Engineering Thermodynamics 1 & 2

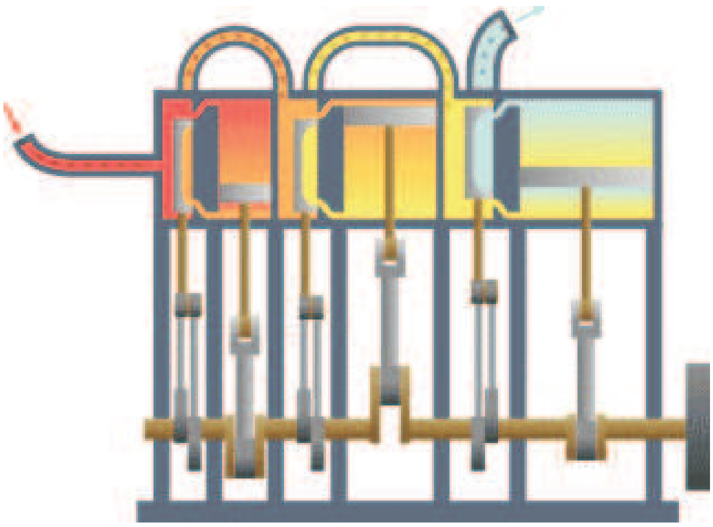
Programme Mechanical Engineering

part of

ME module 2, Energy and Materials

ME module 3, Energy and Sustainability

Study Problems



University of Twente

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Preface

This document contains **study problems** for the course **Engineering Thermodynamics 1 and 2** (202000109 & 202000115) for students **Mechanical Engineering of the University of Twente**. These courses are part of module 2, *Energy and Materials* (202000108) and module 3, *Energy and Sustainability* (202000114) of the Mechanical Engineering Bachelor programme. The book used in the courses is: ***Thermodynamics, An Engineering Approach****, by Y.A. Çengel and M.A. Boles.* Part of the study problems in this document are based on problems of this book. Beside the book ***Thermodynamics****: An Integrated Learning System, by Philip S. Schmidt, Ofodike A. Ezekoye, John R. Howell en Derek K. Baker.* is used as a source for the study problems.

The document contains over 180 study problems. About half of the problems will be treated during the tutorials. See table 1 on the next page for the division of the chapters and problems over the classes. The remaining problems can be used for extra practice. At the beginning of each chapter there are some conceptual questions about theoretical aspects. However, most of the questions are about application of the theory. Answers to the problems are provided in a separate document which will be available to the students after the tutorial is finished. There are also sub problems that need to be solved using *Matlab* and the packages *XSteam* or *gasprop*. They are designated by *Matlab* in front of the sub exercise.

The problems in the chapters 9, 10 and 11 are representative for the questions of the exam. However, the problems of the other chapters provide a basis to be able to understand the problems of the last chapters. Pay also special attention to the ones at the end of chapter 4. Chapter 8 about Exergy / Second Law Analysis is not covered in the course Engineering Thermodynamics. However, it is part of the projects *Analysis of an Energy System* and *Design of an Energy System* in modules 2 and 3, respectively.

Genie Stoffels
November 2021

Content of the course

The table below contains an overview of the division of the different chapters over the classes as well as an overview of the problems treated during the tutorials. Chapters refer to chapters in the book: **Thermodynamics, An Engineering Approach**, by Y.A. Çengel and M.A. Boles.

#	**Subject**	**Chapter**	**problems**
1	Introduction, thermodynamic concepts and terminology	1	1.1, 1.2, 1.3, 1.6, 1.7, 1.8, 1.9, 1.15, 1.18, 1.10
2	Energy, work, heat transfer, enthalpy, entropy, efficiency	2, 4.1, 4.2	2.17, 2.18, 2.6, 2.11, 2.12, 2.13, 2.2, 2.7, 2.9, 2.14
3	State principle, phase transitions, liquids, saturated mixture, superheated steam, tables en diagrams	3.1 - 3.5	3.6, 3.9, 3.10, 3.11, 3.12, 3.13, 3.8
4	The first law of thermodynamics (conservation of energy) for open and closed systems	4.2, 5.1 - 5.4	4.3, 4.5, 4.9, 4.11, 4.12, 4.13, 4.17, 4.14
5	(Ir)reversible processes, entropy, the second law (entropy always increases) and second law applications	6.1, 6.6, 7.1 - 7.8, 7.12	5.2, 5.6, 5.9, 6.4, 6.5, 6.6, 6.7, 5.12, 5.4, 5.5, 5.8
6	Thermodynamic cycles for work, heat/cold, Carnot cycle, efficiencies and COP, perpetual mobiles	6.2 - 6.10, 9.2	7.5, 7.6, 7.7, 7.10, 7.11, 7.13, 7.12
7	Simple Rankine (vapor) cycle (steam turbine), compare to Carnot, design parameters	10.1 - 10.4	10.2, 10.4, 10.5, 10.6, 10.8
8	Advanced Rankine cycle (reheating, feed water heating), co-generation	10.4 - 10.5	10.11, 10.12, 10.15, 10.19, 10.16, 10.18, 10.9
	Exergy (second law analysis), quality of energy, Sankey and Grassmann diagrams	8, 9.12, 10.7	8.12, 8.2, 8.4, 8.7, 8.8, 8.11
9	Gases, ideal gas law, specific heat, internal energy and enthalpy of gases	3.6-3.8, 4.3-4.5, 7.9	3.17, 3.20, 3.22, **5.21**, 3.18
10	Gas cycles, simple Brayton cycle (gas turbine)	9.1, 9.3, 9.8	9.16, 9.17
11	Advanced Brayton cycle (inter cooling, reheating, regeneration), combined cycles, jet engines	9.9 - 9.11, 10.9	9.19, 9.18, 10.13, 10,14, 9.20, 9.15
13	Refrigeration and heat pump cycles, reversed Rankine cycle, coefficient of performance (COP)	11.1-11.4, 11.7	11.2, 11.3, 11.7, 11.5, 11.6
14	Reciprocating engines, Stirling, Otto, Diesel cycles	9.1 - 9.5	9.7, 9.12, 9.11, 9.6, 9.2, 9.10, 9.5, 9.9, 9.3
15	More about entropy	7.1 - 7.9, 7.13	5.10, 5.15, 5.28, 5.17, 5.16, 5.29, 5.21, 5.11

Table 1: *Subjects and problems covered in the lectures and tutorials.*

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1 Introduction, Thermodynamic Concepts and Terminology

1.1 Engineering thermodynamics

a: What is Thermodynamics and where is it applied?

b: What is Engineering Thermodynamics?

c: What are the two main objectives of the thermodynamic device which are studied in the course Engineering Thermodynamics? How are these devices called?

1.2 Heat engines and refrigeration systems / heat pumps

a: What is a heat engine (or heat cycle also refered to as a power engine or power cycle)?

b: What is a refrigerator or a heat pump?

c: Energy is conserved. In a thermodynamanic device it is only converted into a different from. What energy conversion process takes place in de heat engine? What energy conversion process takes place in a refrigeration device or a heat pump?

d: Calculate the amout of net work, W_{net} that is produced in a heat engine which receives an amount of heat $Q_{in} = 100$ kJ form a hot temperature source and rejectes an amount of heat $Q_{out} = 60$ kJ to a low temperature sink.

e: Calculate the amout of heat, $Q_{in} = Q_L$ that is transferred from a cold space to a hot space by a refrigeration system which rejects an amount of $Q_{out} = Q_H = 45$ kJ to the hot environment using a net work input of $W_{net} = 10$ kJ.

f: Calculate the amout of heat, $Q_{out} = Q_H$ that is transferred from a cold space to a hot space by a heat pump which receives an amount of $Q_{in} = Q_L = 60$ kJ from the cold environment using a net work input of $W_{net} = 20$ kJ.

1.3 Open, closed and isolated systems

a: What is a system and what is the system boundary?

b: What is the difference between an open and a closed system regarding mass and energy.

c: What is the difference with an isolated system.

d: A large fraction of the thermal energy generated in the engine of a car is rejected to the air by the radiator through the circulating water. Should the radiator be analyzed as a closed or as an open system? Explain.

e: A can of soft drink at room temperature is put into the refrigerator so that it will cool down. Would you model the can of soft drink as a closed or as an open system? Explain.

1.4 Thermodynamic state and thermodynamic properties

a: What is a thermodynamic property and give some examples?

b: What is a thermodynamic state?

c: Not all properties are independent. What is an independent property? Give some examples of independent and dependent properties.

d: How many independent variables are necessary to describe the state of a thermodynamic system containing a single pure substance?

e: The state of a system can change, and this change is marked by a change in the values of the properties of the system. How is it called when an system goes from a certain state to an other state?

f: How is the state of a system that does not change in time called?

1.5 Intensive and extensive properties

a: What are intensive properties and give some examples of them?

b: What are extensive properties and give some examples of them?

c: Which ones are easier to measure?

d: What is a specific property?

e: Suppose you have a volume with a certain temperature, pressure, mass and energy. What happens to these properties if you multiply the volume by a factor of λ? What happens to the specific energy?

1.6 Processes

a: The state of a system can change, and this change is marked by a change in the values of the properties of the system. The change of a system's thermodynamic state is called a process. Define isothermal, isobaric and isochoric processes?

b: What is an adiabatic process?

c: What is a steady-flow process?

d: What is a cyclic process?

e: What is a quasi-equilibrium process and what is its importance in engineering?

1.7 Dimensions

a: Give the seven fundamental dimensions and their units in the metric, international system (SI)?

b: Write the following dimensions into the fundamental units: Force, Pressure, Energy and Power.

c: Show that the kinetic energy and the potential energy indeed have the dimension of energy, Joule [J].

1.8 Mass and volume

a: A plastic tank of mass M, length l, broadness b and height h is filled with a substance of density ρ. Determine the mass of the substance and of the combined system. What is the specific volume of the substance and of the combined system?

b: Assume $M = 3$ kg, $l = 1$ m, $b = 40$ cm and $h = 50$ cm. Calculate the mass of the substance and the combined system in case the substance is liquid water. Give also the specific volume of the water and calculate the specific volume of the combined system.

c: Compare this to the case where the substance is air.

1.9 Ideal gases

A chamber contains 1.5 kg of an ideal gas that has a gas constant of $R = 0.14304$ kJ/kgK at a temperature of 42 degree Celsius and a pressure of 1.20 Bars. What are the specific volume of the gas, the total volume of the gas and the density of the gas? (Note, $Pv = RT$ and take care of the dimensions!)

1.10 Galileo thermometer

A Galileo thermometer as seen at the left in figure 1, is based on a thermoscope invented by Galileo Galilei, an Italian physicist, in the early 1600s. The Galileo thermometer consists of a sealed glass tube that is filled with water (or another clear fluid) and several floating bubbles whose densities are such that they rise or fall as the temperature changes. The bubbles are glass spheres filled with a colored liquid mixture.

Attached to each bubble is a little metal tag that indicates a temperature. These metal tags are actually calibrated counterweights. The weight of each tag is slightly different from the others. Since the bubbles are all hand-blown glass, they are not exactly the same size and shape. The bubbles are calibrated by adding a certain amount of fluid to them so that they have exact the same density. So, after the weighted tags are attached to the bubbles, each differs very slightly in density (the ratio of mass to volume) from the other bubbles, and the density of all of them is very close to the density of the surrounding liquid.

The operation of the Galileo thermometer is based on the principle of buoyancy (the ability of an object to float) and is described by the *Law of Archimedes*. The Law of Archimedes states that the upward force that an object in the water encounters is equal to the weight of water displaced by the body. Based on the Law of Archimedes, one can formulate the following rules:

- An object sinks if the density of the object is larger than the density of the fluid.
- An object floats *on* the fluid if the density of the object is smaller than the density of the fluid.
- An object floats *in* the fluid if the density of the object is equal to the density of the fluid.

The basic idea is that as the temperature of the air outside the thermometer changes, also the temperature of the fluid surrounding the bubbles changes. As the temperature of the fluid changes, it either expands or contracts, thereby changing its density. So, at any given density, some of the bubbles will float and others will sink.

Assume the fluid in the thermometer as well as in the bubbles is water and the bubbles are all identical spheres with a diameter of 2.5 cm. There are 7 bubbles with temperature tags ranging from 18 degree Celsius to 24 degree Celsius. The density of water as a function of temperature is given in figure 1.

a: Where are bubbles if the outside temperature is 30 degree Celsius and if the outside temperature is only 10 degree Celsius?

b: Where is the bubble that indicates the right temperature?

c: Which bubble is the heaviest and which is the lightest?

d: If it is 20 degree Celsius, the bubble with tag number 20 floats in the middle of the thermometer. Give the formula that can be used to calculate the mass of the bubble and determine the mass.

e: What is the mass difference of the bubble with the highest and the lowest temperature tag? What is the relative mass difference of two bubbles? Could they make a thermometer like this in Galileo's time?

Temperatuur oC	Dichtheid kg/m3
15	999.1026
16	998.9460
17	998.7779
18	998.5986
19	998.4082
20	998.2071
21	997.9955
22	997.7735
23	997.5415
24	997.2995
25	997.0479
26	996.7867

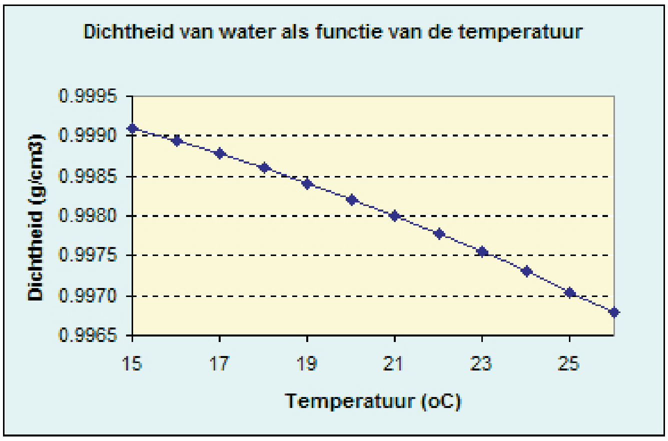


Figure 1: *Galileo thermometer and the density of water as a function of the temperature.*

1.11 Acceleration and force

a: The acceleration of high-speed aircraft is sometimes expressed in g's (i.e. in multiples of the standard acceleration of gravity). Determine the net force, F, that an object, with mass M, would experience in an aircraft whose acceleration is $6g$'s.

b: On the moon the local gravity is only 0.17 times the standard acceleration of gravity. Determine also the force of the object on the moon.

c: Calculate the net force in the aircraft and the force on the moon for a man of 90 kg and a woman of 55 kg.

1.12 Temperature

a: What is the absolute zero temperature, can the absolute temperature be negative, what is its unit?

b: What is a relative temperature and can it be negative?

c: What are the most common temperature scales in the SI system and how are they related?

d: Which thermodynamic principles are used to define the Celsius temperature scale?

1.13 Pressure

a: How is pressure defined and what is its unit?

b: What is the difference between vacuum pressure, atmospheric pressure, gauge pressure and absolute pressure and how are they related?

1.14 Pressure on a diver

a: Determine the relations describing the absolute and the relative pressure exerted on a diver at a distance h below the free surface of a lake. Assume the barometric pressure is P_{atm} and the density of water is ρ.

b: What are these pressures at h =15 m and at h =30 m in normal water? Take P_{atm} = 101 kPa.

c: Is the absolute pressure pressure doubled and the relative?

d: Repeat the calculation at b for seawater with $\rho_{seawater}$ = 1030 kg/m^3.

e: What is the atmospheric pressure if the diver at a depth of 30 meters in the sea reads a pressure of 398.8 kPa on his manometer.

1.15 Pressure and height

a: There is a relation between the barometric pressure and the height. Therefore, the barometric pressure can be used to measure the height. Give the relation between the height, h, and the barometric pressure, P, neglecting the effect of altitude on the local gravitational acceleration, g for air of density, ρ.

b: Determine the vertical height a mountain hiker climbed, if his barometer reads 930 mBar at the beginning of the trip and 780 mBars at the end. The average air density is 1.20 kg/m^3 and take an average g of 9.7 m/s^2.

c: Make an estimate of the barometric pressure difference between the bottom and the roof of the Horst Tower. Guess a reliable value for the height of the tower.

1.16 Pressure in a tank

a: The water in a tank is pressurized by air and the pressure is measured by a multi fluid manometer as shown in figure 2a. Determine the gauge pressure of air in the tank as a function of h_1, h_2 and h_3 and the densities of water (ρ_{water}), mercury ($\rho_{mercury}$) and oil (ρ_{oil}).

b: Take the densities of water, mercury and oil to be 1000 kg/m^3, 13600 kg/m^3 and 850 kg/m^3, respectively. Determine the gauge pressure if $h_1 = 0.2$ m, $h_2 = 0.3$ m and $h_3 = 0.46$ m.

c: What happens if the oil is replaced by mercury?

d: And if both oil and mercury are taken out?

e: What is the advantage of using oil or mercury in stead of water?

1.17 Pressure and manometer

a: A manometer is connected to an air duct to measure the pressure inside. The difference in the manometer levels is h mm, the density of the fluid is ρ, and the atmospheric pressure is P_{atm}. Judging from figure 2b determine if the pressure in the duct is above or below the atmospheric pressure. Draw how the situation would be in the other case.

b: Give the relation for the relative and the absolute pressure in the duct.

c: Calculate both pressures for the case the fluid is water with $\rho = 1000$ kg/m^3 and the height difference $h = 15$ mm, while $P_{atm} = 1$ bar; repeat for $h = 30$ mm. Compare the results.

d: Also calculate the pressures if the fluid is mercury with has $\rho = 13600$ kg/m^3. Compare the results with the results of c.

e: What would h be if the absolute pressure in the duct is two times the atmospheric pressure in the case of water and in the case of mercury?

1.18 Pressure in a cylinder

a: A gas is contained in a vertical, frictionless piston-cylinder device as seen in figure 2c. The piston has mass M and a cross-sectional area of A. A compressed spring above the piston exerts a force F on the piston. Give the relation for the absolute pressure inside the cylinder if the atmospheric pressure is P_{atm}.

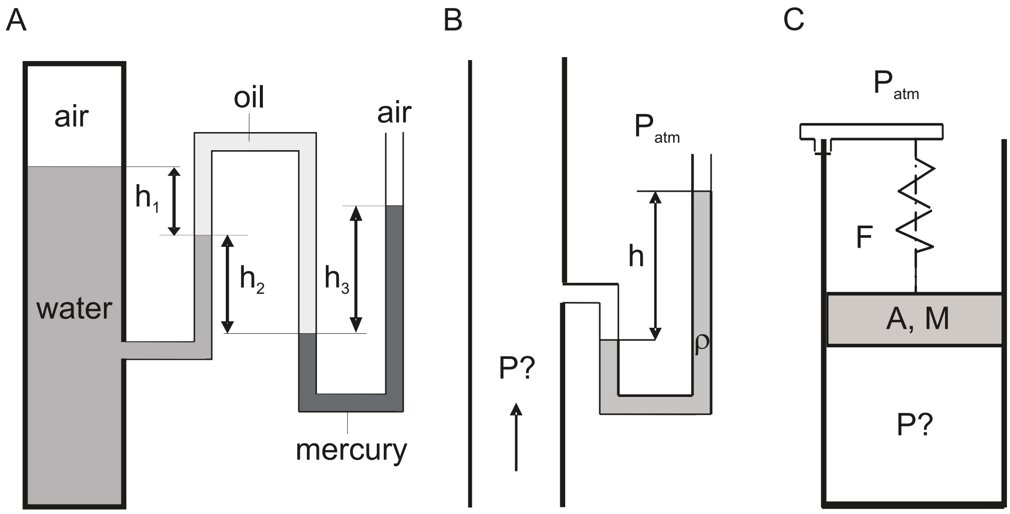


Figure 2: *A: Water in a tank pressurized by air (problem 1.16); B: Air duct of problem 1.17; C: Piston-cylinder device of problem 1.18.*

b: Calculate the pressure if $F = 60$ N, $A = 35$ cm^2, $M = 4$ kg and $P_{atm} = 95$ kPa.

c: How much is F if the pressure in the cylinder is two times the atmospheric pressure.

2 Energy, Work, and Heat Transfer

2.1 Basics of energy

a: What is total energy? Which forms of energy contribute generally to the total energy of a system in thermodynamics?

b: Is the absolute value of the total energy important in thermodynamics?

c: Is the total energy of a new state dependent on the path followed to go from the old to the new state?

d: List the forms of energy that contribute to the internal energy of a system.

e: Give the expressions for kinetic and potential energy?

2.2 Energy transfer mechanisms

The energy of a system is defined by the properties of the system (velocity, height, pressure, temperature, internal energy). These properties can be changed by transfer of energy to or from a closed or open system.

a: Which two mechanisms can transfer energy across the boundaries of a closed system? Give also their dimensions.

b: Are these mechanisms also present in an open system?

c: Which extra energy transfer mechanism plays a role in an open system?

2.3 Energy transfer by work and power

a: Write down in differential form the general relation for work, W, performed by a force, F, on a system displaced by a distance, $\mathrm{d}S$.

b: Also write this relation in integral form in the case of volume work.

c: Is the work done dependent on the integration path, explain?

d: Work added from the surroundings to the system is denoted by W_{in}. Is this a positive or a negative value? And what about the sign of W_{out}, work taken from the system to the surroundings?

e: How is power, the rate of doing work, given by the symbol $\dot{W}$, or $\dot{w}$, defined.

2.4 Work of piston-cylinder device

a: A gas is contained within a piston-cylinder arrangement. The initial pressure is P_1 and the initial volume is V_1. The final volume is V_2. Sketch the process in a $P-v$ diagram and determine the final pressure P_2, if the gas is compressed and the pressure obeys the relation: $Pv^{1.4} = c$ where c is a constant value?

b: What is the graphical interpretation of the work in the $P-v$ diagram. Give the relation for the work done on the gas.

c: What is the value of the final pressure, P_2, for an initial pressure $P_1 = 100$ kPa, initial volume of $V_1 = 1$ m^3 and a final volume $V_2 = 0.1$ m^3. Also calculate the work done on the gas with these values.

d: Alternatively the gas can be compressed following a linear relation, $\Delta P = c^*\Delta V$, in which c^* is a constant value. Sketch also this process in the $P-v$ diagram. Give the differential expression for this relation between P and V and determine from the differential expression the relation between pressure and volume.

e: Determine the work done on the gas in this case.

f: Is the work dependent on the path? Can you find another path?

g: Which path costs minimum work and which path maximum?

2.5 Work done by compression

A gas is compressed from an initial volume of 0.42 m^3 to a final volume of 0.12 m^3. During the quasi-equilibrium process, the pressure changes with volume according to the relation $P = aV + b$, where $a = -1200$ kPa/m^3 and $b = 600$ kPa.

a: Calculate the work done during this process by plotting the process on a $P-v$ diagram and finding the area under the process curve.

b: Calculate the work done during this process by performing the necessary integrations.

2.6 Work done by lifting a mass

A 10 kg mass is moved from the floor to a position on a staircase 10 m above the floor. The new position is reached by the following paths:

a: The mass is lifted directly upwards by a frictionless pulley in a block-and-tackle system.

b: The mass is pushed on horizontal using a dolly with a force $F_{push} = 2$N on a distance $L = 1$m. After this, the elevator moves up to the required height. The next step is taking the mass out of the elevator applying the same force F on the same distance L.

In these two cases, find the work done on the mass in moving it to the final position. Discuss whether the work, which is a path function, depended upon the path in these two cases. What is the type of energy that appears in both cases and is dependent on the change in height? Is this type of energy a state function or path function? **Note**: think about the definition formula of work: $W_{1-2} = \int_1^2 F dS$.

2.7 Heat transfer

a: What is heat transfer?

b: Can there be heat transfer in an isolated system?

c: And in an adiabatic process?

d: The amount of heat transferred during a process is Q. How is the rate of heat transfer (the amount of heat transferred per unit time), given by $\dot{Q}$ defined?

2.8 Work and heat transfer of a piston-cylinder device

A cylinder with a movable piston contains some gas of which is given that, for an adiabatic, quasi-static change of state it obeys the relation: $PV^{5/3} = constant$ (i.e. path c). The system goes from state A, with pressure P_A and volume V_A, to state B, with pressure P_B and volume V_B. The process can follow different quasi-static paths (a, b and c) as sketched in figure 3.
Note: U is a state function and $\Delta U = Q + W$.

a: What is an adiabatic quasi-static change of state?

b: Determine relations for the amount of heat and work if the system follows path c, i.e. adiabatic expansion.

c: Determine relations for the amount of heat and work if the system follows path a, i.e. expansion $V_A \rightarrow V_B$ at constant P_A during addition of heat, followed by pressure decrease, $P_A \rightarrow P_B$ at constant V_B during release of heat.

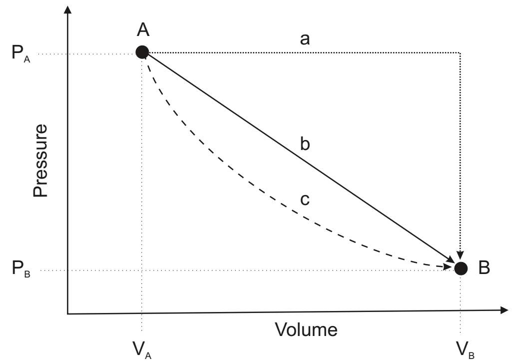


Figure 3: *Change of the piston-cylinder device from state A to state B via three different paths.*

d: Determine relations for the amount of heat and work if the system follows path b, i.e. expansion during addition of heat in such a way that $\Delta P = c\Delta V$, in which c is a constant. Remember the area under the graph in the Pv-diagram is equal to the amount of work.

e: Calculate the amount of work and heat in all three cases if $P_A = 48$ bar, $P_B = 1$ bar, $V_A = 1$ liter and $V_B = 12$ litre.

2.9 Flow work and enthalpy 1

a: What is flow work?

b: Give a formula that describes the flow work.

c: Which energy terms play a role in the total energy crossing the boundary of an open system, i.e. the energy crossing the boundary with the mass that flows into the system?

d: How is the combination of internal energy u and flow work Pv called, what is its dimension?

2.10 Flow work and enthalpy 2

a: Consider an open system, e.g. a tube with mass flowing through it. Each unit of mass flowing into and out of the system carries kinetic, potential and internal energy. Give the expression for the energy $\mathrm{d}E_{mass-in}$ carried by an element of mass $\mathrm{d}m$.

b: In the analysis of the open system an other form of work is involved. That is the work required to push mass across the system boundary into the open system. This work is called flow work. A unit of mass $\mathrm{d}m$ has a volume $\mathrm{d}V v\mathrm{d}m$. The process of the mass flowing in can be seen as the volume of a cylinder $\mathrm{d}V$ (area A) that is pushed inside the tube by a piston over a distance $\mathrm{d}x$ (i.e. volume work as seen before). Give the expression for the work done by the flow to push the unit of mass into the tube.

c: Give the expression for the energy $\mathrm{d}E_{in}$ crossing the system boundary with the mass unit $\mathrm{d}m$.

d: Mass leaving the system must also be considered. The energy, $\mathrm{d}E_{mass-out}$, crossing the boundary and leaving with a unit of mass $\mathrm{d}m$, can again be considered to be the energy carried out within the element of mass, $\mathrm{d}E_{mass-out}$, plus the work done to push the mass across the boundary , out the system. Give the expression for the energy going out the system.

e: Note that in both the expressions in c and d the group of properties $u + Pv$ appears. This group is made to a new property. How is this property called and what is its dimension?

2.11 Enthalpy of steam

Steam enters a turbine at a temperature of 300°C and a pressure of P_1. At this state its specific internal energy u is u_1 and its specific volume v is v_1. It leaves as a vapor at P_2, with u_2 and v_2.

a: Give the formula for the change in specific enthalpy between the inlet and the exit of the turbine.

b: Calculate the change in specific enthalpy if the steam enters at a pressure of $P_1 = 0.4$ MPa, a specific internal energy u_1 of 2804.4 kJ/kg and a specific volume v_1 of 0.6548 m^3/kg and it leaves the turbine as a vapor at $P_2 = 0.03$ MPa, where $u_2 = 2467.7$ kJ/kg and $v_2 = 5.2298$ m^3/kg.

2.12 Internal combustion engine

An internal combustion engine consumes fuel at a rate of $\dot{m} = 2.5$ gram/s. The heating value of the fuel is $h_{fuel} = 46$ MJ/kg. The engine converts part of the energy from the fuel into a net work output and the rest of the energy is released as waste heat at the outlet is. The power of the waste heat is, $\dot{Q}_{out} = 50$ kW.

a: Calculate the power, $\dot{Q}_{in}$, that is consumed by the engine.

b: Calculate the net power output of the engine.

c: Calculate the thermal efficiency of the engine.

2.13 Hydroelectric power plant

In a hydroelectric power plant, 65 m^3/s of water flows from an elevation of 90 m to a turbine, where electric power is generated. The overall efficiency of the turbine generator is 48%. Disregarding frictional loses in piping, estimate the electric power output of this plant.

2.14 Energy and power

a: Consider a nuclear power plant that consumes an amount of nuclear heat coming from a nuclear reaction per second as power input denoted by: $\dot{Q}_{fuel-nuclear}$ in MJ/s = MW. The nuclear power plant has a conversion efficiency of 30 percent. Assuming continuous operation, determine the amount of nuclear heat per second consumed by this plant if it produces $\dot{Q}_{out}$ [MW] of electric power as output.

b: Consider a coal power plant that burns coal, with a rate of $\dot{m}$, whose heating value is h [MJ/kg]. The coal is in the power plant transformed into electricity with an efficiency of 50%. Assuming continuous operation, determine the amount of coal consumed by this plant per second if it produces $\dot{Q}_{out}$ [MW] of electric power.

c: Calculate how much both power plants consume per year if the produced power is $\dot{Q}_{out} =$ 1000 MW, assume $h = 28$ MJ/kg? Is it easy to compare both plants?

2.15 Energy and Environment 1

a: When fuel is burnt CO_2 (carbon dioxide), which is the principal gas causing the greenhouse effect and thus global climate change, is formed. Determine the amount of CO_2 production that is due to the refrigerators in a city with X households (each only one refrigerator), if a household refrigerator uses p kWh per year and when Q kg of CO_2 is produced for each kWh of electric energy generated from the power plant that burns the fuel.

b: Assume a household refrigerator consumes 300 kWh per year and the city has 200000 households. Calculate the average production of CO_2 in the case hydrocarbon fuel is burnt. For hydrocarbon fuel on average $Q = 0.59$ kg/kWh.

c: Also calculate the production of CO_2 for a power plant that burns coal. The average production of CO_2 in this case is 1.1 kg/kWh.

2.16 Energy and Environment 2

a: Nitrogen oxides (NO_x) causes smog in major population areas. Determine the amount of NO_x emission to the air per year for a household that contributes to the NO_x emissions by the cars it has and the gas and electricity it uses. There are X cars that each drive a km a year and and emit Q_{car} kg NO_x per km. Further the household consumes Y_e kWh electricity and Y_g m^3 natural gas per year. Natural gas burned emits Q_{gas} of NO_x per m^3 and the electric power plant emits $Q_{electric}$ per kWh of electricity produced to the air.

b: Assume $Q_{car} = 0.57$ kg/km, $Q_{gas} = 4.3$ g/m^3 and $Q_{electric} = 7.1$ g/kWh, the household has two cars that drive 15000 km a year each and uses 3000 kWh electricity and 2500 m^3 gas a year.

c: What has the most influence on the production of NO_x, the use of gas, electricity or driving the cars.

2.17 Power needs of a car

Consider a car with mass m cruising steadily on a level road at an initial velocity v_i. The car accelerates to a velocity v in t seconds.

a: Give the formula that determines the additional work needed to accelerate the car.

b: Give also the formula that determines the average power needed.

c: Now the car at velocity v starts to climb a hill that is sloped at an angle α from the horizontal. Assume that the velocity of the car remains constant during the climb. Give the formula that determines the additional power that must be delivered by the engine. Note: use potential energy and remember power is energy per time.

d: Calculate the answers for a car of mass $m = 1200$ kg with an initial velocity $v_i = 20$ km/h and a final velocity $v = 80$ km/h that accelerates in a time $t = 20$ seconds. The slope of the hill is α is 30°.

2.18 Cooking with potential energy

In order to gain an intuitive appreciation for the relative magnitudes of the different forms of energy we consider the (tongue-in-cheek) example of an attempt to cook a turkey by potential energy. The turkey is brought to the top of a high building (height h) and then dropped from the ledge. The potential energy is thus converted into kinetic energy, and finally on impact the kinetic energy is converted into internal energy. The increase in internal energy, U is represented by an increase in temperature, ΔT, and hopefully, if this experiment is repeated enough times the temperature increase will allow the turkey to cook. This remarkable experiment was first reported by R.C. Gimmi and Gloria J. Browne - *Cooking with Potential Energy*, published in the *Journal of Irreproducible Results* (Vol 33, 1987, pp 21-2).

a: Derive an expression for the velocity of the turkey when it hits the ground.

b: Derive an expression that can be used to calculate how often you have to repeat this experiment to cook the turkey. (Formula for internal energy in this case: $U = m \cdot c \cdot \Delta T$, where c is the specific heat of the turkey and m the mass).

c: Assume the outside temperature is 10°C, the turkey is cooked at 210°C, the height of the building is 100 m (about 30 stories) and the specific heat of the turkey is $c = 3000$ J/kgK. Fill in the values and calculate the velocity when the turkey hits the ground. Also calculate how often you need to repeat this experiment to cook the turkey.

d: Discuss the answer, what can you say about the magnitude of the change of temperature/internal energy compared to the height/potential energy and to the velocity/kinetic energy?

e: How do the answers (velocity and times to repeat the experiment) change if the building is two times higher? How often do we have to do this experiment if we take a second turkey which is only half the mass of the first turkey?

f: Is it necessary to know the velocity in order to calculate how often you need to repeat the experiment to cook the turkey?

3 Thermodynamic Properties of Pure Substances

3.1 Phases of matter

a: Which are the three phases that matter can have?

b: Which are the six phase transitions that can occur?

c: What can be said about the relation between pressure and temperature if a substance starts to boil.

d: How is the area called in which substances exist in two phases?

e: How is the substance called if it exists in two phases?

f: How are the temperature of the gas and the liquid related for thermodynamic equilibrium in a mixture. And what about the pressure of the gas and the liquid in a mixture.

g: What happens to the pressure and temperature of a mixture if heat is added to the mixture in an open system?

h: How do we call the energy (heat) necessary to vaporize the liquid?

i: What is the relation between the energy necessary to vaporize liquid and the energy necessary to condense the vapor?

3.2 $T - v$ diagram

a: Make a $T - v$ diagram and draw the vapor dome that divides the diagram in different regions.

b: Which point in the diagram is called the critical point?

c: Where in the diagram do we have saturated liquid?

d: Where in the diagram do we have saturated vapor?

e: In which area in the diagram do we have a compressed liquid?

f: In which area in the diagram do we have a saturated mixture?

g: In which area in the diagram do we have a superheated vapor?

h: Draw the isobar of 80, 100 and 150 kPa in the diagram.

3.3 Incompressible liquid

a: What is an incompressible liquid and what is the most important property of an incompressible liquid?

b: Determine the coefficient of thermal expansion, β and the isothermal compressibility, κ for an incompressible liquid.

3.4 Mixtures

If a substance is in the saturated liquid phase the subscript l is used. If a substance is in the saturated vapor (gas) phase the subscript v is used. The difference between the two properties is denoted by the subscript lv.

a: Draw a $T - v$ diagram and denote the points v_l and v_v at a certain temperature, T.

b: Where in the diagram can you find v_{lv} and what is the relation between v_l, v_v and v_{lv}.

c: Draw a $h - s$ diagram and denote the pairs of points s_l and h_l and s_v and h_v.

d: Where in the diagram can you find s_{lg} and h_{lv}. What is the relation between s_l, s_v and s_{lv} and the relation between h_l, h_v and h_{lv}.

3.5 Quality of a mixture

a: During a vaporization process a substance exists as a mixture of saturated liquid and saturated vapor. Give the relation between the total mass m of the mixture and the mass of the saturated liquid, m_l and the mass of the saturated vapor, m_v.

b: To analyse the mixture the proportions of the liquid and the vapor phase in the mixture have to be known. For this the property x, the quality of the mixture is introduced. How is the quality defined?

c: Does quality have significance for the compressed liquid and the superheated vapor regions?

d: Which are the values that quality can have?

e: What is the quality of a system consisting of saturated liquid?

f: What is the quality of a system consisting of saturated vapor?

g: Do the properties of a saturated liquid (or saturated vapor) in a mixture change during a vaporization (or condensation) process? And the quality of the mixture does it change?

h: Draw the lines of constant quality in the $T - v$ diagram.

3.6 Use of tables: water

Complete these tables for water using the tables in the book and draw the points in a diagram.

T (°)	*P (kPa)*	*v* (m^3/kg)	*Phase description*
50		4.16	
	200		Saturated vapor
250	400		
110	600		

T (°)	*P (kPa)*	*h (kJ/kg)*	x	*Phase description*
	200		0.7	
140		1800		
	950		0.0	
80	500			
	800	3161.4		

3.7 Use of tables, refrigerant 134a

Complete these tables for refrigerant 134a using the tables in the book.

T (°)	*P (kPa)*	*v (m³/kg)*	*Phase description*
-8	500		
30		0.022	
	320		Saturated vapor
100	600		

T (°)	*P (kPa)*	*u (kJ/kg)*	*Phase description*
20		95	
-12			Saturated Liquid
	400	300	
6	600		

3.8 Boiling of water

a: Water is being heated in a vertical piston-cylinder device. The piston has a mass of 20 kg and a cross-sectional area of 100 cm^2. The local pressure is 100 kPa. Determine the temperature at which the water will start boiling.

b: If we go high up in the mountains, will the water boil at a lower or higher temperature?

c: What temperature will the water boil if the local pressure decreases to 95 kPa?

3.9 Vessel with 2 kg refrigerant 134a

A rigid vessel contains 2 kg of refrigerant 134a at 900 kPa and 80 °C. Determine the volume of the vessel and the total internal energy.

3.10 Vessel with refrigerant 134a

A 0.5 m^3 vessel contains 10 kg of refrigerant 134a at -20 °C.

a: Determine the pressure in the vessel.

b: Determine the total internal energy.

c: Determine the volume occupied by the liquid phase.

3.11 Water mixture of liquid and vapor

A piston cylinder device contains 0.1 m^3 of liquid water and 0.9 m^3 of water vapor in equilibrium at 800 kPa. Heat is transferred at constant pressure until the temperature reaches 350 °C.

a: Show the process on a $P - v$ and a $T - v$ diagram with respect to the saturation lines.

b: What is the initial temperature of the water?

c: Determine the total mass of the water. What is mixture fraction, x, at the beginning?

d: Calculate the final volume. What is the volume at the point all water has just turned into vapor, i.e. the saturated vapor moment?

3.12 Vaporization of water at constant pressure

A piston-cylinder device initially contains 50 l of liquid water at 25 °C and 300 kPa. Heat is added to the water at constant pressure until the entire liquid is vaporized.

a: Show the process on a $T-v$ diagram with respect to the saturation lines.

b: What is the final temperature?

c: Give the formula that determines the mass of the water and calculate the mass of the water?

d: Give the formula that determines the total enthalpy change and calculate the total enthalpy change.

3.13 Work done by heating 1

A frictionless piston-cylinder device initially contains 200 l of saturated liquid refrigerant 134a. The piston is free to move, and its mass is such that it maintains a pressure of 800 kPa on the refrigerant. The refrigerant is now heated until its temperature rises to 50 °C.

a: Show the process on a $T-v$ diagram with respect to the saturation lines.

b: Give the formula that determines the specific work done during this process as well as the formula that can be used to determine the total work during this process.

c: Calculate the specific work and the total work done during this process.

3.14 Work done by heating 2

A mass of 5 kg of saturated water at 200 kPa is heated at constant pressure until the temperature reaches 300 °C. Calculate the work done by the steam during this process.

3.15 Ideal gas

a: What is an ideal gas?

b: Give the equation of state (the relation between $P-v-T$) for an ideal gas with the gas constant R and the specific volume v in it. Give it also for the case the volume is not a specific volume but a volume V. Finally give the relation for the case of the universal gas constant R_u. How are R and R_u related to each other.

c: Determine the coefficient of thermal expansion, β and the isothermal compressibility, κ.

3.16 A balloon

a: A spherical balloon with diameter D is filled with a gas at temperature T and pressure P. Determine the relation for the mole number of the gas in the balloon.

b: Determine the relation for the mass of the gas in the balloon.

c: Assume the diameter is 6 m, the temperature is 20°C and the pressure is 200 kPa. Calculate the mole number and the mass in the case the gas is helium.

d: Also calculate the mole number and the mass in the case the gas is nitrogen.

3.17 An automobile tire

a: The pressure of an automobile tire depends on the temperature of the air in the tire. The air temperature is T_1 the pressure gauge reads a pressure P_1 and the volume of the tire is V_1. Give a relation for the pressure rise in the tire when the air temperature in the tire rises to T_2. Assume that the tire is rigid and therefore the volume is constant.

b: Also give a relation for the amount of air that must be bled off to restore the pressure to its original value at the temperature T_2.

c: Assume $P_1 = 210$ kPa, $T_1 = 25$°C, $V_1 = 0.025$ m^3 and the atmospheric pressure is 100 kPa. Calculate the pressure rise if the temperature rises to $T_2 = 50$°C.

d: Also calculate the amount of air that must be bled off to restore the pressure to its original value, $P_1 = P_2 = 210$ kPa at $T_2 = 50$ °C.

3.18 Two tanks with air

A tank (1) with volume V_1, temperature T_1 and pressure P_1 is connected through a valve to another tank (2) containing m_2 kg of air at temperature T_2 and pressure P_2. The valve is opened and the entire system is allowed to reach thermal equilibrium with the surroundings at temperature T_3.

a: Give a relation that can be used to determine the volume V_2 of the second tank.

b: Give the relation for the final equilibrium pressure, P_3 of the air.

c: Assume $P_1 = 500$ kPa, $T_1 = 25$ °C, $V_1 = 1$ m^3, $P_2 = 200$ kPa, $T_2 = 35$°C, $m_2 = 5$ kg and $T_3 = 20$ °C and calculate the volume V_2 of the second tank.

d: Also calculate the final equilibrium pressure P_3 of the air.

3.19 Enthalpy change of nitrogen

Determine the enthalpy change Δh of nitrogen, in kJ/kg, as it is heated from 600 K to 1000 K.

a: Use the empirical specific heat equation for C_p as a function of temperature (polynomial expression Table A-2c).

b: Use the C_p value at the average temperature (Table A-2b).

c: Use the C_p value at room temperature (Table A-2a).

d: What can you conclude from the answers from, a, b and c?

3.20 Heat transfer and work at constant enthalpy

a: An amount of gas, which can be treated as ideal undergoes a reversible process in which the pressure, P_1 and volume, V_1, change to pressure, P_2 and volume, V_2. The enthalpy is constant during the process. Determine the relation between the temperature T_1 and T_2.

b: Give the relation between the pressure and the volume.

c: Determine the relation between the amount of heat and work added to the system if is given that $du = \delta q + \delta w$.

d: Give the expression that can be used to calculate the work.

e: Calculate the heat and work if the state of the system changes from state 1, where $P_1 = 1$ bar and $V_1 = 1$ m^3 to state 2 where $V_2 = 2$ m^3.

3.21 Air in a turbine

Air enters the turbine section of a jet engine at a temperature of 1500°C and leaves at 500°C. Compute the change in specific enthalpy (kJ/kg) through the turbine in four different ways.

1. Assuming constant specific heat evaluated at the inlet temperature using table A-2b.
2. Assuming constant specific heat evaluated at the outlet temperature using table A-2b.
3. Assuming constant specific heat evaluated at the mean temperature using table A-2b.
4. Integrating the polynomial function in table A-2c to account for variable specific heat.
5. Using the h values tabulated in table A-17.

Compare your results for methods 1, 2, 3 and 4 with those of method 5. Do the h values of table A-17 take variable specific heat into account?

3.22 Oxygen in a rigid tank

A rigid insulated tank whose volume is V contains pure oxygen initially at a pressure P_1 and a temperature T_1. A fan inside the tank, driven by a shaft that passes through the tank wall, is used to stirr the oxygen. After a while the pressure in the tank rises to a pressure P_2.

a: Which process is responsible for the pressure rise?

b: Give the relation that describes how much internal energy is added to the oxygen. The specific heats of oxygen can be assumed constant and can be evaluated at the mean temperature for this process.

c: Calculate how much internal energy (kJ) the fan added to the oxygen if $V = 0.3$ m^3, $P_1 =$ 100 kPa, $P_2 = 150$ kPa and $T_1 = 27$°C.

3.23 Two closed rigid system in thermal equilibrium

An isolated, combined system, consists of two subsystems (a) and (b). They are divided by a rigid, impermeable, but un insulated (diabetic) wall (i.e. mass cannot, but heat can cross the wall). Given are two state equations:

$$\frac{1}{T_a} = \frac{3}{2} R_u \frac{N_a}{U_a} \quad \text{and} \quad \frac{1}{T_b} = \frac{5}{2} R_u \frac{N_b}{U_b}, \tag{1}$$

in which R_u is the universal gas constant. The initial temperatures at time, $t = 1$ are T_{a1} and T_{b1}. After some time at $t = 2$ the system reached thermal equilibrium.

a: Give the condition for thermal equilibrium. What happens to the total internal energy of both subsystems?

b: Determine a relation for U_{a2} and U_{b2} in case the combined system is in thermal equilibrium. Also give the relation for the total internal energy of the system in thermal equilibrium ($U_a 2 + U_b 2 = U_2$).

c: With $N_a = 2$ mol, $N_b = 3$ mol, $T_{a1} = 250$ K and $T_{b1} = 350$ K calculate the equilibrium temperature in case the system is in thermal equilibrium.

d: Also calculate the values of U_{a2} and U_{b2} in case the system is in thermal equilibrium.

3.24 Two closed movable systems in equilibrium

Consider again the system of problem 3.23. However, the wall between both subsystems now can move (like a piston), but is still impermeable and un insulated. The conditions are as in problem 3.23 and the total volume is V_t. Also given are two additional state equations:

$$\frac{P_a}{T_a} = R_u \frac{N_a}{V_a} \quad \text{and} \quad \frac{P_b}{T_b} = R_u \frac{N_b}{V_b}. \tag{2}$$

a: Give the conditions for equilibrium.

b: Determine the values of the internal energy for both subsystems (U_{a2} and U_{b2}) in equilibrium and determine the equilibrium temperature.

c: Determine relations for the volumes in equilibrium (V_{a2} and V_{b2}).

d: With $V_t = 80$ litres calculate the values of V_{a2} and V_{b2} in case the system is in equilibrium.

e: Also calculate the equilibrium pressure.

4 The First Law of Thermodynamics, Conservation of Energy

4.1 First law of thermodynamics

a: What is the first law of thermodynamics?

b: Give the expression for first law of thermodynamics.

c: What changes to the expression for first law in steady state operation?

d: Simplify the first law for application to a compressor or a turbine by neglecting terms and making some assumptions.

e: Simplify the first law for application to a mixer or open feed water heater by neglecting terms and making some assumptions.

f: Simplify the first law for application to a nozzle by neglecting terms and making some assumptions.

g: What changes to the first law for a closed system?

4.2 Conservation of mass principle

a: What is stated by the conservation of mass principle?

b: Give the expression for the conservation of mass principle.

c: What is the mass flow rate and give a relation for it?

d: What is the volume flow rate, give a relation for it and how is it related to the mass flow rate?

e: What changes to the expression for the conservation of in steady state operation?

4.3 Conservation of mass in a nozzle

Air enters a nozzle steadily at 2.21 kg/m^3 and 30 m/s and leaves at 0.762 kg/m^3 and 180 m/s. The inlet area of the nozzle is 80 cm^2.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine a relation for the mass flow rate through the nozzle and calculate the mass flow rate through the nozzle.

b: Determine a relation for the exit area of the nozzle and calculate the exit area of the nozzle.

4.4 Conservation of mass in a hair dryer

A hair dryer is basically a duct of constant diameter in which a few layers of electric resistors are placed. A small fan pulls the air in and forces it through the resistors where it is heated. The the density of air is 1.20 kg/m^3 at the inlet and 1.05 kg/m^3 at the exit.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the percent increase in the velocity of air as it flows through the dryer.

4.5 Work and power input for a compressor

Refrigerant 134a enters the compressor of a refrigerator system as saturated vapor at 0.14MPa and leaves as superheated vapor at 0.8 MPa and 50°C at a rate of 0.04 kg/s. Assume the kinetic and potential energies to be negligible.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the specific work required to compress the refrigerant.

b: Determine the power required to compress the refrigerant.

4.6 Cooling a closed system

A 3-m^3 rigid tank contains hydrogen at 250 kPa and 500 K. The gas is now cooled until its temperature drops to 300 K. Assume hydrogen to be a perfect gas.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the final pressure in the tank.

b: Determine the amount of heat transfer.

4.7 An insulated rigid tank

An insulated rigid tank is divided into two equal parts by a partition. Initially, one part contains 6 kg of an perfect gas at 800 kPa and 50°C, and the other part is evacuated. The partition is now removed, and the gas expands into the entire tank.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the final pressure and temperature in the tank.

4.8 Nozzle

Air enters an adiabatic nozzle steadily at 300 kPa, 200°C and 30 m/s and leaves at 100 kPa and 180 m/s. The inlet area of the nozzle is 80 cm^2.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the mass flow rate through the nozzle.

b: Determine the exit temperature of the air.

c: Determine the exit area of the nozzle.

4.9 Steam turbine

Steam flows steadily through an adiabatic turbine. The inlet conditions of the steam are 10 MPa, 450°C and 80 m/s and the exit conditions are 10 kPa, 92 percent quality and 50 m/s. The mass flow rate of steam is 12 kg/s. Potential energy change can be neglected (but kinetic energy change not).
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the change in the rate of kinetic energy.

b: Determine the power output.

c: Determine the turbine inlet area.

4.10 Refrigerant compressor

Refrigerant 134a enters an adiabatic compressor as saturated vapor at -20°C and leaves at 0.7 MPa and 70°C. The mass flow rate of the refrigerant is 1.2 kg/s.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the power output to the compressor.

b: Determine the volume flow rate of the refrigerant at the compressor inlet.

4.11 Throttling valve

Refrigerant 134a is throttled from the saturated liquid state at 800 kPa to a pressure of 140 kPa.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the temperature drop during this process.

b: Determine the final specific volume of the refrigerant.

4.12 Feed water heater

In steam power plants, open feed water heaters are frequently utilized to heat the feed water by mixing it with steam bled off the turbine at some intermediate stage. Consider an open feed water heater that operates at a pressure of 800 kPa. Feed water at 50°C is to be heated with superheated steam at 200°C and 800 kPa. In an ideal feed water heater the mixture leaves the heater as a saturated liquid at the feed water pressure.
State the variables involved in this problem. What are the main equations governing this problem.

a: What is meant with saturated liquid and what does this imply for the heater exit data?

b: Why is it unattractive to heat above the saturated liquid temperature?

c: Determine the ratio of the mass flow rates of the feed water and the superheated vapor for this case.

4.13 Steam/water heat exchanger

Steam at a temperature of 50°C is to be condensed in the condenser of a steam power plant from the saturated vapor state to the saturated liquid state with cooling water from a nearby lake, which enters the tubes of the condenser at 18°C at a rate of 101 kg/s and leaves at 27°C.
Kinetic and potential energy changes may be neglected and there are no work and heat interactions between the condenser and the surroundings.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the rate of heat transfer to the cooling water in the heat exchanger.

b: Determine the rate of condensation of the steam (i.e. the mass flow rate of the steam) in the condenser.

4.14 Steam turbine 2

Steam enters an adiabatic turbine at 10 MPa and 500°C and leaves at 10 kPa with a quality of 90 percent. The power output is 5 MW. Neglect the changes in kinetic and potential energies.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the mass flow rate for this adiabatic turbine.

b: Determine also the mass flow rate if the turbine is not adiabtic but losses heat at a rate of 500 kW.

4.15 Turbine with Argon

Argon gas enters an adiabatic turbine steadily at 1600 kPa and 450°C with a velocity of 55 m/s and leaves at 150 kPa with a velocity of 150 m/s. The inlet area of the turbine is 60 cm^2. The power output of the turbine is 190 kW. Neglect changes in potential energy.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the mass flow rate of the argon.

b: Determine the exit temperature of the argon.

4.16 Helium compressor

Helium is to be compressed from 120 kPa and 310 K to 700 kPa and 430 K. A heat loss of 20 kJ/kg occurs during the compression process. Neglect changes in kinetic and potential energy.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the power input required for a mass flow rate of 90 kg/min.

4.17 Mixing chamber

A hot water stream at 80°C enters a mixing chamber with a mass flow rate of 0.5 kg/s where it is mixed with a stream of cold water at 20°C. It is desired that the mixture leaves the chamber at 42°C. All streams are at a pressure of 250 kPa.
Kinetic and potential energy changes may be neglected and there are no work and heat interactions between the condenser and the surroundings.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the mass flow rate of the cold-water stream and the stream leaving the mixing chamber.

4.18 Refrigerant-134a heat exchanger

Refrigerant-134a at 800 kPa, 70°C, and 8 kg/min is cooled by water in a condenser until it exists as a saturated liquid at the same pressure. The cooling water enters the condenser at 300 kPa and 15°C and leaves at 30°C at the same pressure.
Kinetic and potential energy changes may be neglected and there are no work and heat interactions between the condenser and the surroundings.
State the variables involved in this problem. What are the main equations governing this problem.

a: Determine the mass flow rate of the cooling water required to cool the refrigerant.

b: Determine the rate of heat transfer to the cooling water.

5 Entropy and the Second Law of Thermodynamics

5.1 Reversible and Irreversible Processes

a: Define a reversible process.

b: When can a reversible process take place?

c: How is the process opposite to a reversible process called?

d: How can the system after a reversible or irreversible process be restored to its initial state?

e: What conditions must the system fulfil to be reversible?

f: Give examples of the same process, but once when it is reversible and once irreversible?

g: Do reversible processes take place in nature?

h: Why are engineers interested in reversible processes even though they can never be achieved?

i: A cold canned drink is left in a warmer room where its temperature rises as a result of heat transfer. Is this a reversible process?

5.2 Coffee

Suppose you drop a cup of coffee that smashes into pieces and the coffee spills all over the floor. If you record this event with a video camera and you ran the film backwards, probably it would be obvious to you that the film was running backwards. Which law is violated and explain why?

1. Conservation of energy
2. Conservation of mass
3. Second Law of Thermodynamics
4. All above

5.3 Insulated piston-cylinder device

A perfectly insulated piston-cylinder device encloses an ideal gas. Initially, the gas has a temperature T_1 and a pressure P_1. Assume that the amount of work you can deliver is the same for the reversible and the irreversible process.

a: Sketch the $P - V$ and $T - V$ curves if the piston-cylinder is frictionless and the gas is first compressed to a volume V_2 and expanded back to V_1.

b: On the same graph, sketch the $P - V$ and $T - V$ curves for the process of part (a) if the piston has frictional losses to the wall of the cylinder

c: On a new graph, sketch the $P - V$ and $T - V$ curves for a sequence of compression-expansion processes under the conditions of part (b). Each successive process begins at the end state of the previous process.

5.4 Frictionless piston-cylinder device

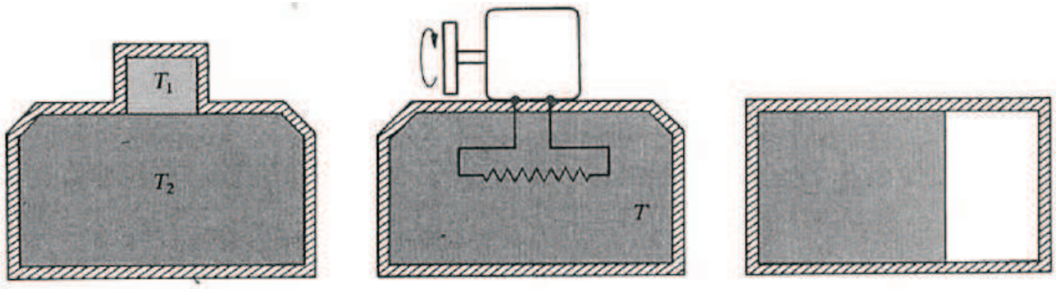
A frictionless piston-cylinder encloses an ideal gas. Initially, the gas has a temperature T_1 and a pressure P_1, and the surroundings are at $T_0 < T_1$.

a: Sketch the $P - V$ and $T - V$ curves if the piston-cylinder has ideal insulation and gas is first compressed to volume V_2, and is then expanded back to V_1.

b On the same graph, sketch the $P-V$ and $T-V$ curves for the process of part (a) if the insulation is removed, and heat transfer can occur with the surroundings.

c: On a new graph, sketch the $P - V$ and $T - V$ curves for a sequence of compression-expansion processes under the conditions of part (b). Each successive process begins at the end state of the previous process.

5.5 Rigid adiabatic systems



(a) (b) (c)

Consider three different systems, each enclosed in a rigid adiabatic boundary. Initially we have:

a: A small reservoir at higher temperature T_1 in contact with a much larger reservoir at lower temperature T_2.

b: A freely rotating flywheel is connected to an electrical generator which in turn is connected by wires to a resistor in reservoir.

c: Gas is confined in the left portion of the container by a membrane, with the remainder of the container being evacuated. The membrame will transmit slowly gas molecules as time proceeds.

What do you expect to happen in each of these cases as time progresses? Is it possible to reverse each of these processes? How do you call the processes? Is the total energy conserved in each of the processes? Do you know a physical law that determines the direction in which a process can take place?

5.6 Steady flow

Consider a steady flow of an ideal gas, it undergoes reversible and irreversible compression from pressure P_1 to pressure P_2. Draw both processes in a $T - s$ diagram. Explain the difference.

5.7 Basics of entropy

a: In nature natural processes will likely go in a predictable direction and systems will go to equilibrium. A system or process can not spontaneously go in the reversed direction and a system will not go to spontaneously to a non equilibrium state. How is a process called that cannot go in the reversed direction?

b: If in an idealized world a process can go in the reversed direction, how is this called?

c: To be able to describe systems and processes as an engineer you want to quantify the physical property that can measure the irreversibility of systems and processes. How is this property called? Which symbol is used for it and what is its dimension.

d: Is entropy an intensive or an extensive property?

e: What is the value of the entropy if the system is in equilibrium?

f: Give the equation that can be used to compute the entropy change from an amount of reversible heat transfer.

g: What changes to the equation if the heat transfer is not reversible?

h: What three different mechanisms can cause the entropy of a system to change?

i: What is the effect on the entropy if there is heat transfer to the system and if there is heat transfer from the system?

j: What is the effect of irreversibility on the entropy?

k: A system undergoes a process between two fixed states first in a reversible manner and then in an irreversible manner. For which case is the entropy change greater? Why?

l: What is an isentropic process?

m: The entropy of a hot block of iron decreases as it cools. Is this a violation of the increase of entropy principle? Explain.

n: Is an isothermal process necessarily reversible? Explain your answer with an example.

o: Is a process that is reversible and adiabatic necessarily isentropic? Explain.

5.8 Basics of the second law of thermodynamics

a: What is stated in the second law of thermodynamics?

b: Why was the second law of thermodynamics “invented”?

c: Consider a person who organizes his room and thus decreases the entropy of the room. Does this process violate the second law of thermodynamics?

5.9 Isothermal expansion

Refrigerant 134a expands isothermally from an initial state at $P_1 = 300$ kPa, $T_1 = 40°$C to a final state at $P_2 = 150$ kPa. Find the change in specific entropy of the refrigerant that occurs in this process using the entropy values given in the tables.

5.10 Entropy change of an ideal gas in a rigid tank

A rigid tank contains a an ideal gas at 40°C that is being stirred by a paddle wheel. The paddle wheel does 200 kJ of work on the ideal gas. It is observed that the temperature of the ideal gas remains constant during during this process as a result of heat transfer between the system and the surroundings at 25°C.
State the variables involved in this problem and give the main equations governing this problem.

a: Determine the minimum entropy lost by the system for the process due to the heat transfer.

b: Determine the minimum entropy gained by the environment for the process due to the heat transfer, and compare with a. What is the total change in entropy of the universe due to this process of heat transfer? Does the process satisfy the second law?

c: Determine the total change in entropy of the ideal gas in the rigid tank.

5.11 Entropy change of compressed air

Air is compressed by a compressor driven by a 12 kW motor from P_1 to P_2. The air temperature is maintained constant at 25°C during this process as a result of heat transfer to the surrounding medium at 10°C.
State the assumptions made in solving this problem. State the variables involved in this problem and give the main equations governing this problem.

a: Determine the rate of heat loss of the air.

b: Determine the rate of entropy change of the air.

c: Determine the rate of entropy change of the environment.

5.12 Radiator

The radiator of a steam heating system has a volume of 20 L and is filled with superheated water vapor at 200 kPa and 200°C. At this moment both the inlet and the exit valves to the radiator are closed. After a while the temperature of the steam drops to 80°C as a result of heat transfer to the room air.
State the variables involved in this problem and give the main equations governing this problem.

a: Determine the steam pressure and vapor mass fraction.

b: Determine the entropy change of the steam during this process in kJ/K.

5.13 Non adiabatic compressor

Air is compressed steadily by a compressor driven by a 5 kW motor from 100 kPa and 17°C to 600 kPa and 167°C at a rate of 1.6 kg/min. During this process, some heat transfer takes place between the compressor and the surrounding medium at 17°C. Assume the air to behave like a perfect gas, take C_p and R values from tables.
State the variables involved in this problem and give the main equations governing this problem.

a: Determine the rate of heat loss during this process.

b: Determine the rate of entropy change of the air during this process.

5.14 Entropy change of a copper block

a: A hot copper block of mass M_{copper}, initially at T_{copper}, is dropped into an insulated tank that contains a volume of V liters of water at a temperature T_{water}. Determine the relation for the final equilibrium temperature T_{equi}.

b: Determine also the relation for the total entropy change, ΔS, for this process.

c: Calculate the final temperature, T_{equi}, and the total entropy change, ΔS, if $M_{copper} = 50$ kg, $T_{copper} = 80$ °C, $V = 120$ liters and $T_{water} = 25$ °C.

5.15 Entropy change of an iron block

a: A hot block iron of mass M_{iron}, initially at T_{iron}, is quenched in an insulated tank that contains a mass of water M_{water} at a temperature T_{water}. Assuming the water that vaporizes during the process condenses back in the tank, determine the relation for the total entropy change, ΔS, during this process.

b: Calculate the entropy change, ΔS, if $M_{iron} = 12$ kg, $T_{iron} = 350$ °C, $M_{water} = 100$ kg and $T_{water} = 22$ °C.

5.16 Entropy change of an aluminum block

a: An aluminum block of mass $M_{aluminum}$, initially at $T_{aluminum}$, is brought into contact with a block of iron of mass M_{iron} and temperature T_{iron} in an insulated enclosure. Determine the relation for the final equilibrium temperature T_{equi}.

b: Determine also the relation for the total entropy change, ΔS, for this process.

c: Calculate the final temperature, T_{equi}, and the total entropy change, ΔS, if $M_{iron} = 20$ kg, $T_{iron} = 100$ °C, $M_{aluminum} = 20$ kg and $T_{aluminum} = 200$ °C.

5.17 Entropy change of ideal gases

a: Starting with $\mathrm{d}u = T\mathrm{d}s - P\mathrm{d}v$ obtain the relation for the entropy change of ideal gases under the constant-specific-heat assumption: $s_1 - s_2 = C_{v,av} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$.

b: Starting with $\mathrm{d}h = T\mathrm{d}s + v\mathrm{d}P$ obtain the relation for the entropy change of ideal gases under the constant-specific-heat assumption: $s_1 - s_2 = C_{p,av} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$.

c: Prove that the two relations for entropy change of ideal gases

$$s_1 - s_2 = C_{v,av} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} \quad \text{and} \quad s_1 - s_2 = C_{p,av} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} \tag{3}$$

under the constant-specific-heat assumptions are equivalent.

5.18 Entropy change of ideal gases in an isothermal process

a: Give the condition for an isothermal process.

b: Can the entropy of an ideal gas change during an isothermal process?

c: What changes to the relations found in exercise 5.17a and b for an isothermal process.

d: An ideal gas undergoes a process between two specified temperatures, first at constant pressure and then at constant volume. For which case will the ideal gas experience a larger entropy change? Explain.

5.19 Entropy change of ideal gases in an isentropic process

a: Give the condition for an isentropic process.

b: Combine the relations found in exercise 5.17a and b and show that for an is entropic process: Pv^{γ} is constant, where $\gamma = \frac{C_p}{C_v}$.
Note: divide the equations by C_v and C_p respectively and subtract them and rearrange it using the ln rules to find the relation.

5.20 Entropy change of oxygen in piston-cylinder device

a: Oxygen gas is compressed in a piston-cylinder device from an initial state with specific volume, v_1 and specific temperature, T_1 to a final state of specific volume v_2 and temperature T_2. Determine a relation for the entropy change of the oxygen, ΔS, during this process. Assume constant specific heats. Oxygen can be treated as an ideal gas.

b: Calculate the entropy change, ΔS, if $v_1 = 0.8$ m^3/kg, $T_1 = 25$ °C, $v_2 = 0.1$ m^3/kg and $T_2 = 287$ °C.

5.21 Entropy change of nitrogen in piston-cylinder device

a: A piston-cylinder device contains m kg of nitrogen gas at P_1 and T_1. The gas is now compressed slowly in a polytropic process during which $Pv^{1.3} =$ constant. The process ends when the volume is reduced by one-half. Determine the relation for the entropy change, ΔS, of nitrogen during this process. Nitrogen can be treated as an ideal gas.

b: Calculate the specific entropy change, Δs, and the total entropy change, ΔS, if $P_1 = 120$ kPa, $T_1 = 27$ °C and m=1.2 kg.

5.22 Reversible condensation

Calculate the total heat transfer during a non flow process where 3.5 kg of H_2O is cooled reversibly and isobarically from a saturated vapor to a saturated liquid at 1400 kPa.

5.23 Reversible isothermal expansion

Air (0.2 kg) is allowed to expand in a piston-cylinder device from 5.0 MPa and 800 K to a pressure of 0.1 MPa. The process is reversible and isothermal. Determine the total heat transfer and total work done.

5.24 Reversible processes for helium

Helium in a non-flow device undergoes the reversible process shown in figure 4. Determine the heat transfer and work (kJ/kg) for each process. For He, $C_p = 5/2R$.

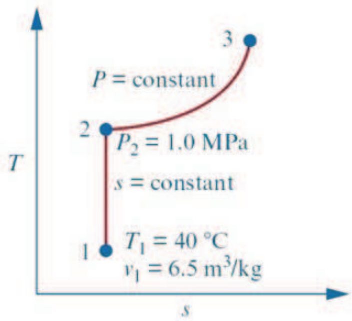


Figure 4: *Process paths for helium for exercise 5.24*

5.25 Melting ice

A bucket of ice water initially contains 50 percent ice and 50 percent liquid water by mass. The ice water undergoes heat transfer with the surroundings, which are at T_0, until the liquid water in the glass reaches very nearly a temperature of T_0. The enthalpy of melting (latent heat of fusion) of ice is $h_{ls} = 335$ kJ/kg. Note, in solving this problem think what steps happen in the process.

a: If $T_0 = 27$°C, and the entropy generation is $S_{gen} = 3$ kJ/K, what is the total mass of water in the bucket during the process?

b: At what value of T_0 is $S_{gen} = 0$ for the process described? (Prove your result.)

5.26 Adiabatic steady flow device

In the adiabatic steady flow device shown in figure 5, there is work done, but its direction is unknown. Determine the direction of the air flowing through the device. (Hint: Assume a flow direction and calculate s_{gen} for the device, the specific heat can be taken at the average value.)

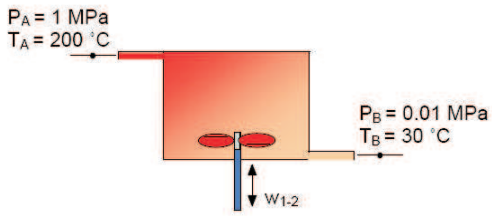


Figure 5: *Steady flow device for exercise 5.26*

5.27 Throttling valve

An incompressible fluid flows through a throttling valve with $P_1 > P_2$ shown in figure 6.

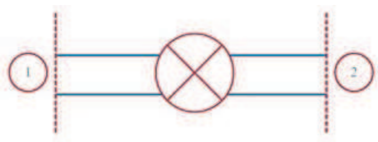


Figure 6: *Throttling valve for exercise 5.27*

a: Show that the entropy increases during this process.

b: Develop an explicit relationship for the entropy generation per unit mass for this process in terms of P_1, T_1, P_2, and C_p.

5.28 Stainless steel ball bearings

Stainless steel ball bearings ($\rho = 8085\ kg/m^3$ and $c_p = 0.480$ kJ/kg°C) having a diameter of 1.8 cm are to be quenched in water at a rate of 1100 balls per minute. The balls leave the oven at a uniform temperature of 900°C and are exposed to air at 20°C until the temperature of the balls drop to 850°C before they are dropped into the water for quenching. See Figure 7.

a: Determine the rate of heat transfer from the ball to the air.

b: Determine the rate of entropy generation due to this heat transfer.

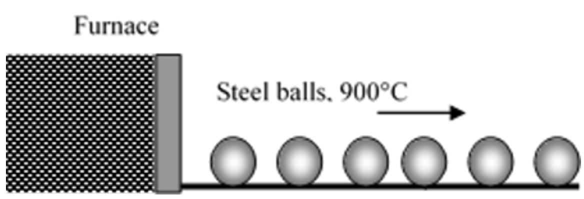


Figure 7: Figure corresponding to exercise 5.28

5.29 Egg

An ordinary egg can be approximated as a 5.5-cm-diameter sphere. The egg is initially at a uniform temperature of 8°C and is dropped into boiling water at 97°C. Take the properties of the egg to be $\rho = 1020\ kg/m^3$ and $c_p = 3.32$ kJ/kg°C.

a: Determine the amount of heat transfer to the egg by the time it is cooked (the temperature of the egg rises to 70°C.

b: Determine the amount of entropy generation associated with this heat transfer process.

6 Second Law Applications

6.1 Neon in an insulated container

Neon is in an insulated container at an initial state defined by P_1 and T_1. Work is done until the system comes to a final state P_2 and T_2. One of the possible states of the process has $P_A = 1$ atm, and $T_A = 25°\text{C}$. The other has $P_B = 2$ atm and $T_B = 139.7°\text{C}$. Which state, A or B, is the initial state and which state is the final state?

6.2 Air in the cylinder of an automobile engine

Air enclosed in the cylinder of an automobile engine is initially at 300 K and 100 kPa. The air is compressed adiabatically to one-eighth of its original volume. It may be assumed that the specific heats of air are constant for this process.

a: If the process were reversible, what would be the work of compression (kJ/kg) and the final temperature (K) and pressure (kPa)?

b: Suppose the compression process occurs along a path defined by Pv1.5=constant. Would this process be reversible or irreversible? What would be the work of compression, the final temperature and pressure, and the compression efficiency?

6.3 Isentropic efficiencies of steady flow devices

a: Describe the ideal process for an adiabatic turbine and an adiabatic compressor and define the isentropic efficiency for those devices. Make a graph (h-s diagram) to clear your answer.

b: On a T-s diagram, does the actual exit state (state 2) of an adiabatic turbine have to be on the right-hand side of the isentropic exit state (state 2s)? Why?

6.4 Adiabatic steam turbine 1

Steam enters an adiabatic steam turbine at 8 MPa and 500°C with a mass flow rate of 3 kg/s and leaves at 30 kPa. The isentropic efficiency of the turbine is 0.9. Neglect the kinetic energy change of the steam.

a: Draw the process in a T-s and h-s diagram.

b: Determine the temperature at the turbine exit.

c: Determine the power output of the turbine.

6.5 Adiabatic steam turbine 2

Steam enters an adiabatic steam turbine at 6 MPa, 600°C and 80 m/s and leaves at 50 kPa, 100°C and 140 m/s. The power output of the turbine is 5 MW.

a: Draw the process in a T-s and h-s diagram.

b: Determine the mass flow rate of the steam flowing through the turbine.

c: Determine the isentropic efficiency of the turbine.

6.6 Refrigerant compressor

Refrigerant-134a enters an adiabatic compressor as saturated vapor at 120 kPa at a rate of $0.3\text{m}^3/\text{min}$ and exits at 1 MPa pressure. The isentropic efficiency of the compressor is 80 percent.

a: Draw the process in a T-s and h-s diagram.

b: Determine the temperature of the refrigerant at the exit of the compressor.

c: Determine the power input.

6.7 Turbine curve in Mollier diagram

What is the shape of the line that depicts the expansion proces in the turbine in the Mollier diagram? To find that out consider a turbine with an inlet pressure of 50 bar, an inlet temperature of 500°C and an isentropic efficiency of 80%. Determine the enthalpy at the exit for outlet pressures of 30 bar, 10 bar, 5 bar, 2 bar, 1 bar and 0.1 bar and draw the points in the Mollier diagram. Comment on your findings.

6.8 Steam turbine coupled to an air compressor

A steam turbine (efficiency 72 percent) drives an air compressor (efficiency 80 percent) as shown in figure 8. Assuming air can be treated as an ideal gas with constant specific heat, what mass flow rate of air, in kilograms per hour, can be compressed?

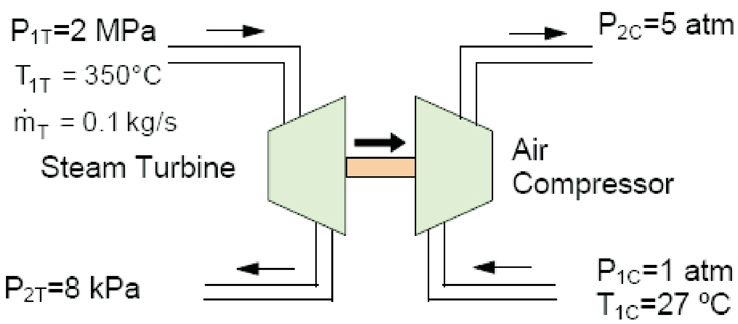


Figure 8: *Steam turbine coupled to an air compressor for exercise 6.8.*

6.9 Two stage compressor

A two-stage air compressor is compressing air at a rate of 2 kg/s at the conditions shown in figure 9. The first stage is operated as an adiabatic compressor, the second stage is operated isothermally. The actual power required to drive the compressor is 650 kW.

a: What would the T_3 be if each stage of the compressor were reversible?

b: What power input would be required to drive the compressor if each stage were reversible?

c: If T_3 for the actual compressor were 250°C, how much power is required to drive the second stage?

6.10 Nozzle

Hot combustion gasses enter the nozzle of a turbojet engine at 260 kPa, 747°C and 80m/s, and they exit at a pressure of 85 kPa. Assume an isentropic efficiency of 92 percent and treat the combustion gases as air.

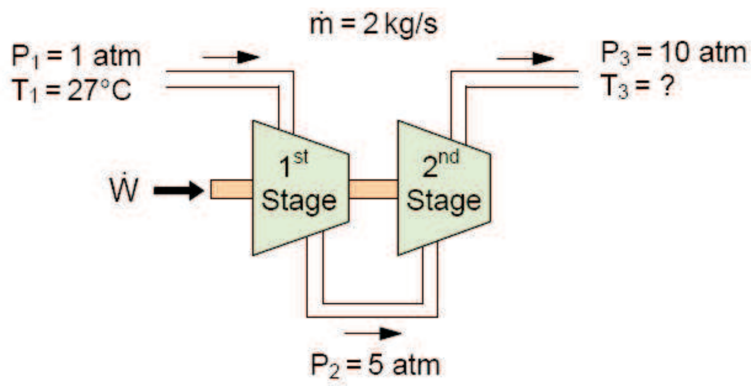


Figure 9: *Two stage compressor for exercise 6.9.*

a: Determine the exit velocity.

b: Determine the exit temperature.

c: Determine the specific rate of heat loss in the nozzle.

d: Determine the specific rate of entropy change.

6.11 Adiabatic device

The adiabatic device shown in figure 10 uses H_2O as the medium.

a: Determine T_3.

b: Does the device violate the second law of thermodynamics?

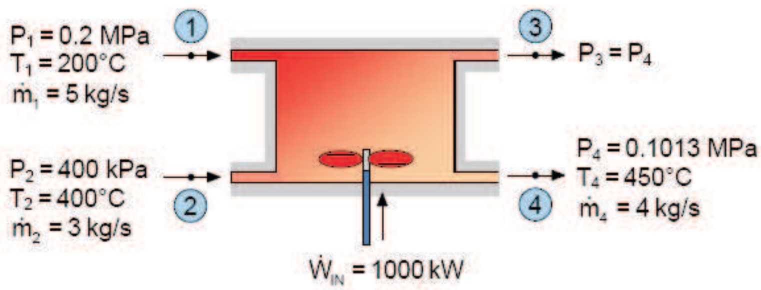


Figure 10: *Adiabatic device with four streams for exercise 6.11.*

6.12 Steady-state steady-flow adiabatic device

Is the steady-state steady-flow adiabatic device for air, shown in figure 11 possible? Assume constant specific heats.

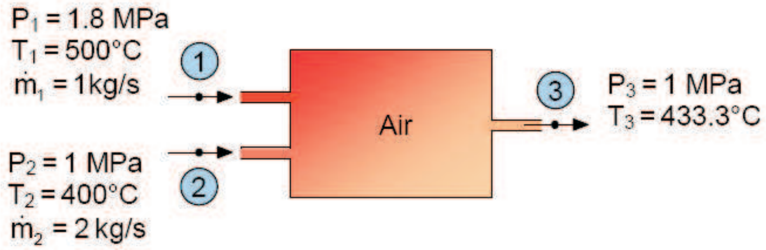


Figure 11: *Steady-state steady-flow adiabatic device with three streams for exercise 6.12.*

6.13 Venturi

Water is flowing through a venturi meter in order to measure the mass flow rate. A venturi is a cylindrical tube with a contraction, called the throat. The diameter of the tube is D_1 at the entrance part and D_2 in the throat. The gage pressure is measured to be P_1 at the entrance and P_2 at the throat. Frictional effects are neglected.

a: Make a sketch of the situation and mark clearly all the characteristic locations.

b: Give an expression for the volume flow rate and the mass flow rate of the water through the venturi as a function of P_1, P_2, D_1, D_2 and ρ, the density of water.

7 Thermodynamic Cycles for Work, Heat and Cold, Carnot

7.1 Thermodynamic cycles

Power generation and refrigeration are two important areas of the application of thermodynamics. Both power generation and refrigeration are accomplished by systems that operate on a thermodynamic cycle. These cycles are therefore divided into two general categories: power cycles and refrigeration cycles. Besides this general division thermodynamic cycles can be categorized in different ways.

a: What is the difference between gas cycles and vapor cycles?

b: What is the difference between open and closed cycles?

c: Heat engines can be categorized in internal combustion and external combustion engines. What is the difference between these?

d: What is an ideal cycle?

7.2 Thermal efficiency

What is the thermal efficiency and how is it expressed.

7.3 Coefficient of performance

a: How is in general the coefficient of performance (COP) defined?

b: How is the expression for the specific case of the refrigerator.

c: How is the expression for the specific case of the heat pump.

d: A heat pump and a refrigerator have the same Q_L and Q_H. Find the COP_{HP} if the COP_R is known.

7.4 Carnot

a: What is the Carnot efficiency?

b: How is the Carnot efficiency defined?

c: What is a Carnot cycle?

d: Draw the Carnot cycle in a $P - v$ and in a $T - s$ diagram?

e: Name the processes involved in the cycle.

f: Point the work and heat in this diagram. What is the net work equal to?

g: Is the Carnot cycle a reversible or irreversible process. Explain.

h: The Carnot cycle can be use as a heat engine, is it possible to use it also for refrigeration? Explain.

7.5 Geothermal energy

An innovative way of power generation involves the utilization of geothermal energy - the energy of hot water that exists naturally underground - as a heat source. A supply of hot water at 140°C is discovered at a location where the environmental temperature is 20°C. Determine the maximum thermal efficiency of a geothermal plant built at that location. Will this efficiency be reached in reality? What happens to the efficiency in winter when the environmental temperature is lower?

7.6 A heat pump

A heat pump is to be used to heat a house during the winter. The house is to be maintained at T_{house} at all times. The house is estimated to be losing heat at a rate $\dot{Q}_{loss}$ when the outside temperature drops to $T_{outside}$.

a: Give the formula for the coefficient of performance of the heat pump if it is reversible, $COP_{HP,rev}$.

b: Give an expression for the minimum power required to drive this heat pump, if the heat pump is reversible.

c: Calculate the coefficient of performance and determine the minimum power required to drive this heat pump, if the heat pump is reversible when $T_{house} = 20°\text{C}$, $T_{outside} = -5°\text{C}$ and $\dot{Q}_{loss} = 75000$ kJ/h.

7.7 Carnot engine

A Carnot engine operates between two temperature reservoirs a high temperature one and a low temperature one maintained at $T_H = 200°\text{C}$, and $T_L = 20°\text{C}$, respectively. The net output of the engine is $\dot{W}_{net} = 15$ kW.

a: Give a formula for the thermal efficiency (η_{th}) and determine the thermal efficiency.

b: Give an expression for the heat transfer rate from the high temperature reservoir to the engine, $\dot{Q}_H$ and for the heat transfer rate from the engine to the low temperature reservoir $\dot{Q}_L$. Calculate both heat transfer rates.

c: Check the second law for this cycle, i.e. check if for this Carnot cycle the inequality of Clausius is satisfied.

7.8 Air conditioner

When a man returns to his well-sealed house on a summer day, he finds that the house is at $T_{initial}$. He turns on the air conditioner with a coefficient of performance COP_R, which cools the entire house to T_{final} in t minutes. The entire mass in the house is m kilo of air.

a: Give a formula for the power drawn by the air conditioner.

b: If $T_{initial} = 32°\text{C}$, $T_{final} = 20°\text{C}$, the time necessary for the cooling is 15 minutes and the COP of the air-conditioning system is 2.5, determine the power drawn by the air conditioner. Assume the entire mass within the houses is equivalent to $m = 800$ kg of air with $c_V = 0.72$ kJ/(kgC) and $c_P = 1$ kJ/(kgC).

c: Also calculate the amount of heat extracted from the house (Q_H).

7.9 Refrigerator

A refrigerator is cooling a space to T_{L1} by rejecting energy to the atmosphere at T_H. It is desired to reduce the temperature in the refrigerated space to T_{L2}.

a: Give an expression for the minimum percentage increase in work required, by assuming a Carnot refrigerator, for the same amount of energy removed.

b: Calculate the minimum percentage increase in work required, by assuming a Carnot refrigerator, for the same amount of energy removed, when $T_{L1} = -5°\text{C}$, $T_{L2} = -25°\text{C}$ and $T_H = 20°\text{C}$.

7.10 Heat engine

A heat engine is designed to have a thermal efficiency of 27%. It will be used to supply power to a remote farm. The engine will be operated near a large pool, which will act as a low temperature reservoir. However, due to environmental considerations, a heat transfer of only 50.0 kJ/min may be rejected to the pool. If the farm requires 1.8 kW of power, will this engine provide sufficient power?

7.11 Nuclear power plant

A Carnot engine is used in a nuclear power plant. It receives 1500 MW of power as heat transfer from a source at 327°C, and rejects thermal waste to a nearby river at 27°C. The river temperature rises by 3°C because of this power rejection by the plant.

a: What is the efficiency of the power plant?

b: What is the net power output of the plant?

c: What is the mass flow rate of the river?

7.12 Ideal Carnot steam cycle

The steam cycle given in figure 12 operates as an ideal heating Carnot cycle between pressures of 40 bar and 0.05 bar. In the boiler heat is added to the working fluid at a constant temperature, T_{hot}, which causes the fluid to evaporate from saturated fluid to saturated vapor(isothermal expansion). In the condenser heat is rejected from the working fluid at a constant temperature T_{cold}, as a result of the condensing vapor (isothermal compression). In the compressor the saturated mixture is compressed isentropic to saturated fluid causing the temperature of the mixture to increase from T_{cold} to T_{hot}. In the turbine the vapor is expanded isentropic to the saturated mixture region causing the temperature of the vapor to decrease from T_{hot} to T_{cold}.

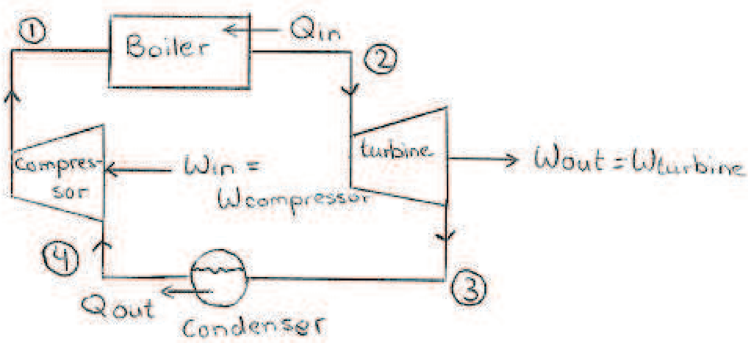


Figure 12: *Steam heating cycle for exercise 7.12*

a: Draw the process in a $T-s$ diagram.

b: Use the tables to look up the temperatures T_{hot} and T_{cold}.

c: Calculate the heat and work transfers and cycle efficiency for steam operating in this ideal Carnot heating cycle.

d: Calculate the heat and work transfers and cycle efficiency for steam operating in this heating cycle if it not ideal but the turbine and compressor have isentropic efficiencies of 0.8. Draw the non ideal process in a $T-s$ diagram. Discus the difference with the ideal case.

e: Check the second law for this cycle for the case the cycle is ideal as well as for the case the cycle is not ideal, i.e. check if for this Carnot cycle the inequality of Clausius is satisfied. Explain the difference between both cases.

7.13 Perpetual - motion machines

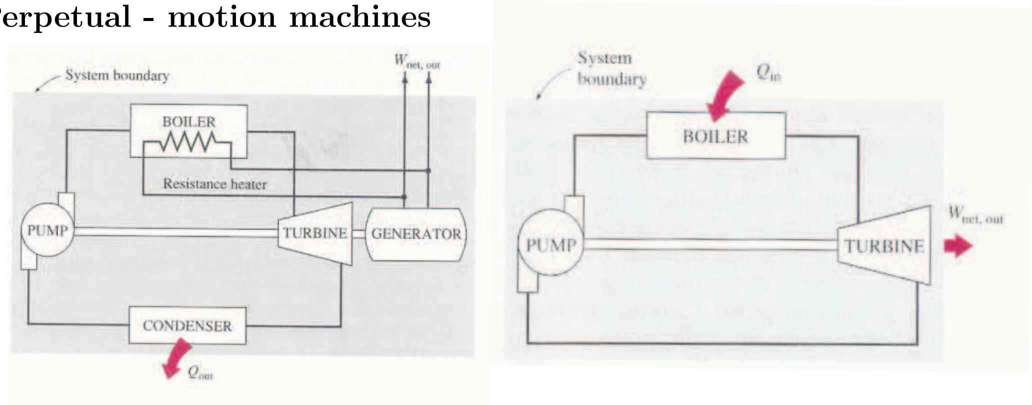


Figure 13: *Perpetual - motion machines for exercise 7.13*

a: Consider the power plant given at the left side of figure 13. It is proposed to heat steam by resistance heaters placed inside the boiler, instead of by the energy supplied from fossil fuel or nuclear fuels. Part of the electricity generated by the plant is to be used to power the resistors as well as the pump. The rest of the electric energy is to be supplied to the electric network as the net work output. The inventor claims that once the system is started, this power plant will produce electricity indefinitely without requiring any energy input from the outside and it will solve the world's energy problem.

Is the claim of the inventor reasonable or has the inventor developed a perpetual - motion machine? Explain your answer and if the machine is a perpetual - motion machine, is it one of the first or the second kind.

b: Consider the power plant given at the right side of figure 13. It is proposed to heat steam in the boiler by an external source. The heated steam is expanded in the turbine to generate electricity. The steam leaving the turbine is sent to the pump immediately. It is not first condensed in a condenser (which is done in the present steam turbine cycles) as that device discards a lot of the heat supplied in the boiler to the environment. This way all the heat transferred to the steam in the boiler will be converted to work, and thus the power plant will have a theoretical efficiency of 100%. Of course some heat losses and friction between moving components will occur, but still the inventor expects that the machine has an efficiency no less than 80% (as opposed to 40% in actual power plants) for a well designed system.

Is the claim of the inventor reasonable or has the inventor developed a perpetual - motion machine? Explain your answer and if the machine is a perpetual - motion machine, is it one of the first or the second kind.

7.14 Combined engine and heat pump

An inventor plans a system that operates as follows: A heat engine receives energy from a source at 540°C, gives work output of 0.50 kJ/kg for each 1 kJ/kg of heat transferred to the working fluid at that temperature, and rejects the remaining energy to the environment at 25°C. Part of the work output from the heat engine drives a heat pump with coefficient of performance of 4. The heat pump is used to take energy from the environment at 25°C and heat it to 540°C, where it becomes the energy source for the heat engine. Since the coefficient of performance is 4, only 0.25 kJ/kg of work from the heat engine is required to drive the heat pump for each 1 kJ/kg delivered to the heat engine. Thus, no outside energy source is required to drive the heat engine, and 0.25 kJ/kg is left of the engine work output to do useful work. Is there an error of mistake in this device? Discuss your answer in terms of the second law of thermodynamics and a detailed analysis of the possible efficiency of the heat engine and the possible coefficient of performance, COP, for the heat pump.

8 Exergy, Second Law Analysis of Systems

8.1 Exergy

a: What is exergy?

b: What is anergy?

c: Give the formula for exergy.

d: Give the formula for anergy.

e: Which temperature is represented by T_0?

f: Is the temperature T_0 fixed?

8.2 A geothermal well

A geothermal well produces steam at the wellhead at 220°C and 1 MPa.

a: What is the flow exergy for this source?

b: What is the reversible work for this source?

8.3 Steady-state steady-flow heater

Air is heated in a steady-state, steady-flow heater as shown in figure 14. What would be the net reversible work $(w_{out} - w_{in})_{rev}$ (kJ/kg) to carry out the process adiabatically and reversibly?

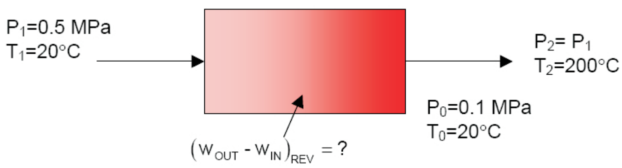


Figure 14: Steady-state steady-flow heater of exercise 8.3

8.4 A solar tower

A solar tower produces steam at 515°C and 1 MPa that transfers energy to mineral oil for storage at 304°C.

a: Calculate the flow exergy of the tower-generated steam.

b: Calculate the flow exergy of the steam produced at 300°C and 1 MPa from the oil via a steam generator.

c: What is the difference in the exergy between both exergy flows, do you win or loss exergy? Why would you do something like this?

8.5 Ammonia compressor

Ammonia vapor at -10°C and 100 kPa enters an adiabatic compressor and compressed to a final pressure of 250 kPa. The compressor has an isentropic efficiency of 70%.

a: Find the actual compressor work.

b: Calculate the reversible work for the prescribed process.

c: What is the flow exergy of the ammonia entering the compressor?

d: Find the flow exergy of the ammonia leaving the compressor.

8.6 Rankine steam cycle

Find the second law efficiency of a Rankine steam cycle operating at a boiler pressure of 6 MPa with a superheat temperature of 400°C, a condenser pressure of 8 kPa, and an isentropic turbine and pump.

8.7 Solar pond

A solar pond (lake) 3 m deep produces energy at the pond bottom that can be withdrawn at up to the saturation temperature at the pond bottom. Assume, for simplicity, that the specific volume of the pond water can be taken as an average of 8.83×10^{-4} m^3/kg.

a: What is the flow exergy for this source?

b: What is the reversible work for this source?

8.8 Turbine

Steam enters an adiabatic turbine at 8 Mpa and 500°C with a mass flow rate of 3 kg/s and leaves at 30 kPa. The isentropic efficiency of the turbine is 0.90. Neglect the kinetic energy change of the steam.

a: Sketch this process in the Mollier diagram and show the exergy and anergy of the inlet and outlet on the diagram. Also draw the line for T_0.

b: Determine the exergy in the inlet and outlet.

c: Sketch a Sankey diagram.

d: Sketch a Grassmann diagram.

8.9 Compressor

Air enters an adiabatic compressor at 100 kpa and 17°C with a rate of 2.4 m^3/s and it exits at 257°C. The compressor has an isentropic efficiency of 84 percent. Neglect the changes in kinetic and potential energies.

a: Sketch this process in the Mollier diagram and show the exergy and anergy of the inlet and outlet on the diagram. Also draw the line for T_0.

b: Determine the exergy in the inlet and outlet.

c: Sketch a Sankey diagram.

d: Sketch a Grassmann diagram.

8.10 Nozzle

Hot combustion gases enter the nozzle of a turbojet engine at 260 kpa, 747°C, and 80 m/s, and they exit at a pressure of 85 kPa. Assume an isentropic efficiency of 92 percent and treat the combustion gases as air.

a: Sketch this process in the Mollier diagram and show the exergy and anergy of the inlet and outlet on the diagram. Also draw the line for T_0.

b: Determine the exergy in the inlet and outlet.

c: Sketch a Sankey diagram.

d: Sketch a Grassmann diagram.

8.11 Heat exchanger

A well-insulated, shell-and-tube heat exchanger as shown in figure 15 is used to heat water (C_p = 4.18 kJ/kgK) in the tubes from 20°C to 70°C at a rate of 4.5 kg/s. Heat is supplied by hot oil (C_p = 2.30 kJ/kgK) that enters the shell side at 170°C at a rate of 10 kg/s. Disregard any heat loss from the heat exchanger.

a: Determine the exit temperature of the oil.

b: Determine the rate of entropy generation in the heat exchanger.

c: Determine the exergy in the inlet and outlet.

d: Sketch a Sankey diagram.

e: Sketch a Grassmann diagram.

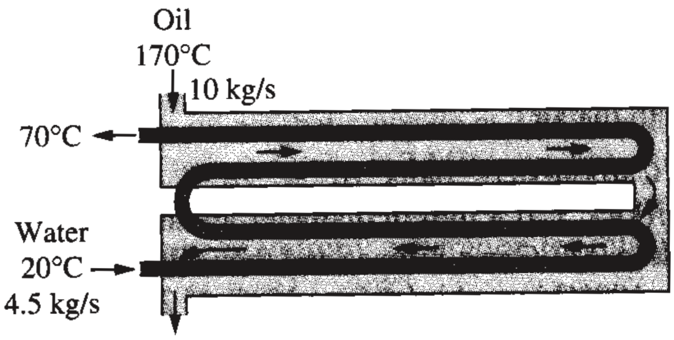


Figure 15: Heat exchanger of exercise 8.11

8.12 Second Law Analysis of an actual Rankine cycle

In assignment 10.4, *Power plant on an actual Rankine cycle* an actual Rankine cycle was analyzed from the point of view of the first law of thermodynamics. The result of this analysis can be used as a starting point for the second law analysis of this cycle.

Perform a second law analysis of this cycle, make Sankey and Grassmann diagrams of the cycle and evaluate and discuss the results. Draw conclusions from the analysis. For the second law analysis and the diagrams at least the following points should be done:

a: Choose a realistic reference state (i.e. a temperature T_0) and motivate this choice.

b: Calculate the energy flow at every point in the cycle.

c: Calculate the exergy flow at every point in the cycle.

d: Calculate the Carnot efficiency and the second law efficiency.

e: Compare the second law efficiency to the thermal efficiency of the cycle.

f: Display the energy flows in a Sankey diagram.

g: Display the exergy flows in a Grassmann diagram.

h: Compare both diagrams and discus them:

- what are the differences?
- where in the cycle are the largest losses?
- suggest some improvements.
- draw conclusions.

9 Gas Power Cycles

9.1 Basics of the Stirling cycle

a: Draw the $P - v$ and $T - s$ diagram of the Stirling cycle.

b: Name the involved processes.

:c Mark heat addition and heat rejection.

d: Is the Stirling cycle executed as an open or close system? Explain.

e: Give expressions for heat addition, heat rejection, work input, work output and cycle efficiency.

9.2 Stirling cycle 1

An engine operates on an ideal air-standard Stirling cycle. The pressure and temperature at the beginning of the isothermal compression are 3.5 MPa and 150°C, respectively. The thermal efficiency of the engine is 40 percent.

a: Draw the cycle in a $P - v$ diagram and indicate the two isothermal processes. Also indicate the heat transferred to the regenerator during the isochoric heat rejection process.

b: Calculate the highest temperature in the cycle.

c: Find the heat transferred to the regenerator during the isochoric heat rejection process.

MatLab: Determine, using *MatLab* and the *gasprop* file, the q_{reg} more precise. Hint: use a for loop.

9.3 Stirling cycle 2

An engine operates on an ideal air-standard Stirling cycle. The pressure and temperature at the beginning of the isothermal compression are 0.8 MPa and 100°C, respectively. The pressure at the beginning and end of the isochoric heat addition process are 1.6 and 3.2 MPa, respectively.

a: Draw the cycle in a $P - v$ diagram and indicate the two isothermal processes. Also indicate the pressures.

b: Calculate the net work of the cycle. Make use of a table to give an overview of the known variables and values at the characteristic points.

MatLab: Now take T_1 as an input range from 300 K till 500 K. Use *MatLab* to determine the net work and make a graph from the results. Is the graph as what you expected?

9.4 Basics of the ideal Otto cycle

a: Draw the $P - v$ and $T - s$ diagram of the ideal Otto cycle.

b: Name the involved processes.

c: Mark heat addition and rejection.

d: Is the Otto cycle executed as an open or close system? Explain.

e: What is the compression ratio and how is it defined?

f: Give expressions for the cycle efficiency, the heat added, the heat rejected and the net work.

9.5 Thermal efficiency Otto engine

Consider an *cold ideal air-standard cycle* for a petrol engine with a cylinder diameter of 50 mm, a stroke of 75 mm, and a clearance volume of 21.3 cm^3. Use $k = 1.4$.

a: What are an *air-standard cycle*, an *ideal air-standard cycle* and an *cold ideal air-standard cycle*?

b: What is the minimum cylinder volume and calculate the maximum cylinder volume.

c: Give the formula for the compression ratio and calculate the compression ratio.

d: Show that the efficiency of the cold ideal air standard cycle for an Otto engine is given by

$$\eta = 1 - \frac{1}{r_v^{k-1}}$$

starting from the basic definition for the thermal efficiency of a thermodynamic heat power cycle

$$\eta = \frac{what\ we\ get}{what\ we\ pay\ for}.$$

e: Calculate the thermal efficiency of this engine.

MatLab: Now take the swept volume as a vector from 50 till 500 cm^3. Use *MatLab* to determine the efficiency and make a graph from the results. Is the graph as what you expected?

9.6 Otto cycle 1

An engine operates on an air-standard Otto cycle. The net work of the cycle is 900 kJ/kg when the maximum cycle temperature is 3000°C. The temperature at the end of the isentropic compression is 600°C.

a: Draw the Pv and Ts-diagram for this Otto cycle.

b: Determine the efficiency of the engine.

c: Determine the compression ratio of the engine.

9.7 Otto cycle 2

An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 95 kPa and 27°C, and 750 kJ/kg of heat is transferred to the air during the constant-volume heat addition process. Assume constant specific heats for air at room temperature.

a: Draw the Pv and Ts-diagram for this Otto cycle.

b: Determine the pressure and temperature at the end of the heat addition process.

c: Determine the net work output.

d: Determine the thermal efficiency.

e: Determine the mean effective pressure for the cycle.

MatLab: Determine, using *MatLab* and the *gasprop* file, the η_{th} more precise. Hint: use the same approach as in 9.2.

9.8 Basics of the ideal Diesel cycle

a: Draw the $P - v$ and $T - s$ diagram of the ideal Diesel cycle.

b: Name the involved processes.

c: Mark heat addition and rejection.

d: Is the Diesel cycle executed as an open or close system? Explain.

e: What is the compression ratio and how is it defined?

f: What is the cut off ratio and how is it defined?

g: Give expressions for the cycle efficiency, the heat added, the heat rejected and the net work.

h: What are the main differences between an Otto and a Diesel engine?

9.9 Thermal efficiency Diesel cycle

A diesel engine has an inlet temperature and pressure of 15°C and 1 bar, respectively. The compression ratio is 12 and the maximum cycle temperature is 1100°C. Use $k = 1.4$.

a: Draw the $P - v$ and $T - s$ diagram of this cycle.

b: Calculate the temperature after compression and expansion.

c: Calculate the ideal air-standard thermal efficiency based on the Diesel cycle.

d: Calculate the second law efficiency for this cycle.

e: Calculate the specific net work delivered by the engine under the assumptions of an ideal air-standard cycle.

9.10 Diesel cycle 1

An engine operating on the ideal air-standard Diesel cycle has a compression ratio of 16. The pressure and the temperature at the beginning of the compression are 0.1 Mpa and 25°C. The heat transfer to the engine is 1000 kJ/kg.

a: Draw the Pv and Ts-diagram for this Diesel cycle.

b: Find the temperature after compression, heat addition and expansion. Make use of a table to give an overview of the known variables and values at the characteristic points.

c: Determine the cycle thermal efficiency.

9.11 Diesel cycle 2

An ideal diesel engine has a compression ratio of 20 and uses air as the working fluid. The state of air at the beginning of the compression process is 95 kPa and 20°C. The maximum temperature in the cycle is not to exceed 2200 K. Assume constant specific heats for air at room temperature.

a: Draw the Pv and Ts-diagram for this Diesel cycle.

b: Determine the thermal efficiency.

c: Determine the mean effective pressure for the cycle.

9.12 Diesel engine with turbocharger

Consider a car powered by a Diesel engine, working according to the air standard Diesel cycle. Air enters the engine at 1 bar and 20°C. The cut-off ratio is 2.5. One cylinder has a maximum volume of 500 cm^3 and a swept volume of 475 cm^3. Assume constant specific heats at room temperature and ideal gas.

a: Draw the P v-diagram and the T s-diagram of the cycle. Give in these diagrams the known pressures and temperatures. Also show where heat or work is added or taken from the cycle. Add the yet unknown pressures and temperatures later.

b: Give the formula to determine the compression ratio and calculate it. Also calculate the specific volume in point 1.

c: Make a table and fill in the known pressures and temperatures and calculate the remaining pressures and temperatures in the cycle.

d: Give the formula to determine the specific net work output and calculate it.

e: Calculate the thermal efficiency of the engine.

f: Calculate the mass in 1 cylinder. The maximum revolution speed of the engine is 4300 rpm. Assume the specific net work output independent of the revolution speed. There are 4 cylinders in total.

g: Calculate the net power output of the engine.

h: Today's Diesel engines are almost always equipped with a Turbocharger. Imagine this engine was also equipped with one. This could be modelled as a higher inlet pressure. Take the pressure at point 1 equal to 1.8 bar and repeat the exercises b to f.

i: Compare the thermal efficiency, specific net work output and net power output with each other. What can you say about the influence of a turbocharger on them?

j: Think about possible reasons why the turbocharger is still used in today's combustion engines to reduce the fuel consumption!

9.13 Closed Brayton cycle

The compressor inlet of an air-standard closed-cycle Brayton engine is at 25°C and 1 atm, and the compressor pressure ratio is 10. The turbine inlet temperature is 900°C. The turbine efficiency is 0.6.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle in a $h - s$ and a $P - v$ diagram.

c: Specify in a table for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, isentropic efficiency).

d: What compressor efficiency is necessary to obtain zero work output from the engine?

9.14 Carnot versus Stirling versus Brayton cycle

Points 2 and 4 on an ideal air-standard Stirling, Brayton, and Carnot cycle $P-v$ diagrams all lie at the same values: $P_2 = 10$ atm, $v_2 = 0.05$ m^3/kg; $P_4 = 1$ atm, $v_4 = 0.40$ m^3/kg.

a: Give a $P-v$ diagram of the three cycles.

b: Find the the temperatures T_2 and T_4.

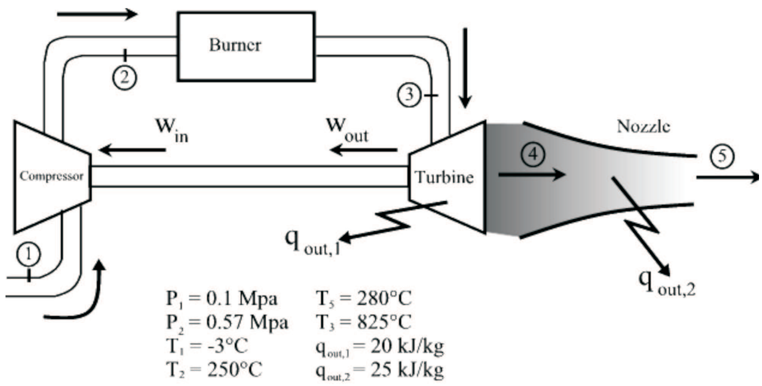
c: Determine the efficiency of the Carnot cycle.

d: Determine the efficiency of the Stirling cycle and calculate the ratio between the efficiency of the Carnot Cycle and the efficiency of the Stirling cycle (i.e. at what fraction of the ideal Carnot efficiency operates the Stirling cycle).

e: Determine the efficiency of the Brayton cycle and calculate the ratio between the efficiency of the Carnot Cycle and the efficiency of the Brayton cycle (i.e. at what fraction of the ideal Carnot efficiency operates the Brayton cycle). Explain the answer.

9.15 Jet propulsion cycle

Consider the jet propulsion cycle shown in the figure below. This engine uses the work from the turbine solely to power the compressor. The enthalpy of the gases leaving the turbine remains very high. This exhaust is then passed through a nozzle to recover as much kinetic energy (and thus momentum change) as possible, producing thrust. The compressor is adiabatic, the turbine and the nozzle are not adiabatic, they loss 20 kJ/kg and 25 kJ/kg, respectively. The turbine and the nozzle may be assumed isentropic.



a: Determine the isentropic efficiency of the compressor (use a systematic approach to organise the data).

b: Determine the specific work input to the compressor, w_{in} (kJ/kg).

c: Find the exit velocity, v_5 (m/s) of the nozzle .

9.16 Simple open Brayton cycle

A gas turbine engine configured like a simple Brayton cycle using air as the working fluid has a pressure ratio of 8. The minimum and maximum temperatures in the cycle are 310 K and 1160 K. Assume an isentropic efficiency of 75% for the compressor and 82% for the turbine.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle in a $T-s$ diagram.

c: Specify for every characteristic position the two known thermodynamic variables (these parameters can be a.o. pressure, temperature, isentropic efficiency).

d: Determine the air temperature at the exit of the turbine using the data in the Mollier diagram. Draw the expansion process of the turbine in the Mollier diagram and indicate the inlet and the outlet with the corresponding numbers.

e: Determine the net work output using the data in the Mollier diagram. Draw the rest of the gas turbine cycle in the Mollier diagram.

f: Determine the thermal efficiency of the gas turbine cycle.

g: Determine the second law efficiency of this cycle.

MatLab: Make this exercise using *MatLab* and *gasprop*.

Once the cycle is programmed in *MatLab* the influence of the pressure ratio and the inlet temperature of the turbine on the thermal efficiency and the net specific work output can be investigated.

Let the pressure ratio vary between 2 and 20 Bar while keeping the inlet temperature of the turbine at 310 K. Make graphs of the thermal efficiency as function of the pressure ratio and of the net specific work output as function of the pressure ratio. Determine at what pressure ratio the thermal efficiency is the highest and at what pressure ratio the specific net work output is the highest? Is this the same pressure ratio?

Now assume the isentropic efficiencies of the compressor and the turbine to be 100%. Make both graphs again. Compare them with the graphs of the cycle with an isentropic efficiency of 75% for the compressor and 82% for the turbine. What is the difference?

Set the pressure ratio back to 8 Bar and use an isentropic efficiency of 75% for the compressor and 82% for the turbine. Let the inlet temperature of the turbine vary between 700 K and 1600 K. Make graphs of the thermal efficiency as function of the inlet temperature of the turbine and of the net specific work output as function of the inlet temperature of the turbine. Is there a maximum efficiency and maximum net specific work output?

Add a regenerator with an effectiveness of 80%. Again let the pressure ratio vary between 2 and 20 bar and again make graphs of the thermal efficiency as function of the pressure ratio and of the net specific work output as function of the pressure ratio. Determine also for the cycle with the regenerator at what pressure ratio the thermal efficiency and the specific net work output are the highest? Compare with the case without regenerator. In addition make a graph of the regenerated specific heat as function of the pressure ratio.

9.17 The 7FA gas turbine

The 7FA gas turbine manufactured by General Electric is reported to have a thermal efficiency of 35.9% in the simple-cyclic mode and to produce 159 MW of net power. The pressure ratio is 14.7 and the turbine inlet temperature is 1288°C. The mass flow rate through the turbine inlet is $1536 \cdot 10^3$ kg/h. Take the ambient conditions to be 20°C and 100 kPa.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, isentropic efficiency).

c: Sketch the cycle with isentropic efficiencies in a $T - s$ diagram.

d: State the two equations that determine the isentropic efficiency of the compressor and the turbine.

e: Draw the cycle in the Mollier diagram of air and solve these equations for the isentropic efficiencies with the use of data in the Mollier diagram.

9.18 The 7FA gas turbine with regeneration

The 7FA gas turbine manufactured by General Electric is reported to have a thermal efficiency of 35.9% in the simple-cyclic mode and to produce 159 MW of net power. The pressure ratio is 14.7 and the turbine inlet temperature is 1288°C. The mass flow rate through the turbine inlet is $1536 \cdot 10^3$ kg/h. Take the ambient conditions to be 20°C and 100 kPa (see exercise 9.17). The gas turbine is improved by adding a regenerator with an effectiveness of 80%.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle in a $T - s$ diagram. What has changed compared to the gas turbine without regenerator?

c: Determine the net power output of this gas turbine cycle using the Mollier digram. Draw the extra points in the Mollier diagram of exercise 9.17. Compare the net power output of the gas turbine with the regenerator with the gas turbine without regenerator. What can be concluded?

d: Determine the heat output, the heat input and the regenerated heat of this gas turbine cycle and compare with the gas turbine without regenerator. What can be concluded? Also denote the regenerated heat in the Mollier diagram.

e: Determine the thermal efficiency of this gas turbine cycle and compare with the gas turbine without regenerator. What can be concluded?

f: Determine the second law efficiency of this cycle.

9.19 Brayton cycle with inter cooling and regenerator

A generator is powered by a gas turbine engine. The gas turbine engine is built as follows: Air with atmospheric conditions (15°C, 1 bar) gets sucked in and is compressed by 2 compressor steps. The pressure ratio of the first compressor step is 4 and of the second step is 3 (relative to the first compression). The isentropic efficiency for both compressor steps is 80%. Between the compression steps the air is isobaric cooled to 40°C. After leaving the second compressor the air is heated by a heat exchanger (the regenerator with an efficiency of 100%). Then the air enters the heating chamber, where it is heated by burning diesel to a temperature of 860°C. The expansion happens in a turbine with an isentropic efficiency of 80%. The turbine powers the generator and both compressors with a gear transmission. This mechanical transmission has an efficiency of 98%. The exhaust gas goes through the heat exchanger before entering the atmosphere.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, isentropic efficiency).

c: Sketch the cycle in a Ts-diagram. Determine the enthalpy at every point using the data in the Mollier diagram of air and draw the cycle in the Mollier diagram. Give the calculations for the processes in the turbine and the compressors.

d: Calculate the work produced by the turbine and the temperature at the turbine exit.

e: Calculate the thermal efficiency of this gas turbine cycle.

f: Calculate the power supplied to the generator if the mass flow of the air 7 kg/s is.

MatLab: Make this exercise using *MatLab* and *gasprop*. Change the pressure ratios between the compressors and try to find the optimum pressure between both compressors.

9.20 Brayton cycle with reheating

A boiler feed water pump is powered by a 2 axle gas turbine engine. The engine is built as follows: air with atmospheric conditions (15°C, 1 Bar) gets sucked in and is compressed by a compressor with an isentropic efficiency of 80%. The pressure ratio is 20. Then the air enters the heating chamber, where it is heated by burning diesel to a temperature of 1060°C. Expansion towards atmospheric pressure happens in 2 steps: in a high and a low pressure turbine, both with an isentropic efficiency of 90%. Between the turbines the air is reheated by injecting diesel to a temperature of 980°C. The high pressure turbine powers the compressor through an axle with 100% efficiency. The low pressure turbine powers the boiler feed water pump through a gear transmission with a 98% efficiency. The mass flow through the system is $\dot{m} = 3$ kg/s.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, isentropic efficiency).

c: Sketch the cycle in a $Ts-$ diagram. Determine the enthalpy at every point using the data in the Mollier diagram of air and draw the cycle in the Mollier diagram. Give the calculations for the processes in the turbine and the compressor.

d: Determine the pressure ratio of both turbines, the temperatures at the turbine exits and the power output produced by the turbines.

e: Calculate the net power delivered to the pump.

f: Calculate the thermal efficiency of this gas turbine cycle.

10 Vapor and Combined Power Cycles

10.1 Rankine cycles

a: What four processes make up the ideal Rankine cycle?

b: How do actual vapor power cycles differ from idealized ones?

c: Show the cycle of an ideal Rankine cycle on a T-s and a h-s diagram with respect to the saturation lines.

b: Show the cycle of an actual Rankine cycle on a T-s and a h-s diagram with respect to the saturation lines.

e: What is the pressure in a condenser that is cooled by river water entering the condenser at 10°C?

f: What is the pressure in a condenser cooled by the outlet air in a country where the temperature in summer is 20°C on average and in winter is 5°C on average?

g: Consider a simple ideal Rankine cycle with fixed turbine inlet conditions. What is the effect (increase, decrease or no effect) of lowering the condenser pressure on pump work input, turbine work output, heat supplied, heat rejected, cycle efficiency and moisture content at the turbine exit.

h: Consider a simple ideal Rankine cycle with fixed turbine inlet temperature and condenser pressure. What is the effect (increase, decrease or no effect) of increasing the boiler pressure on pump work input, turbine work output, heat supplied, heat rejected, cycle efficiency and moisture content at the turbine exit.

i: Consider a simple ideal Rankine cycle with fixed boiler and condenser pressures. What is the effect (increase, decrease or no effect) of superheating the steam to a higher temperature on pump work input, turbine work output, heat supplied, heat rejected, cycle efficiency and moisture content at the turbine exit.

10.2 Power plant on a simple ideal Rankine cycle 1

A steam power plant operates on a simple ideal Rankine cycle between the pressure limits 3 MPa and 50 kPa. The temperature of the steam at the turbine inlet is 400°C and the mass flow rate of steam through the cycle is 60 kg/s.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle on a T-s and a h-s diagram with respect to the saturation lines.

c: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

d: Determine the power delivered by the turbine, the power required by the pump and the heat input to the boiler.

e: Determine the net power output of the plant.

f: Determine the thermal efficiency of the cycle.

10.3 Power plant on a simple ideal Rankine cycle 2

Consider a 210-MW steam power plant that operates on a simple ideal Rankine cycle. Steam enters the turbine at 10 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa.

Note: a Rankine cycle can be analyzed using the enthalpy and entropy values from the tables only and by calculating the mixture fraction at the exit of the turbine in the saturated mixture region and use that to find h values.

Alternatively the enthalpy values in the mixture region can be read from the Mollier diagram of water. This method is less accurate but much faster and gives a better overview of the process. Specially for complicated cycles with more devices that have reheating and/or feed water heating and where more points are located in the mixture region.

In addition a Rankine cycle can be analysed using *MatLab* and *XSteam*. Specially for designing and optimizing complicated cycles this is a very useful method.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle on a T-s and a h-s diagram with respect to the saturation lines.

c: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

d: Determine the vapor mass fraction at the turbine exit.

e: Determine the work delivered by the turbine, the work required by the pump and the heat input to the boiler.

f: Determine the mass flow rate of the steam.

g: Determine the thermal efficiency of the cycle.

MatLab: Make this exercise using *MatLab* and *XSteam*. Make the Ts - diagram using *MatLab*.

10.4 Power plant on an actual Rankine cycle

Repeat problem 10.3 assuming an isentropic efficiency of 85% for both the turbine and the pump. Note: also here the cycle can be analyzed using the tables only, the Mollier diagram for the saturated mixture region or *MatLab*.

MatLab: Make this exercise using *MatLab* and *XSteam*.

Once the cycle is programmed in *MatLab* the influence of the pressure and temperature at the inlet of the turbine on the thermal efficiency and the net specific work output can be investigated.

Let the turbine inlet pressure vary between 10 and 400 Bar and keep the inlet temperature of the turbine at 500°C. Make graphs of the thermal efficiency as function of the turbine inlet pressure and of the net specific work output as function of the turbine inlet pressure. Determine at what turbine inlet pressure the thermal efficiency is the highest and at what turbine inlet pressure the specific net work output is the highest? Is this the same pressure?

Now assume the isentropic efficiencies of the pump and the turbine to be 100%. Make both graphs again. Compare them with the graphs of the cycle with isentropic efficiencies of 85% for the pump and the turbine. What is the difference?

Set the turbine inlet pressure back to 100 Bar and use isentropic efficiencies of 85% for the pump and the turbine. Let the inlet temperature of the turbine vary between 700 ° and 1000 °. Make graphs of the thermal efficiency as function of the inlet temperature of the turbine and of the net specific work output as function of the inlet temperature of the turbine. Is there a maximum efficiency and maximum net specific work output?

10.5 Coal fired steam power plant

Consider a coal fired steam power plant that produces 300 MW of electric power. The power plant operates on a simple ideal Rankine cycle with turbine inlet conditions of 5 MPa and 450°C and a condenser pressure of 25 kPa. The coal used has a heating value (energy released when the fuel is burned) of 30 MJ/kg. Assume that 75% of the energy of the coal is transferred to the steam in the boiler and that the electric generator has an efficiency of 96%.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle on a T-s and a h-s diagram with respect to the saturation lines.

c: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

d: Determine the work delivered by the turbine, the work required by the pump and the heat input to the boiler.

e: Determine the thermal efficiency of the cycle.

f: Determine the overall plant efficiency (the ratio of net electric power output to the energy input as fuel).

g: Determine the mass flow rate of the steam.

h: Determine the required rate of coal supply.

10.6 Solar-pond power plant

Consider a solar-pond power plant that operates on a simple ideal Rankine cycle with refrigerant-134a as the working fluid. The refrigerant enters the turbine as a saturated vapor at 1.6 MPa and leaves at 0.7 MPa. The mass flow rate of the refrigerant is 6 kg/s.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle on a T-s and a h-s diagram with respect to the saturation lines.

c: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

d: Determine the power delivered by the turbine, the power required by the pump and the heat input to the boiler.

e: Determine the net power output of this plant.

f: Determine the thermal efficiency of the cycle

10.7 Ideal power plant cooled by a lake 1

Consider a solar-pond power plant that operates on a simple ideal Rankine cycle and has a net power output of 45 MW. Steam enters the turbine at 7 MPa and 500°C. It is cooled in the condenser at a pressure of 10 KPa by heat exchange with cooling water of 10°C from a lake. The mass flow of the cooling water is 2000 kg/s.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle on a T-s and a h-s diagram with respect to the saturation lines.

c: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

d: Determine the work delivered by the turbine, the work required by the pump and the heat input to the boiler.

e: Determine the thermal efficiency of the cycle.

f: Determine the mass flow rate of the steam.

g: Determine the maximum temperature of the cooling water at the exit of the condenser.

10.8 Actual power plant cooled by a lake

Repeat problem 10.7 assuming an isentropic efficiency of 87% for both the turbine and the pump.

10.9 Reheat Rankine cycle

Consider a steam power plant that operates on a reheat Rankine cycle and has a net power output of 150 MW. Steam enters the high-pressure turbine at 10 MPa and 500°C and the low-pressure turbine at 1 MPa and 500°C. Steam leaves the condenser as a saturated liquid at a pressure of 10 kPa. The isentropic efficiency of the turbine is 80% and that of the pump is 95%. Use the Mollier diagram for data in the saturated mixture region and the tables for data not present on the diagram.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle on a T-s and a h-s diagram with respect to the saturation lines.

c: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

d: Determine the vapor mass fraction (or temperature, if superheated) at the turbine exit using the data from the Mollier diagram for water. Draw the turbine process also in the Mollier diagram and indicate the inlet and outlet of the turbine with the corresponding numbers.

e: Determine the thermal efficiency of the cycle and draw the cycle in the Mollier diagram for the points and processes that take place in the area present at the diagram.

f: Determine the mass flow rate of steam.

g: Determine the second law efficiency of this cycle.

MatLab: Make this exercise using *MatLab* and *XSteam*. Let the reheat pressure variate between 5 and 50 bar. How many bars for the reheat pressure gives the highest efficiency?

10.10 Ideal reheat Rankine cycle

A steam power plant operates on an ideal reheat Rankine cycle between the pressure limits 9 MPa and 10 kPa. The mass flow rate through the cycle is 25 kg/s. Steam enters both stages of the turbine at 500°C. The moisture content of the steam at the exit of the low-pressure turbine is not to exceed 10 percent. Use the Mollier diagram for data in the saturated mixture region and the tables for data not present on the diagram.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle on a T-s and a h-s diagram with respect to the saturation lines.

c: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

d: Determine the pressure at which reheating takes place using the Mollier diagram. Indicate the required points and draw the required processes in the diagram.

e: Determine the total heat input in the boiler.

f: Determine the thermal efficiency of the cycle and draw the cycle in the Mollier diagram for the points and processes that take place in the area present at the diagram.

g: Determine the second law efficiency of this cycle.

10.11 Reheat-regenerative Rankine cycle with open feedwater heater

A steam power plant operates on a reheat-regenerative Rankine cycle and has a net power output of 80 MW. Steam enters the high-pressure turbine at 10 MPa and 550°C and leaves at 0.8 MPa. Some steam is extracted at this pressure to heat the feedwater in an open feedwater heater. The rest of the steam is reheated to 500°C and is expanded in the low-pressure turbine to the condenser pressure of 10 kPa. The isentropic efficiency of the turbines and that of the pumps is 80%. Use the Mollier diagram for data in the saturated mixture region and the tables for data not present on the diagram.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Sketch the cycle on a T-s and a h-s diagram with respect to the saturation lines.

c: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

d: Determine the mass flow rate of water through the boiler draw the cycle in the Mollier diagram for the points and processes that take place in the area present at the diagram.

e: Determine the efficiency of the cycle.

f: Determine the second law efficiency of this cycle.

MatLab: Make this exercise using *MatLab* and *XSteam*. Take the total mass flow as 100 kg/s. Now let the reheat pressure variate between 5 and 50 bar. Also let the mass flow through the second turbine vary between 20 and 90 kg/s. What is the most efficient configuration of the plant? Hint: use a double for loop and make a 3D plot.

10.12 Reheat-regenerative Rankine cycle with closed feedwater heater

Repeat problem 10.11, but replace the open feedwater heater with a closed feedwater heater. Assume that the feedwater leaves the heater at the condensation temperature of the extracted steam. The extracted steam leaves the heater as a saturated liquid and is pumped to the line carrying the feedwater and mixed with the feedwater in a mixing chamber.

10.13 Combined gas-steam power cycle 1

Consider a combined gas-steam power cycle. The first cycle is a gas-turbine cycle that has a pressure ration of 8. Air enters the compressor at 300 K and the turbine at 1300 K. The isentropic efficiency of the compressor is 80 % and that of the gas turbine is 85 %. The second cycle is a simple, ideal Rankine cycle operating between the pressure limits of 7 MPa and 5 kPa. Steam is heated in a heat exchanger by the exhaust gases to a temperature of 500°C. The exhaust gases leave the heat exchanger at 450 K.

a: Draw the schematic process scheme of the combined cycle.

b: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

c: Sketch both cycles on one $T - s$ diagram.

d: Determine the ratio of the mass flow rates of the steam and the combustion gases.

e: Determine the thermal efficiency of the combined cycle.

f: Determine the second law efficiency of this cycle.

MatLab: Make this exercise using *MatLab* and *XSteam*.

10.14 Combined gas-steam power cycle 2

The gas turbine portion of a combined gas-steam power plant has a pressure ratio of 16. Air enters the compressor at 300 K at a rate of 14 kg/s and is heated to 1500 K in the combustion chamber. The combustion gases leaving the gas turbine are used to heat the steam to 400°C at 10 MPa in a heat exchanger. The combustion gases leave the heat exchanger at 420 K. The steam leaving the turbine is condensed at 15 kPa. Assume that all the compression and expansion processes are isentropic.

a: Draw the process scheme of the combined cycle.

b: Specify for every characteristic position the two known variables (these parameters can be a.o. pressure, temperature, phase, isentropic efficiency).

c: Sketch one T-s diagram with both cycles.

d: Determine the mass flow rate of the steam.

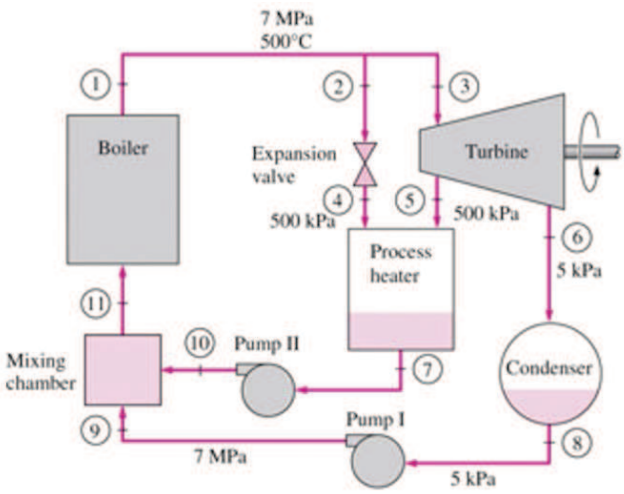
e: Determine the net power output.

f: Determine the thermal efficiency of the combined cycle. For air, assume constant specific heats at room temperature.

g: Determine the second law efficiency of this cycle.

10.15 An ideal cogeneration power plant

Consider the cogeneration plant shown in the figure below. Steam enters the turbine at 7 MPa and 500°C. Some steam is extracted from the turbine at 500 kPa for process heating. The remaining steam continues to expand to 5 kPa. Steam is then condensed at a constant pressure and pumped to the boiler pressure of 7 MPa. At times of high demand for process heat, some steam leaving the boiler is throttled to 500 kPa and is routed to the process heater. The extraction fractions are adjusted so that the steam leaves the process heater as a saturated liquid at 500 kPa. It is subsequently pumped to 7 MPa. The mass flow rate of steam through the boiler is 15 kg/s. Disregard any pressure drops and heat losses in the piping and assume the turbine and the pump to be isentropic.



a: Sketch the cycle on a T-s diagram with respect to the saturation lines.

b: Give the two known variables in every charateristic point in a table and determine the h-value for every point. Use the data from the Mollier diagram of water or the tables from the book when the data lie out of the range of the diagram.

c: Determine the maximum rate at which process heat can be supplied.

d: Determine the utilization factor when the maximum rate of process heat is supplied. What does the outcome mean?

e: Determine the power produced when no process heat is supplied.

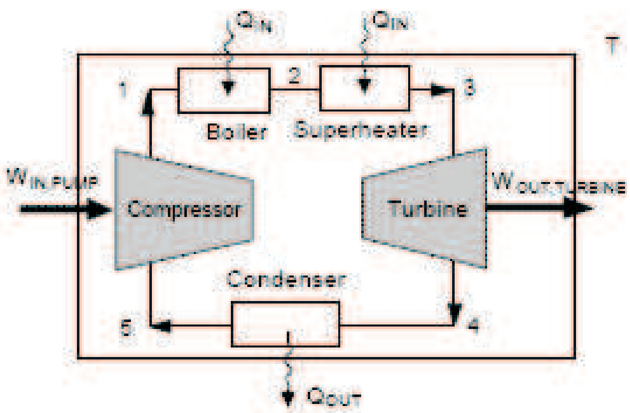
f: Determine the utilization factor and the thermal efficiency when no heat is produced. Compare them and compare the utilization factor to the one found above when the maximum rate of process heat is supplied (question d).

g: Determine the rate of process heat supplied when 10 percent of the total mass flow of the steam is extracted before it enters the turbine and 70 percent of the total mass flow of the steam is extracted from the turbine at 500 kPa for process heating.

h: Determine the utilization factor and the thermal efficiency in the situation sketched in question g. Compare them and compare them to the result of question d and f.

10.16 An improved Rankine cycle

An improved Rankine cycle has been suggested that operates as diagrammed in the figure below. Some of the turbine work is used to drive an isentropic compressor that takes a saturated mixture of quality x_5 from the condenser and compresses it to saturated liquid state 1. The turbine is assumed isentropic, the boiler operates at 6 MPa and the condenser at 8 kPa, and the boiler steam is superheated to 400°C. Use a systematic approach to solve the exercises below (draw a $T-s$ diagram and use a table to organise the data).



a: Find the efficiency of the proposed cycle.

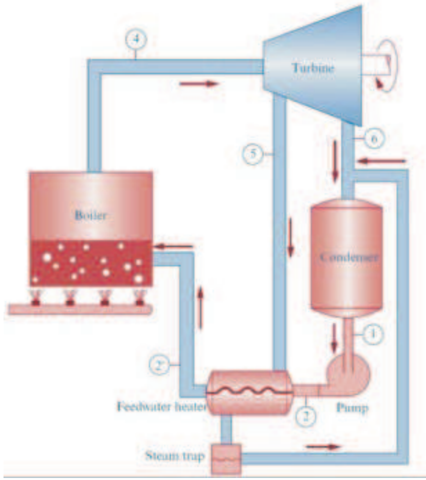
b: Find the efficiency of a usual Rankine cycle operating under the same conditions (that is, use a pump in place of the compressor, with $x_5 = 0$).

c: What are the ratios of the proposed and usual Rankine cycle efficiencies to the appropriate Carnot efficiency?

d: Calculate the efficiency of the proposed cycle with no superheat.

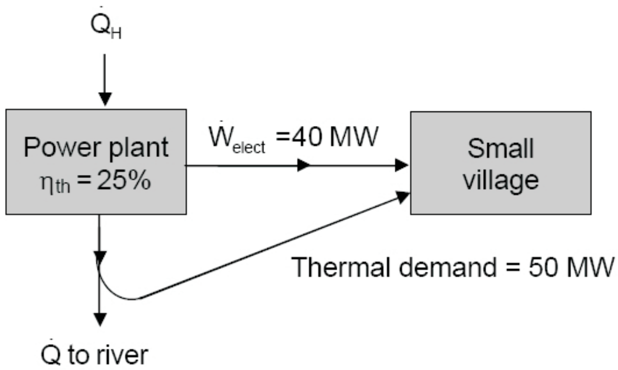
10.17 A Rankine cycle with and without regeneration

A Rankine cycle with superheat as shown below has a condenser pressure of 8 kPa, a boiler pressure of 6 MPa, and a turbine efficiency of 88 percent and superheats the steam leaving the boiler to 400°C. Compare this cycle efficiency to that of a regeneration cycle using a closed feedwater heater in which 10 percent of the entering turbine mass flow is bled off at 200 kPa to the feedwater heater. Condensate is returned to the system as shown in the figure below. Think of, and use, a systematic approach to determine the cycle efficiencies.



10.18 City heating

In a 'total energy system', enough electricity is produced to satisfy the user's electrical demand, and as much of the waste heat as possible is used to satisfy the user's thermal demand (space heating, water heating, etc). Considering the total energy system shown in the figure below, find the rate of heat transfer to the river.



10.19 Rankine cycle with vapor-liquid separator

Consider the Rankine cycle shown in figure 16. Steam enters the first turbine at a pressure of 5000 kPa and a temperature of 500 °C. In the ideal turbine air is expanded to 100 kPa, end it is led into a vapor-liquid separator where all vapor is separated from the liquid. The saturated vapor is reheated to 250 °C, and in a second ideal turbine expanded to 10 kPa. After that, it is fully condensed and the pressure is pumped up (with an ideal pump) to 100 kPa. Then, this flow is mixed with the saturated liquid from the separator in an open mixing chamber. The resulting flow is pressurized by an ideal pump, after which it is led back into the boiler.

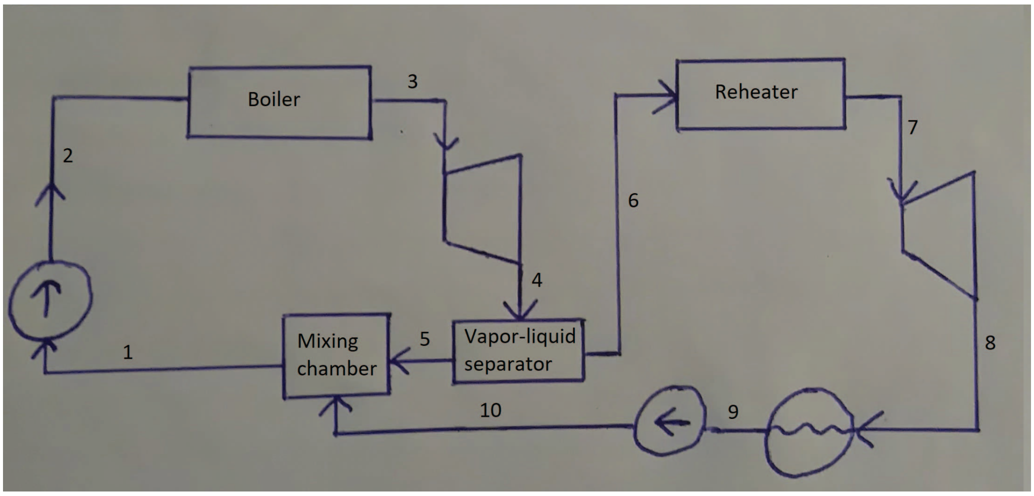


Figure 16: Schematic overview of the cycle of assignment 10.19

a: Sketch the cycle on a T-s diagram with respect to the saturation lines.

b: Give the two known variables in every characteristic point in a table and determine the h-value for every point. Use the data from the Mollier diagram of water where possible, and use the tables from the book when the data lie out of the range of the diagram. Draw the cycle in the Mollier diagram as far as possible.

c: Determine the thermal efficiency of the cycle.

d: The operator of the power plant wants to deliver a net power output of 80 MW. Calculate the required mass flows in the cycle.

10.20 Thomas Newcomen's steam engines

Thomas Newcomen's engines operated by spraying cold water into a cylinder filled with saturated steam near 1-atm pressure. The condensing steam then reduced the volume of the resulting liquid-vapor mixture, and atmospheric pressure pushed a piston into the cylinder. A Newcomen engine with a piston diameter of 1 m and a stroke of 2 m reaches a minimum volume in the cylinder at the end of the stroke of 0.2 m^3.

a: Find the amount of water at 20°C necessary to be injected into the cylinder to just complete the stroke.

b: Find the work output per stroke from the engine.

c: No work was obtained from the Newcomen engine on the return stroke, which was carried out by allowing a system of weights to return the piston to its original position. If the engine could operate at 1 cycle/min, and the piston is assumed to be of negligible weight, find the power output of the engine.

11 Refrigeration and Heat Pumps

11.1 The vapor compression cooling cycle

a: The vapor compression refrigeration cycle is the the most widely used cycle for refrigerators, air conditioning systems, and heat pumps. Of which four processes consists this cycle?

b: Give a schematic overview of the vapor compression refrigeration cycle and show the cycle on a Ts and a Ph-diagram with respect to the saturation lines.

c: How is the coefficient of performance of a refrigerator and that of a heat pump defined?

d: Give the relation between the heat removed from the refrigerated space (Q_L), the heat rejected to the hot environment (Q_h) and the work input required for the compressor (W_{comp}).

e: In which way does an actual vapor compression cycle differ from an ideal one?

11.2 An ideal refrigerator

A refrigerator uses refrigerant-134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.12 and 0.7 MPa. The mass flow rate of the refrigerant is 0.05 kg/s.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Show the cycle on a T-s diagram with respect to the saturation lines.

c: Make a table in which for every characteristic position the two parameters that are known are given (these parameters can be pressure, temperature, phase, isentropic efficiency).

d: Determine the rate of heat removal from the refrigerated space.

e: Determine the power input to the compressor.

f: Determine the rate of heat rejection to the environment.

g: Determine the coefficient of performance (COP).

11.3 An non ideal refrigerator

Refrigerant-134a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and -10°C at a rate of 0.12 kg/s, and leaves it at 0.7 MPa and 50°C. The refrigerant is cooled in the condenser to 24°C and 0.65 MPa, and is throttled to 0.15 MPa. Disregard any heat transfer and pressure drop in the connecting lines between the components.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Show the cycle on a T-s diagram with respect to the saturation lines.

c: Make a table in which for every characteristic position the two parameters that are known are given (these parameters can be pressure, temperature, phase, isentropic efficiency).

d: Determine the rate of heat removal from the refrigerated space.

e: Determine the power input to the compressor.

f: Determine the isentropic efficiency of the compressor.

g: Determine the coefficient of performance (COP).

11.4 Refrigerator on ammonia

A vapor compression refrigerator using ammonia as a working fluid has a 2 hp motor driving the compressor. The compressor efficiency is 70 percent, and it has an inlet pressure 0.05 MPa and temperature -40°C, while the exit pressure is 0.9 MPa. The condenser exit pressure and quality are 0.75 MPa and zero. The adiabatic expansion valve exit pressure is 0.06 MPa. One horse power (hp) is 0.7457 kJ/s.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Show the cycle on a P-h and a T-s diagram with respect to the saturation lines.

c: Determine the rejected heat transfer in kW.

d: Determine the coefficient of performance (COP).

e: Determine the refrigeration capacity in kW.

11.5 Carnot engine driving an ideal refrigerator

A Carnot engine operating between two temperature reservoirs of 817°C and 25°C rejects 20 kJ/s. The engine drives the compressor of an ideal vapor compression refrigerator working on refrigerant R-134a. The inlet and exit pressures are 0.17 and 1.1 MPa, respectively.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Show the cycle on a T-s diagram with respect to the saturation lines.

c: Calculate the coefficient of performance (COP).

d: Calculate the refrigerator's capacity in kW.

11.6 Refrigerator on refrigerant

Refrigerant-134a enters the compressor of a refrigerator at 140 kPa and -10°C at a rate of 0.3 m^3/min and leaves at 1 MPa. The isentropic efficiency of the compressor is 78 percent. The refrigerant enters the throttling valve at 30°C and 0.95 MPa and leaves the evaporator as saturated vapor at -18.5°C.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Show the cycle on a T-s diagram with respect to the saturation lines.

c: Make a table in which for every characteristic position the two parameters that are known are given (these parameters can be pressure, temperature, phase, isentropic efficiency).

d: Determine the rate of heat removal from the refrigerated space.

e: Determine the power input to the compressor.

f: Determine the pressure drop in the line between the evaporator and the compressor.

g: Determine the rate of heat gain in the line between the evaporator and the compressor.

11.7 Heat pump

A heat pump using refrigerant-134a heats a house by using underground water at 8°C as a heat source. The house is losing heat at a rate of 60.000 kJ/h. The refrigerant enters the compressor at 280 kPa and 0°C, and it leaves at 1 MPa and 60. The refrigerant exits the condenser at 30°C.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Show the cycle on a T-s diagram with respect to the saturation lines.

c: Make a table in which for every characteristic position the two parameters that are known are given (these parameters can be pressure, temperature, phase, isentropic efficiency).

d: Determine the power input to the compressor.

e: Determine the rate of heat absorption from the water.

f: Determine the increase in electric power if an electric resistance heater is used instead of a heat pump.

11.8 Reverse Brayton cycle

A closed reverse air-standard Brayton cycle is used for cooling. It works between pressures of 1 atm and 5 atm. The temperature of the air entering the turbine is 80°C and the temperature of the air entering the compressor is 0°C. The compressor has an efficiency of 68 percent, and the turbine has an efficiency of 72 percent.

a: Give a schematic overview of the setup and indicate with numbers the characteristic positions.

b: Show the cycle on a T-s diagram.

c: Give the two known values for every characteristic position in a table, calculate the h-values at every position and determine the coefficient of performance of this refrigeration cycle.

11.9 Aircraft cabin cooling

Aircrafts commonly employ open reverse Brayton cooling systems for providing cabin and avionics cooling. For a particular design, as in figure 17, air entering the engine compressor is at 70 kPa and 20°C and has v = 250 m/s. The main compressor outlet pressure is 2.5 MPa. The air leaving the turbine is at 100 kPa and 15°C and has v = 0 m/s. The compressor and the turbine have an isentropic efficiency of 70 percent. How much heat transfer per kg of cabin air must be provided by the heat exchanger to meet the design requirements? Use a systematic approach to solve the problem (schematic overview, table, known properties, Ts-diagram, determine h values).

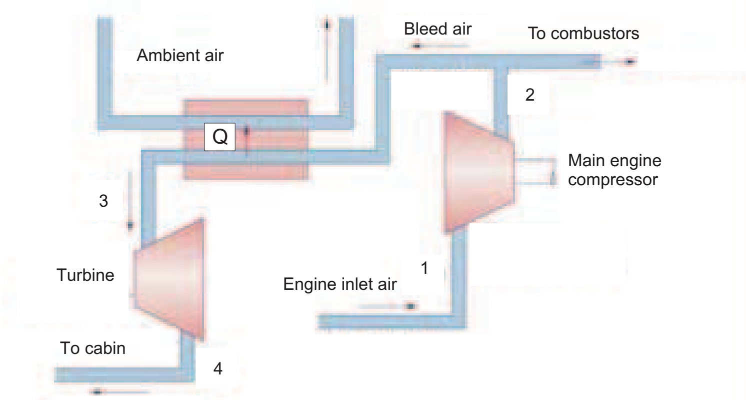


Figure 17: *Reverse Brayton cycle for aircraft cabin cooling, problem 11.9*