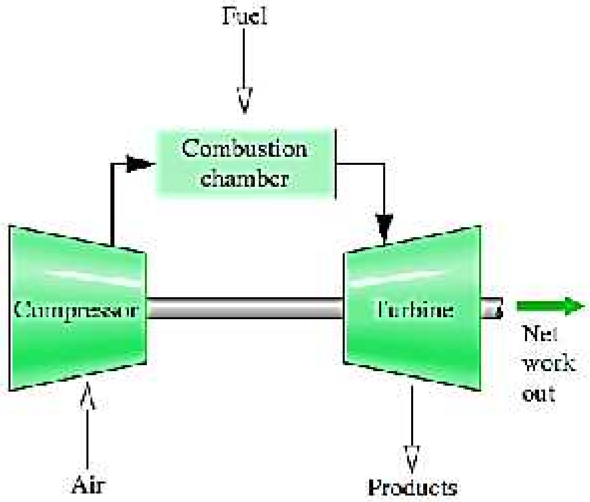
Heat Engine

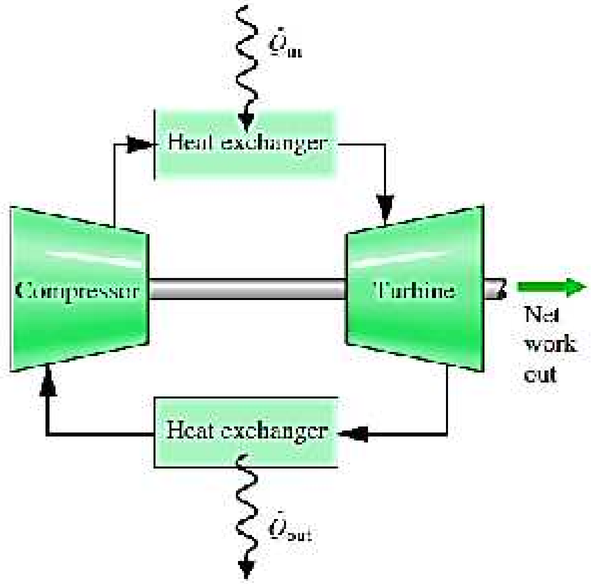
Steam turbine







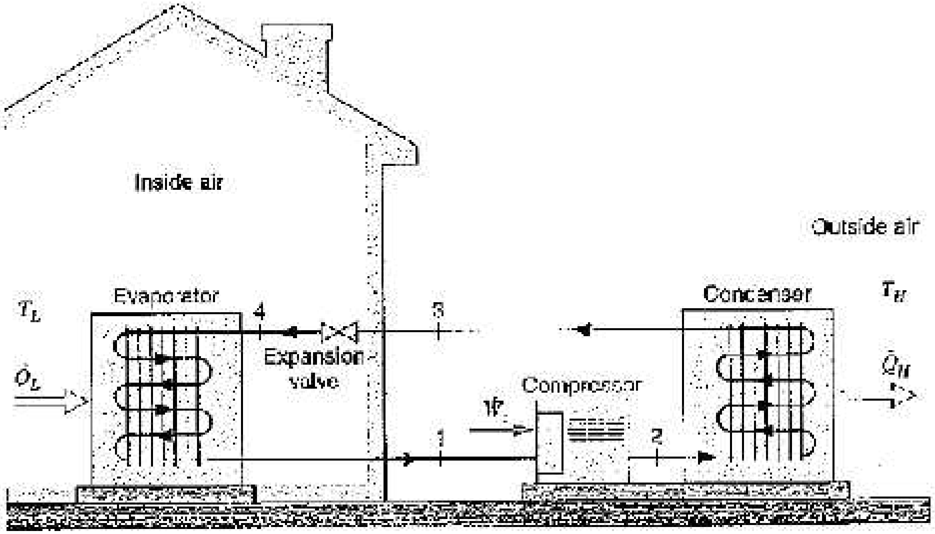




$$\eta_{thermal} = \frac{W(\text{energy sought})}{Q_H(\text{energy that costs})} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

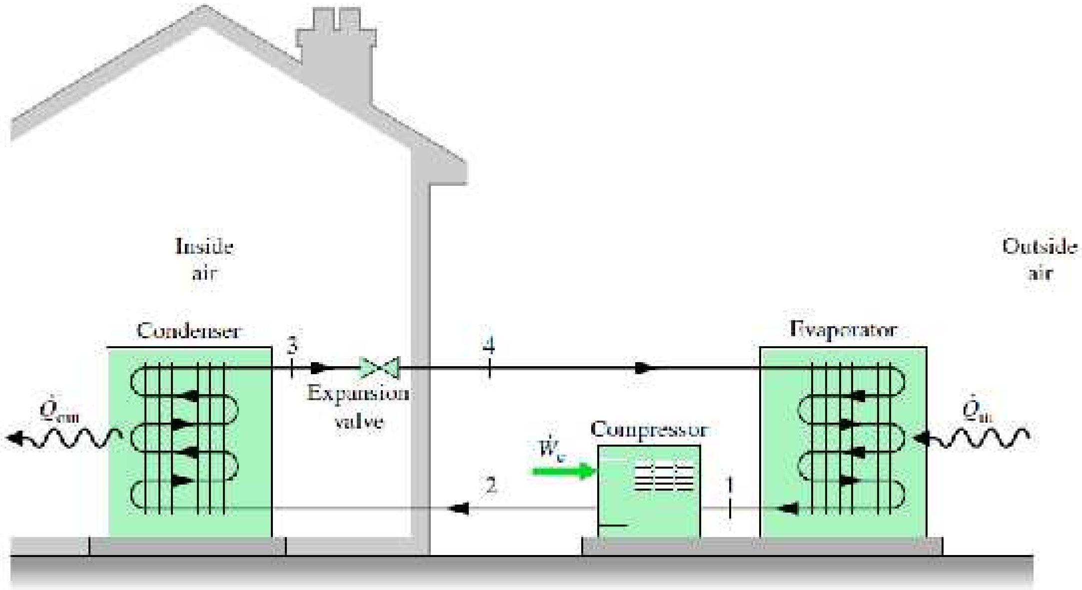
gas turbine

Heat Pump and Refrigerator



An air conditioner in cooling mode

Refrigerator



Heat Pump

Example

An automobile engine produces 136 hp on the output shaft with a thermal efficiency of 30%. The fuel it burns gives 35 000 kJ/kg as energy release. Find the total rate of energy rejected to the ambient and the rate of fuel consumption in kg/s.

Solution

From the definition of a heat engine efficiency, Eq. 7.1, and the conversion of hp from Table A.1 we have:

$$\dot{W} = \eta_{eng}\dot{Q}_H = 136 \text{ hp} \times 0.7355 \text{ kW/hp} = 100 \text{ kW}$$

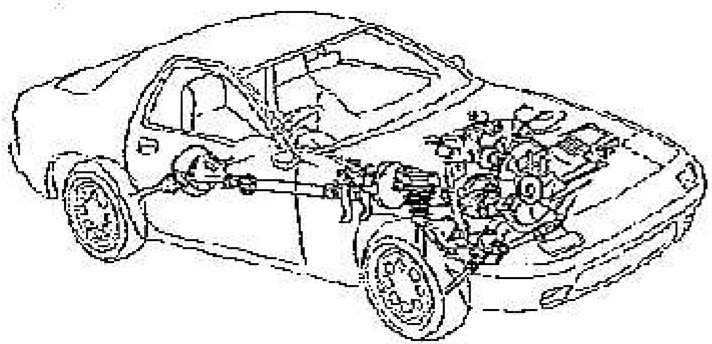
$$\dot{Q}_H = \dot{W}/\eta_{eng} = 100/0.3 = 333 \text{ kW}$$

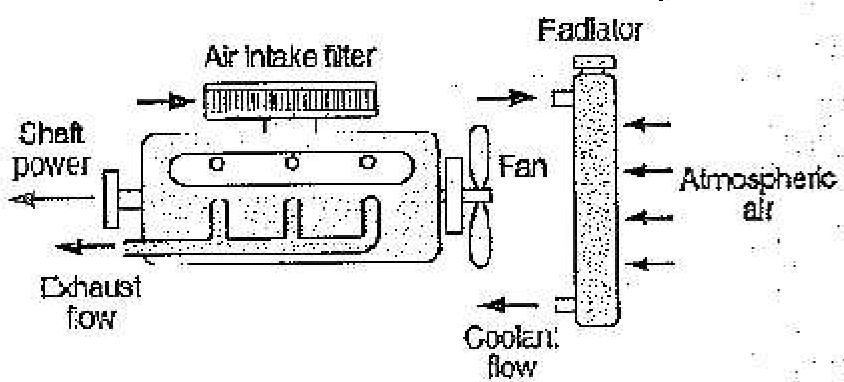
The energy equation for the overall engine gives:

$$\dot{Q}_L = \dot{Q}_H - \dot{W} = (1 - 0.3)\dot{Q}_H = 233 \text{ kW}$$

From the energy release in the burning we have: $\dot{Q}_H = \dot{m}q_H$, so

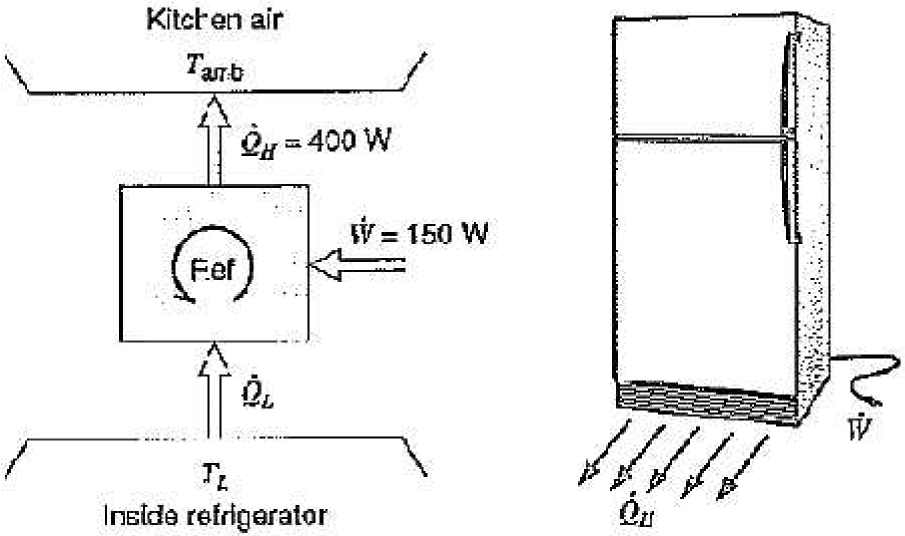
$$\dot{m} = \dot{Q}_H/q_H = \frac{333 \text{ kW}}{35\,000 \text{ kJ/kg}} = 0.0095 \text{ kg/s}$$





Example

The refrigerator in a kitchen shown in Fig. 7.7 receives an electrical input power of 150 W to drive the system, and it rejects 400 W to the kitchen air. Find the rate of energy taken out of the cold space and the coefficient of performance of the refrigerator.



Solution

C.V. refrigerator. Assume steady state so there is no storage of energy. The information provided is $\dot{W} = 150$ W, and the heat rejected is $\dot{Q}_H = 400$ W.

The energy equation gives:

$$\dot{Q}_L = \dot{Q}_H - \dot{W} = 400 - 150 = 250 \text{ W}$$

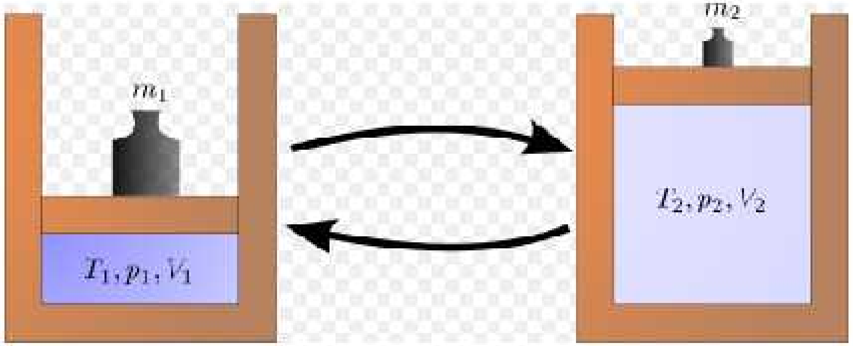
This is also the rate of energy transfer into the cold space from the warmer kitchen due to heat transfer and exchange of cold air inside with warm air when you open the door.

From the definition of the coefficient of performance, Eq. 7.2

$$\text{COP}_{\text{refrig}} \quad \frac{\dot{Q}_L}{\dot{W}} = \frac{250}{150} = 1.67$$

5.3 Reversibility

عملية عكوسية في الكيمياء و الفيزياء (بالإنجليزية : reversible process) تسمى عملية أو دورة بأنها عكوسية عندما يمكن عكسها بواسطة تغير طفيف لأحد خصائص النظام بدون فقد للطاقة. ونظرا لأن التغيرات في النظام تكون طفيفة جدا يكون النظام خلال هذا التغير في حالة توازن حراري. وتحتاج عملية عكوسية إلى فترة زمنية لكي تتم ، ولذلك لا تتم عملية أو دورة عكوسية مثاليا في وقت قصير . وتتسم دورة عكوسية بعدم تغير طاقة النظام وما حوله أثناء الدورة ، أي تكون طاقة النظام وما حوله هي نفسها عند بدء العملية وعند نهايتها . كما يمكن تعريف العملية العكوسية بأنها العملية التي يمكن عكسها بعد انتهائها من غير حدوث أي تغير فيها ولا في الجو المحيط . وبصيغة الحركة الحرارية thermodynamic تعرف العملية أو الدورة بأنها عملية تحول من حالة ترموينواميكية ابتدائية إلى حالة ترموديناميكية أخرى .



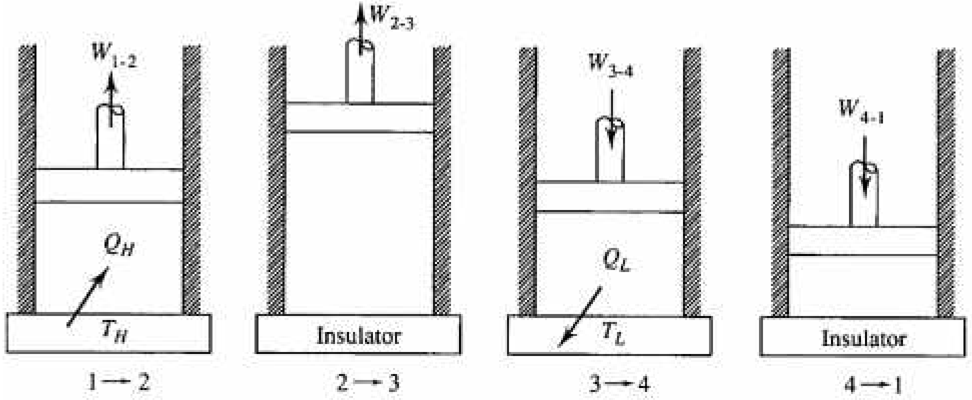
irreversibility

تسمى العملية التي لا تكون عكوسية بأنها عملية "غير عكوسية" . وعند أداء عملية غير عكوسية يتغير النظام ولا يكون النظام خلال سريان العملية في حالة توازن حراري. وقد يكون النظام عند نفس النقطة في دورة عكوسية في نفس الحالة ، ولكن الجو المحيط به يكون قد تغير بعد كل دورة .

أمثلة على تغير الحالات غير عكوسية نذكرها مثل انتقال الحرارة من جسم ساخن إلى جسم بارد ، و اختلاط غازين ، أو اختلاط السوائل ، والاحتكاك حيث تتحول طاقة حركة إلى طاقة حرارية ، وعملية تنفيث الضغط (حيث يتغير الضغط الماء أو الغاز إلى حركة) .

5.5 The Carnot Engine

The heat engine that operates the most efficiently between a high-temperature reservoir and a low-temperature reservoir is the *Carnot engine.* It is an ideal engine that uses reversible processes to form its cycle of operation; thus it is also called a *reversible engine.* We will determine the efficiency of the Carnot engine and also evaluate its reverse operation.



1 → 2: *Isothermal expansion.* Heat is transferred reversibly from the high-temperature reservoir at the constant temperature T_H. The piston in the cylinder is withdrawn and the volume increases.

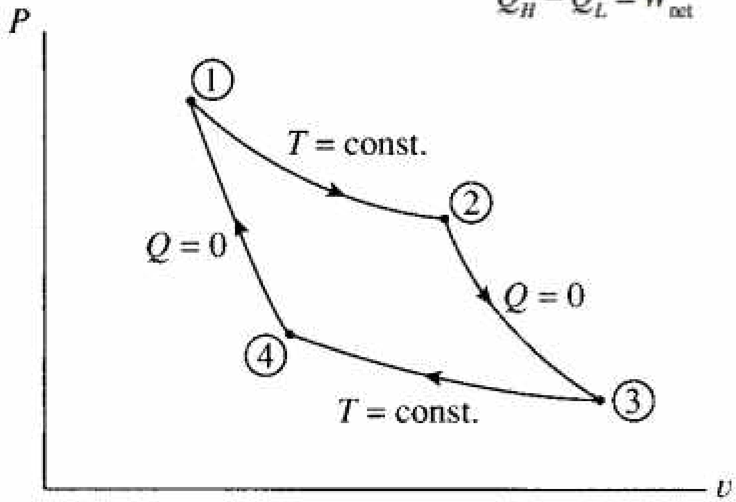
2 → 3: *Adiabatic reversible expansion.* The cylinder is completely insulated so that no heat transfer occurs during this reversible process. The piston continues to be withdrawn, with the volume increasing.

3 → 4: *Isothermal compression.* Heat is transferred reversibly to the low-temperature reservoir at the constant temperature T_L. The piston compresses the working substance, with the volume decreasing.

4 → 1: *Adiabatic reversible compression.* The completely insulated cylinder allows no heat transfer during this reversible process. The piston continues to compress the working substance until the original volume, temperature, and pressure are reached, thereby completing the cycle.

Applying the first law to the cycle, we note that

$$Q_H - Q_L = W_{net}$$



Applying the first law to the cycle, we note that

$$Q_H - Q_L = W_{\text{net}}$$

where Q_L is assumed to be a positive value for the heat transfer to the low-temperature reservoir. This allows us to write the thermal efficiency [see Eq. (5.2)] for the Carnot cycle as

$$\eta = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

The following examples will be used to prove the following three postulates:

Postulate 1 *It is impossible to construct an engine, operating between two given temperature reservoirs, that is more efficient than the Carnot engine.*

Postulate 2 *The efficiency of a Carnot engine is not dependent on the working substance used or any particular design feature of the engine.*

Postulate 3 *All reversible engines, operating between two given temperature reservoirs, have the same efficiency as a Carnot engine operating between the same two temperature reservoirs.*

5.6 Entropy

مصطلح **إنتروبي** (**entropy** يعرب أحيانا بكلمة **اعتلاج** أصل الكلمة مأخوذ عن اليونانية ومعناها **"تحول"** . أصبحت الإنتروبيا أو الإنتروبي مصطلحا أساسيا في الفيزياء والكيمياء ضمن قوانين التحريك الحراري في الغازات أو السوائل ، وخاصة بالنسبة للقانون الثاني للثرموديناميك، الذي يتعامل مع العمليات الفيزيائية للأنظمة الكبيرة المكونة من جزيئات بالغة الأعداد ويبحث سلوكها كعملية تتم تلقائيا أم لا. ينص القانون الثاني للديناميكا الحرارية على مبدأ أساسي يقول : أي تغير يحدث تلقائيا في نظام فيزيائي لا بد وأن يصحبه ازدياد في مقدار "إنتروبيته".

يميل أي نظام مغلق إلى التغير أو التحول تلقائيا بزيادة أنتروبيته حتى يصل إلى حالة توزيع متساو في جميع أجزائه، مثل تساوي درجة الحرارة ، وتساوي الضغط ، وتساوي الكثافة وغير تلك الصفات. وقد يحتاج النظام المعزول الوصول إلى هذا التوازن بعضا من الوقت. مثال على ذلك إلقاء قطرة من الحبر الأزرق في كوب ماء، نلاحظ أن قطرة الحبر تذوب وتنتشر رويدا رويدا في الماء حتي يصبح كل جزء من الماء متجانسا بما فيه من حبر وماء، فنقول أن أنتروبية النظام تزايدت. أي أن مجموع إنتروبية نقطة الحبر النقية + إنتروبية الماء النقية تكون أقل من إنتروبية النظام "حبر ذائب في ماء" . قد أصبح للإنتروبيا كأحد الصفات الطبيعية لنظام أهمية من خلال علاقة الإنتروبيا **بتحول** الطاقة الحرارية إلى شغل ميكانيكي. فنجدها تلعب دورا هاما في تحديد كفاءة آلات ، مثل محرك الاحتراق الداخلي ومحرك الديزل وغيرها.

ولوصف مدلول الإنتروبيا نفترض المثال المذكور أعلاه وهو مثال الماء ونقطة الحبر الذائبة فيه فنجد أن اختلاط نقطة الحبر بالماء سهل ويتم طبيعيا، أما إذا أردنا فصل نقطة الحبر ثانيا عن الماء ليصبح لدينا ماء نقي وحبر نقي فتلك عملية صعبة ولا تتم إلا ببذل شغل. فنقول أن حالة المخلوط له إنتروبيا كبيرة، بينما حالة الماء النقي والحبر النقي فهي حالة يكون أنتروبيتها منخفضة.

وتصادفنا مثل تلك العملية عمليات يومية مثل فصل السكر عن محلول قصب السكر ، إننا نقوم بذلك عن طريق تبخير المحلول ، أي بتسخين المحلول وبذل شغل ، أي بذل طاقة ، لفصل السكر عن الماء.

لماذا الإنتروبيا؟

الطاقة **تتحول** من صورة إلى أخرى ولكنها لا تستهلك ، أي لا تفنى ! فمثلا يمكن للطاقة أن تتحول إلى شغل ديناميكي أو إلى حرارة (هذا ما ينص عليه القانون الأول للديناميكا الحرارية وكذلك ما ينص عليه قانون بقاء الطاقة). خلال عمل محرك يعمل بالبنزين فإنه يستخدم الطاقة المخزونة في الوقود في تحريك السيارة (شغل ميكانيكي) ويطرد بعض الحرارة مع غاز العادم. ونظرا لأن حركة أجزاء السيارة وحركة السيارة نفسها تتحول بالاحتكاك إلى حرارة ، فنجد أن الطاقة التي كانت أصلا مخزونة في الوقود تتحول أخيرا إلى حرارة تنتشر في الجو ، بصرف النظر عن تحول بعضها إلى طاقة الوضع كصعود جبل أو طاقة خزنت بعضها في بطارية السيارة. نجد أن **الطاقة لا تفنى** وإنما "تتحول" من صورة إلى أخرى. لهذا نحتاج إلى كمية نعرف بها "إمكانية إنتاج شغل" من الطاقة حيث أن كمية الطاقة وحدها لا تعطينا كمية الشغل المستفاد من الطاقة.

على سبيل المثال يوجد في محيطات العالم طاقة مخزونة هائلة. ولكن نظرا لأن درجة حرارة البحار تساوي تقريبا درجة حرارة الجو ، فلا يمكننا الاستفادة من الطاقة المخزونة في البحار.

صاغ العالم رودولف كلاوسيوس معادلة الإنتروبيا وتبين له أنه يمكن تحويل كمية من الحرارة إلى شغل ميكانيكي خلال دورة حيث تنتقل الحرارة من درجة حرارة عالية إلى وسط ذو درجة حرارة منخفضة ، وأنه كلما زادت درجة الحرارة الابتدائية في آلة كلما زادت كمية الشغل المكتسبة من فرق درجتي الحرارة الابتدائية والنهائية.

وفي مثالنا السابق عن محرك احتراق داخلي يشتعل الوقود داخل أسطوانة المحرك وتصل درجة حرارة الغاز المحترق بين ٢٠٠٠ و ٢٥٠٠ درجة مئوية ويخرج من المحرك وتكون درجة حرارته النهائية قد انخفضت إلى نحو ٨٠٠ درجة مئوية ، ويخرج كغاز عادم. وباستخدام معادلات كلاوسيوس يمكننا تقدير كمية الشغل الناتج الذي يعطيه المحرك على أفضل الشروط.

الطاقة التي زودنا بها المحرك عن طريق الوقود كان لها إنتروبي منخفض بينما حرارة العادم فلها إنتروبي عالي. وعن طريق تعيين الفرق بينهما يمكننا حساب الشغل المكتسب. وطبقا ل القانون الثاني للديناميكا الحرارية يقول أنه في دورة عكوسية يكون الإنتروبي ثابتا، بينما في دورة غير عكوسية فلا بد له من أن يزداد. هذا مايقوله القانون الثاني للديناميكا الحرارية

5.6 Entropy

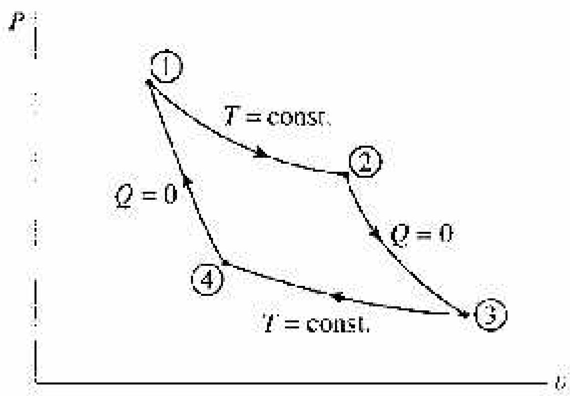
To allow us to apply the second law of thermodynamics to a process we will identify a property called entropy. This will parallel our discussion of the first law; first we stated the first law for a cycle and then derived a relationship for a process.

Consider the reversible Carnot engine operating on a cycle consisting of the processes described in Sec. 5.5. The quantity $\oint \delta Q/T$ is the cyclic integral of the heat transfer divided by the absolute temperature at which the heat transfer occurs. Since the temperature *TH* is constant during the heat transfer *QH* and *TL* is constant during heat transfer *QL*, the integral is given by

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \qquad *$$

where the heat *QL* leaving the Carnot engine is considered to be positive. Using Eqs.

$$\eta = 1 - \frac{T_L}{T_H} \qquad \eta = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$



we see that, for the Carnot cycle,

$$\frac{Q_L}{Q_H} = \frac{T_L}{T_H} \quad \text{or} \quad \frac{Q_H}{T_H} = \frac{Q_L}{T_L}$$

Substituting this into Eq. *, we find the interesting result

$$\oint \frac{\delta Q}{T} = 0$$

Thus, the quantity $\delta\, Q/T$ is a perfect differential, since its cyclic integral is zero. We let this differential be denoted by *dS*, where *S* depends only on the state of the system. This, in fact, was our definition of a property of a system. We shall call this extensive property *entropy;* its differential is given by

$$dS = \left.\frac{\delta Q}{T}\right|_{\text{rev}}$$

where the subscript “rev” emphasizes the reversibility of the process. This can be integrated for a process to give

$$\Delta S = \int_1^2 \frac{\delta Q}{T}\bigg|_{\text{rev}}$$

From the above equation we see that the entropy change for a reversible process can be either positive or negative depending on whether energy is added to or extracted from the system during the heat transfer process. For a reversible adiabatic process (Q = 0) the entropy change is zero. If the process is adiabatic but irreversible, it is not generally true that ΔS = 0.

We often sketch a temperature-entropy diagram for cycles or processes of interest. The Carnot cycle provides a simple display when plotting temperature vs. entropy; it is shown in Fig. 5.7. The change in entropy for the first isothermal process from state 1 to state 2 is

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} = \frac{Q_H}{T_H}$$

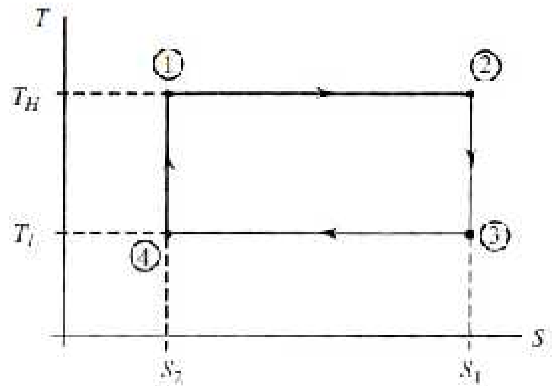


Figure 5.7 The Carnot cycle.

The entropy change for the reversible adiabatic process from state 2 to state 3 is zero. For the isothermal process from state 3 to state 4 the entropy change is negative that of the first process from state 1 to state 2; the process from state 4 to state 1 is also a reversible adiabatic process and is accompanied with a zero entropy change. The heat transfer during a reversible process can be expressed in differential form as

$$dS = \frac{\delta Q}{T}\bigg|_{\text{rev}} \qquad \delta Q = TdS \qquad \text{or} \qquad Q = \int_1^2 TdS$$

Hence, the area under the curve in the *T-S* diagram represents the heat transfer during any reversible process. The rectangular area in Fig. 5.6 thus represents the net heat transfer during the Carnot cycle. Since the heat transfer is equal to the work done for a cycle, the area also represents the net work accomplished by the system during the cycle. For this Carnot cycle $Q_{\text{net}} = W_{\text{net}} = \Delta T \Delta S.$

The first law of thermodynamics, for a reversible infinitesimal change, becomes, using the last equation ,

$$TdS - PdV = dU$$

This is an important relationship in our study of simple systems. We arrived at it assuming a reversible process. However, since it involves only properties of the system, it holds for any process including any irreversible process. If we have an irreversible process, in general, $\delta W \neq PdV$ and $\delta Q \neq TdS$ but previous equation still holds as a relationship between the properties since changes in properties do not depend on the process. Dividing by the mass, we have

$$Tds - Pdv = du \qquad **$$

where the specific entropy is $s = S/m$.

To relate the entropy change to the enthalpy change we differentiate the definition of enthalpy and obtain

$$dh = du + Pdv + vdP$$

Substituting into Eq. ** for *du,* we have

$$Tds = dh - vdP \qquad ***$$

Equations ** and *** will be used in subsequent sections of our study of thermodynamics for various reversible and irreversible processes.

A rigid tank of volume $0.5m^3$ contains saturated water mixture with quality of 50% at 120°C is heated until its temperature becomes 200°C. Find (a) final state of the water and pressure, (b) heat transfer (c) change of entropy.

Solution: The given rigid tank $V=0.5m^3$ sat water T1=120°C, x1=0.5

The final temperature is T2=200°C

At T_1= 120°C and from sat. Water table it is found that

$v_{f1} = 0.001060 m^3/kg \quad v_{g1} = 0.8919 m^3/kg$

$u_{f1} = 503.5 kJ/kg \quad u_{fg1} = 2025.8 kJ/kg$

$s_{f1} = 1.5276 kJ/kg.K \quad s_{fg1} = 5.602 kJ/kg.K$

$$v_1 = v_{f1} + x_1(v_{g1} - v_{f1}) = 0.00106 + 0.5 \times (0.8919 - 0.00106) = 0.44648 m^3/kg$$

$$m = \frac{V}{v_1} = \frac{0.5}{0.44648} = 1.12 kg$$

$$u_1 = u_{f1} + x_1 u_{fg1} = 503.5 + 0.5 \times 2025.8 = 1516.4 kJ/kg$$

$$s_1 = s_{f1} + x_1 s_{fg1} = 1.5276 + 0.5 \times 5.602 = 4.3286 kJ/kg.K$$

Because the tank is rigid $v_1 = v_2$

$v_2 = 0.44648 m^3/kg \quad at \quad T_2 = 200^o C$

It is found that the second state is super-heated steam because $v_2 > v_g$ at the temperature 200°C. The pressure is between 0.4MPa and 0.5MPa

And by using the interpolation as follows

P MPa	v m³/kg	u kJ/kg	s kJ/kg.K
0.4	0.5342	2646.8	7.1706
.48	0.44648	2643.67	7.0812
0.5	0.4249	2642.9	7.0592

(a) the final pressure is P_2=480kPa

(b) because the tank is rigid

$$Q = \Delta U = m\Delta u = 1.12(2646.67 - 1516.4) = 1265.9 kJ$$

$$\Delta S = m\Delta s = m(s_2 - s_1) = 1.12(7.0812 - 4.3286) = 3.083$$

Piston cylinder contains 2kg of steam at a pressure of 200kPa and quality of 75% is heated with constant pressure until it becomes dry saturated vapor. Find (a) the work done (b) the heat transfer and (c) the change in entropy.

Solution: the given sat. water mixture at P_1=200kPa and x_1=0.75 m=2kg, the final state is sat. vapor at the same pressure of 200kPa.

(a) $v_1 = v_f + x_1 v_{fg}$ *and* $v_2 = v_g$ *at* $P = 200\,kPa$

$$W = P(V_2 - V_1) = Pm(v_2 - v_1) = Pm(v_g - (v_f + x_1 v_{fg}))$$

$$W = Pm(v_{fg} - x_1 v_{fg})Pm(1 - x_1)(v_g - v_f) = 200 \times 2 \times (1 - 0.75)(0.8857 - 0.001061)$$

$$W = 88.464\,kJ$$

(b) $h_1 = h_f + x_1 h_{fg}$ and $h_2 = h_g$

$$Q = m\Delta h = m(h_2 - h_1) = m(1 - x_1)h_{fg} = 2 \times (1 - 0.75) \times 2209.1 = 1104.55\,kJ$$

(c) $s_1 = s_f + x_1 s_{fg}$ *and* $s_2 = s_g$

$$\Delta S = m(s_2 - s_1) = m(1 - x_1)s_{fg} = 2 \times (1 - 0.75) \times 5.597 = 2.7985\,kJ / K$$

Piston cylinder device contains 0.5kg of refrigerant-12 at 20°C and quality of 40%. The refrigerant is expanded isothermally until its final pressure becomes 240kPa. Find (1) the change in entropy (2) heat transfer (3) the work done.

Solution: the given R-12 $T_1=T_2=20°C$, $x_1=0.4$, $P_2=240kPa$

At the initial state

$$u_1 = u_f + x_1 u_{fg} = 54.44 + 0.4 \times (178.32 - 54.44) = 103.992\, kJ/kg$$

$$s_1 = s_f + x_1 s_{fg} = 0.2078 + .4 \times (0.6884 - 0.2078) = 0.4\, kJ/kg.K$$

At the final state

$$u_2 = 182.53\, kJ/kg \quad s_2 = 0.7624\, kJ/kg.K$$

(1) $\Delta S = m(s_2 - s_1) = 0.5 \times (0.7624 - 0.4) = 0.1812\, kJ/K$

(2) The process is isothermal so T=constant

$$Q = \int TdS = T\int dS = T\Delta S = (20 + 273) \times 0.1812 = 53.092\, kJ$$

(3) $W = Q - \Delta U = 53.092 - 0.5 \times (182.53 - 103.992) = 13.787\, kJ$

One kg of steam at a pressure of 700kPa and quality of 80% is expanded hyperbolically to a pressure of 150kPa. Determine (a) the final state of the vapor and (b) change in entropy

Solution: the given m=1kg , P_1=700kPa, x_1=0.8 , P_2=150kPa

The Process is hyperbolically $P_1V_1=P_2V_2$

At P_1=700kPa, x_1=0.8

$$v_1 = v_f + x_1\left(v_g - v_f\right) = 0.001108 + 0.8\times\left(0.0.2729 - 0.001108\right) = 0.21854\,m^3/kg$$

$$s_1 = s_f + x_1 s_{fg} = 1.9922 + 0.8\times 4.7158 = 5.7648\,kJ/kg.K$$

$$v_2 = \frac{P_1 v_1}{P_2} = \frac{700\times 0.21854}{150} = 1.01985\,m^3/kg$$

$$v_2 < v_g \quad at \quad P_2 = 150\,kPa$$

$$x_2 = \frac{v_2 - v_f}{v_g - v_f} = \frac{1.0198 - 0.001053}{1.1593 - 0.001053} = 0.8796 = 87.96\%$$

$$s_2 = s_f = x_2 s_{fg} = 1.4336 + 0.8796\times 5.7897 = 6.526\,kJ/kg.K$$

$$\Delta S = m\left(s_2 - s_1\right) = 1\times\left(6.526 - 5.7648\right) = 0.7612\,kJ/K$$

ENTROPY FOR AN IDEAL GAS WITH CONSTANT SPECIFIC HEATS

Assuming an ideal gas

$Tds - Pdv - du$ becomes $ds = \frac{du}{T} + \frac{Pdv}{T} = C_v \frac{dT}{T} + R\frac{dv}{v}$ where we have used $du = C_v\, dT$ and $Pv = RT$.

Last equation is integrated, assuming constant specific heat, to yield

$$s_2 - s_1 = C_v \ln\frac{T_2}{T_1} + R\ln\frac{v_2}{v_1} \qquad ...1$$

$Tds - dh - vdP$ Similarly, this equation is rearranged and integrated to give $s_2 - s_1 = C_p \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}$ ...2

Note again that the above equations were developed assuming a reversible process; however, they relate the change in entropy to other thermodynamic properties at the two end states. Since the change of a property is independent of the process used in going from one state to another, the above relationships hold for any process, reversible or irreversible, providing the working substance can be approximated by an ideal gas with constant specific heats.

If the entropy change is zero, as in a reversible adiabatic process, Eqs. 1 and 2 can be used to obtain

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} \qquad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} \qquad \frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{k}$$

These are, of course, identical to the equations obtained in Chap. 4 for an ideal gas with constant specific heats undergoing a quasiequilibrium adiabatic process. We now refer to such a process as an ***isentropic process***.

EXAMPLE 5.6

Air is contained in an insulated, rigid volume at 20°C and 200 kPa. A paddle wheel, inserted in the volume, does 720 kJ of work on the air. If the volume is 2m^3, calculate the entropy increase assuming constant specific heats

Solution

To determine the fi nal state of the process we use the energy equation, assuming zero heat transfer. We have $-W = \Delta U = m\, C_v\, \Delta T$. The mass *m* is found from the ideal-gas equation to be

$$m = \frac{PV}{RT} = \frac{200 \times 2}{0.287 \times 293} = 4.76 \text{ kg}$$

The first law, taking the paddle-wheel work as negative, is then

$$-W = mC_v \Delta T$$

$$-(-720) = 4.76 \times 0.717 \times (T_2 - 293) \qquad \therefore T_2 = 504.0 \text{ K}$$

Using Eq. (1) for this constant-volume process there results $\Delta S = mC_v \ln \frac{T_2}{T_1} = 4.76 \times 0.717 \times \ln \frac{504}{293} = 1.851 \text{ kJ/K}$

EXAMPLE 5.7

After a combustion process in a cylinder the pressure is 1200 kPa and the temperature is 350°C. The gases are expanded to 140 kPa with a reversible adiabatic process. Calculate the work done by the gases, assuming they can be approximated by air with constant specific heats.

Solution

The first law can be used, with zero heat transfer, to give $-w = \Delta u = C_v (T_2 - T_1)$. The temperature *T*2 is found from Eq. (2) to be

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = 623 \left(\frac{140}{1200}\right)^{0.4/1.4} = 337 \text{ K}$$

This allows the work to be calculated:

$$w = C_v (T_2 - T_1) = 0.717 \times (623 - 337) = 205 \text{ kJ/kg}$$

$0.05m^3$ of air at a pressure of 800kPa and temperature 20°C expands to eight times its original volume and the final temperature after expansion is 25°C. Calculate the change of entropy of air during this process.

Solution: the givens air V_1=0.05m^3, P_1=800kPa, T_1=20°C=293K

$V_2 = 8\times V_1 = 8\times 0.05 = 0.4m^3$, T_2=25°C=298K

$$m = \frac{P_1V_1}{RT_1} = \frac{800\times 0.05}{0.287\times 293} = 0.476kg$$

$$\Delta S = m\left(CvLn\frac{T_2}{T_1} + RLn\frac{V_2}{V_1}\right) = 0.476\left(0.718\,Ln\frac{298}{293} + 0.287\,Ln\frac{8}{1}\right) = 0.29kJ/K$$

Calculate the change of entropy of 2kg of air, when it is heated at constant volume from 100kPa to 400kPa. Also calculate the heat transfer during the process.

Solution: the given Air m=2kg, P_1=100kPa, P_2=400kPa, and the volume is constant then

$$\Delta S = mCvLn\frac{P_2}{P_1} = 2\times 0.718\,Ln\frac{400}{100} = 1.991kJ/K$$

Air occupies $0.084m^3$ at 1.25MPa and 537°C. It is expanded at a constant temperature to a final volume of $0.336m^3$. Calculate:

(i) the pressure at the end of expansion, (ii) work done during expansion (iii) heat transfer to the air, and (iv) the entropy

Solution: the givens air $V_1=0.084m^3$, $P_1=1250kPa$, $T_1=T_2=537°C=810K$, $V_2=0.336m^3$

(i) $$P_2 = P_1\frac{V_1}{V_2} = 1250 \times \frac{0.084}{0.336} = 312.5kPa$$

(ii) $$W = P_1V_1 Ln\frac{V_2}{V_1} = 1250 \times 0.084 \times Ln\frac{0.336}{0.084} = 145.561kJ$$

(iii) Q=W=145.56kJ

(iv) $$\Delta S = \frac{Q}{T} = \frac{145.561}{810} = 0.18kJ/K$$

A volume of $0.14m^3$ of air at 100kPa and 90°C is compressed to $0.014m^3$ according to $PV^{1.3}$=const. Heat is then added at a constant volume until the pressure is 6600kPa. Determine:

(1) heat exchange with the cylinder walls during compression, and

(2) Change of entropy during each portion of the process.

Solution: given Air V_1=0.14m³, P_1=100kPa, T_1=90°C, V_2=0.014m³, P_3=6600kPa, $P_1V_1^{1.3} = P_2V_2^{1.3}$, $V_2 = V_3$

$$m = \frac{P_1V_1}{RT_1} = \frac{100 \times 0.14}{0.287 \times (90 + 273)} = 0.1855\,kg$$

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{n-1} = 363\left(\frac{0.14}{0.014}\right)^{1.3-1} = 724.28\,K$$

$$P_2 = P_1\left(\frac{V_1}{V_2}\right)^{n} = 100\left(\frac{0.14}{0.014}\right)^{1.3} = 1995\,kPa$$

$$W_{12} = \frac{mR(T_2 - T_1)}{1-n} = \frac{0.1855 \times 0.287 \times (724.28 - 363)}{1-1.3} = -64.11kJ$$

$$\Delta U_{12} = mCv(T_2 - T_1) = 0.1855 \times 0.718 \times (724.28 - 363) = 48.12kJ$$

$$Q_{12} = W_{12} + \Delta U_{12} = -64.11 + 48.12 = 15.99\,kJ$$

$$\Delta S_{12} = \frac{mCv(k-1)}{(n-1)} Ln\frac{T_2}{T_1} = \frac{0.1855 \times 0.718(1.4-1)}{1.3-1} Ln\frac{724.28}{363} = 0.12267\,kJ/K$$

The second process is constant volume process so

$$\Delta S_{23} = mCvLn\frac{P_3}{P_2} = 0.1855 \times 0.718 \times Ln\frac{6600}{1995} = 0.159\,kJ/K$$

ENTROPY FOR STEAM, SOLIDS, AND LIQUIDS

The entropy change has been found for an ideal gas with constant specific heats and for an ideal gas with variable specific heats. For pure substances, such as steam, entropy is included as an entry in the steam tables (given in App. C). In the quality region, it is found using the relation

$$s = s_f + x s_{fg}$$

Note that the entropy of saturated liquid water at 0°C is arbitrarily set equal to zero. It is only the change in entropy that is of interest.

For a compressed liquid it is included as an entry in Table C.4, the compressed liquid table, or it can be approximated by the saturated liquid values *sf* at the given temperature (ignoring the pressure). From the compressed liquid table at 10 Mpa and 100°C, *s* = 1.30 kJ/kg · K, and from the saturated steam table C.1 at 100°C, *sf* = 1.31 kJ/kg · K; this is an insignificant difference.

The temperature-entropy diagram is of particular interest and is often sketched during the problem solution. A *T-s* diagram is shown in Fig. 5.8; for steam it is essentially symmetric about the critical point. Note that the high-pressure lines in the compressed liquid region are indistinguish able from the saturated liquid line. It is often helpful to visualize a process on a *T-s* diagram, since such a diagram illustrates assumptions regarding irreversibilities.

For a solid or a liquid, the entropy change can be found quite easily if we can assume the specific heat to be constant. Returning to Eq. (1), we can write, assuming the solid or liquid to be incompressible so that *dv* = 0,

$$Tds = du = CdT$$

where we have dropped the subscript on the specific heat since for solids and liquids $C_p \cong C_v$, such as Table B.4, usually list values for *Cp*; these are assumed to be equal to *C*. Assuming a constant specific heat, we find that

$$\Delta s = \int_{T_1}^{T_2} C\frac{dT}{T} = C\ln\frac{T_2}{T_1}$$

If the specific heat is a known function of temperature, the integration can be performed. Specifi c heats for solids and liquids are listed in Table B.4.

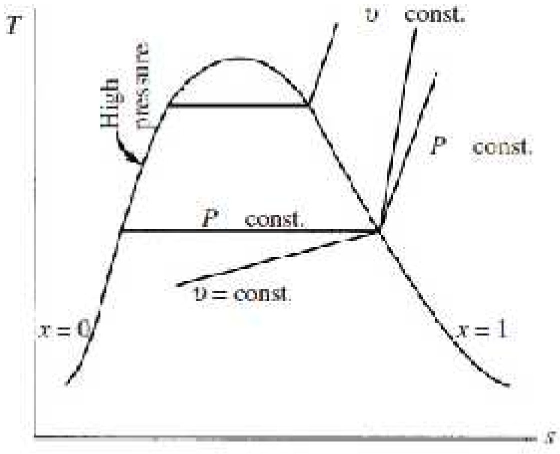


Figure 5.8 The T-s diagram for steam.

EXAMPLE 5.10

Steam is contained in a rigid container at an initial pressure of 600 kPa and 300°C. The pressure is reduced to 40 kPa by removing energy via heat transfer. Calculate the entropy change and the heat transfer.

Solution

From the steam tables, $v_1 = v_2 = 0.4344$ m^3/kg. State 2 is in the quality region. Using the above value for v_2 the quality is found as follows:

$$0.4344 = 0.0011 + x(0.4625 - 0.0011) \qquad \therefore x = 0.939$$

The entropy at state 2 is $s_2 = 1.777 + 0.939 \times 5.1197 = 6.584$ kJ/kg·K.
The entropy change is then

$$\Delta s = s_2 - s_1 = 6.584 - 7.372 = -0.788 \text{ kJ/kg} \cdot \text{K}$$

The heat transfer is found from the first law using $w = 0$ and $u_1 = 2801$ kJ/kg:

$$q = u_2 - u_1 = (604.3 + 0.939 \times 1949.3) - 2801 = -366 \text{ kJ/kg}$$

Quiz No. 1

1. An inventor claims a thermal engine operates between ocean layers at 27 and 10°C. It produces 10 kW and discharges 9900 kJ/min. Such an engine is
   - (A) Impossible
   - (B) Reversible
   - (C) Possible
   - (D) Probable
2. A heat pump is to provide 2000 kJ/h to a house maintained at 20°C. If it is –20°C outside, what is the minimum power requirement?
   - (A) 385 kJ/h
   - (B) 316 kJ/h
   - (C) 273 kJ/h
   - (D) 184 kJ/h
3. Select an acceptable paraphrase of the Kelvin-Planck statement of the second law.
   - (A) No process can produce more work than the heat that it accepts.
   - (B) No engine can produce more work than the heat that it intakes.
   - (C) An engine cannot produce work without accepting heat.
   - (D) An engine has to reject heat.
4. A power plant burns 1000 kg of coal each hour and produces 500 kW of power. Calculate the overall thermal efficiency if each kg of coal produces 6 MJ of energy.
   - (A) 0.35
   - (B) 0.30
   - (C) 0.25
   - (D) 0.20
5. Two Carnot engines operate in series between two reservoirs maintained at 327 and 27°C, respectively. The energy rejected by the first engine is input into the second engine. If the first engine's efficiency is 20 percent greater than the second engine's efficiency, calculate the intermediate temperature.
   - (A) 106°C
   - (B) 136°C
   - (C) 243°C
   - (D) 408°C
6. A heat pump is to maintain a house at 20°C when the outside air is at –25°C. It is determined that 1800 kJ is required each minute to accomplish this. Calculate the minimum power required.
   - (A) 3.87 kW
   - (B) 4.23 kW
   - (C) 4.61 kW
   - (D) 3.99 kW
7. Which of the following entropy relationships is incorrect?
   - (A) Air, $V = \text{const}$: $\Delta s = C_v \ln T_2/T_1$
   - (B) Water: $\Delta s = C_p \ln T_2/T_1$
   - (C) Reservoir: $\Delta s = C_p \ln T_2/T_1$
   - (D) Copper: $\Delta s = C_p \ln T_2/T_1$
8. Two kilograms of air are heated at constant pressure of 200 kPa to 500°C. Calculate the entropy change if the initial volume is 0.8 m^3.
   - (A) 2.04 kJ/K
   - (B) 2.65 kJ/K
   - (C) 3.12 kJ/K
   - (D) 4.04 kJ/K
9. Two kilograms of air are compressed from 120 kPa and 27°C to 600 kPa in a rigid container. Calculate the entropy change.
   - (A) 5.04 kJ/K
   - (B) 4.65 kJ/K
   - (C) 3.12 kJ/K
   - (D) 2.31 kJ/K

10. A paddle wheel provides 200 kJ of work to the air contained in a 0.2-m^3 rigid volume, initially at 400 kPa and 40°C. Determine the entropy change if the volume is insulated.

(A) 0.504 kJ/K

(B) 0.443 kJ/K

(C) 0.312 kJ/K

(D) 0.231 kJ/K

11. 0.2 kg of air is compressed slowly from 150 kPa and 40°C to 600 kPa, in an adiabatic process. Determine the final volume.

(A) 0.0445 m^3

(B) 0.0662 m^3

(C) 0.0845 m^3

(D) 0.0943 m^3

12. A rigid, insulated 4-m^3 volume is divided in half by a membrane. One chamber is pressurized with air to 100 kPa and the other is completely evacuated. The membrane is ruptured and after a period of time equilibrium is restored. The entropy change of the air is nearest

(A) 0.624 kJ/K

(B) 0.573 kJ/K

(C) 0.473 kJ/K

(D) 0.351 kJ/K

13. Ten kilograms of air are expanded isentropically from 500°C and 6 MPa to 400 kPa. The work accomplished is nearest

(A) 7400 kJ

(B) 6200 kJ

(C) 4300 kJ

(D) 2990 kJ

14. Find the work needed to isentropically compress 2 kg of air in a cylinder at 400 kPa and 400°C to 2 MPa.

(A) 1020 kJ

(B) 941 kJ

(C) 787 kJ

(D) 563 kJ

15. Calculate the total entropy change if 10 kg of ice at 0°C are mixed in an insulated container with 20 kg of water at 20°C. Heat of melting for ice is 340 kJ/kg.

(A) 6.19 kJ/K

(B) 3.95 kJ/K

(C) 1.26 kJ/K

(D) 0.214 kJ/K

16. A 5-kg block of copper at 100°C is submerged in 10 kg of water at 10°C, and after a period of time, equilibrium is established. If the container is insulated, calculate the entropy change of the universe.

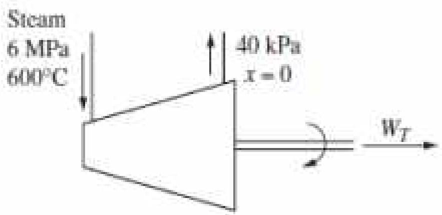
(A) 0.082 kJ/K

(B) 0.095 kJ/K

(C) 0.108 kJ/K

(D) 0.116 kJ/K

17. Find w_T of the insulated turbine shown.



(A) 910 kJ/kg

(B) 1020 kJ/kg

(C) 1200 kJ/kg

(D) 1430 kJ/kg

18. The efficiency of the turbine of Prob. 17 is nearest

(A) 92%

(B) 89%

(C) 85%

(D) 81%

19. A nozzle accelerates steam at 120 kPa and 200°C from 20 m/s to the atmosphere. If it is 85 percent efficient, the exiting velocity is nearest

    (A) 290 m/s

    (B) 230 m/s

    (C) 200 m/s

    (D) 185 m/s

20. A turbine produces 4 MW by extracting energy from 4 kg of steam which flows through the turbine every second. The steam enters at 600°C and 1600 kPa and exits at 10 kPa. The turbine efficiency is nearest

    (A) 82%

    (B) 85%

    (C) 87%

    (D) 91%

Quiz No. 2

1. An engine operates on 100°C geothermal water. It exhausts to a 20°C stream. Its maximum efficiency is nearest

    (A) 21%

    (B) 32%

    (C) 58%

    (D) 80%

2. Which of the following can be assumed to be reversible?

    (A) A paddle wheel

    (B) A burst membrane

    (C) A resistance heater

    (D) A piston compressing gas in a race engine

3. A Carnot engine operates between reservoirs at 20 and 200°C. If 10 kW o power is produced, find the rejected heat rate.

    (A) 26.3 kJ/s

    (B) 20.2 kJ/s

    (C) 16.3 kJ/s

    (D) 12.0 kJ/s

4. An automobile that has a gas mileage of 13 km/L is traveling at 100 km/h. At this speed essentially all the power produced by the engine is used to overcome air drag. If the air drag force is given by $\frac{1}{2}\rho V^2 A C_D$ determine the thermal efficiency of the engine at this speed using projected area $A = 3$ m², drag coefficient $C_D = 0.28$, and heating value of gasoline 9000 kJ/kg. Gasolin has a density of 740 kg/m³.

    (A) 0.431

    (B) 0.519

    (C) 0.587

    (D) 0.652

5. A proposed power cycle is designed to operate between temperature reservoirs of 900 and 20°C. It is supposed to produce 43 hp from the 2500 kJ of energy extracted each minute. Is the proposal feasible?

    (A) No

    (B) Yes

    (C) Maybe

    (D) Insufficient information

6. A Carnot refrigeration cycle is used to estimate the energy requirement in an attempt to reduce the temperature of a specimen to absolute zero. Suppose that we wish to remove 0.01 J of energy from the specimen when it is at 2×10^{-6} K. How much work is necessary if the high-temperature reservoir is at 20°C?

    (A) 622 kJ

    (B) 864 kJ

    (C) 1170 kJ

    (D) 1465 kJ

7. One kilogram of air is heated in a rigid container from 20 to 300°C. The entropy change is nearest

    (A) 0.64 kJ/K

    (B) 0.54 kJ/K

    (C) 0.48 kJ/K

    (D) 0.34 kJ/K

8. Which of the following second law statements is incorrect?

(A) The entropy of an isolated system must remain constant or increase.

(B) The entropy of a hot copper block decreases as it cools.

(C) If ice is melted in water in an insulated container, the net entropy decreases.

(D) Work must be input if energy is transferred from a cold body to a hot body.

9. A piston allows air to expand from 6 MPa to 200 kPa. The initial volume and temperature are 500 cm^3 and 800°C. If the temperature is held constant calculate the entropy change.

(A) 10.9 kJ/K

(B) 9.51 kJ/K

(C) 8.57 kJ/K

(D) 7.41 kJ/K

10. The entropy change in a certain expansion process is 5.2 kJ/K. The nitrogen, initially at 80 kPa, 27°C, and 4 m^3, achieves a final temperature of 127°C. Calculate the final volume.

(A) 255 m^3

(B) 223 m^3

(C) 158 m^3

(D) 126 m^3

11. A piston is inserted into a cylinder causing the pressure in the air to change from 50 to 4000 kPa while the temperature remains constant at 27°C. To accomplish this, heat transfer must occur. Determine the entropy change.

(A) −0.92 kJ/kg · K

(B) 0.98 kJ/kg · K

(C) 1.08 kJ/kg · K

(D) 1.26 kJ/kg · K

12. A torque of 40 N · m is needed to rotate a shaft at 40 rad/s. It is attached to a paddle wheel located in a rigid 2-m^3 volume. Initially the temperature is 47°C and the pressure is 200 kPa; if the paddle wheel rotates for 10 min and 500 kJ of heat is transferred to the air in the volume, determine the entropy increase assuming constant specific heats.

(A) 3.21 kJ/K

(B) 2.81 kJ/K

(C) 2.59 kJ/K

(D) 2.04 kJ/K

13. Four kilograms of air expand in an insulated cylinder from 500 kPa and 227°C to 20 kPa. What is the work output?

(A) 863 kJ

(B) 892 kJ

(C) 964 kJ

(D) 1250 kJ

14. Steam, at a quality of 85 percent, is expanded in a cylinder at a constant pressure of 800 kPa by adding 2000 kJ/kg of heat. Compute the entropy increase.

(A) 3.99 kJ/ kg · K

(B) 3.74 kJ/ kg · K

(C) 3.22 kJ/ kg · K

(D) 2.91 kJ/ kg · K

15. Two kilograms of saturated steam at 100°C are contained in a cylinder. If the steam undergoes an isentropic expansion to 20 kPa, determine the work outpu

(A) 376 kJ

(B) 447 kJ

(C) 564 kJ

(D) 666 kJ

16. Ten kilograms of iron at 300°C are chilled in a large volume of ice and water. Find the total entropy change.

(A) 0.88 kJ/K

(B) 1.01 kJ/K

(C) 1.26 kJ/K

(D) 1.61 kJ/K

17. Five kilograms of ice at –20°C are mixed with 10 kg of water initially at 20°C. If there is no significant heat transfer from the container, determine the net entropy change. It takes 330 kJ to melt a kg of ice.

(A) 0.064 kJ/K

(B) 0.084 kJ/K

(C) 1.04 kJ/K

(D) 1.24 kJ/K

18. Two kilograms of air are stored in a rigid volume of 2 m^3 with the temperature initially at 300°C. Heat is transferred from the air until the pressure reaches 120 kPa. Calculate the entropy change of the air.

(A) –0.292 kJ/K

(B) –0.357 kJ/K

(C) –0.452 kJ/K

(D) –0.498 kJ/K

19. Calculate the entropy change of the universe for Prob. 18 if the surroundings are at 27°C.

(A) 0.252 kJ/K

(B) 0.289 kJ/K

(C) 0.328 kJ/K

(D) 0.371 kJ/K

20. Two hundred kilowatts are to be produced by a steam turbine. The outlet steam is to be saturated at 80 kPa and the steam entering will be at 600°C. For an isentropic process, determine the mass flow rate of steam.

(A) 0.342 kg/s

(B) 0.287 kg/s

(C) 0.198 kg/s

(D) 0.116 kg/s