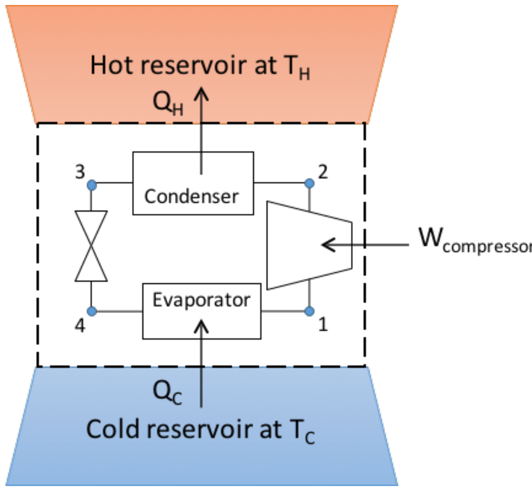
Chapter 10: Vapor-Compression Refrigeration Systems and Vapor-Compression Heat Pump Systems

Table of Contents

Introduction

Refrigeration and heat pump cycles operate by receiving work $W_{cycle} = Q_H - Q_C$ from the surroundings in order to remove energy by heat transfer Q_C from a cold thermal reservoir at temperature T_C and deliver energy by heat transfer Q_H to a hot thermal reservoir at temperature T_H.



Refrigeration Systems

The most common refrigeration systems in use today are **vapor-compression refrigeration systems**.

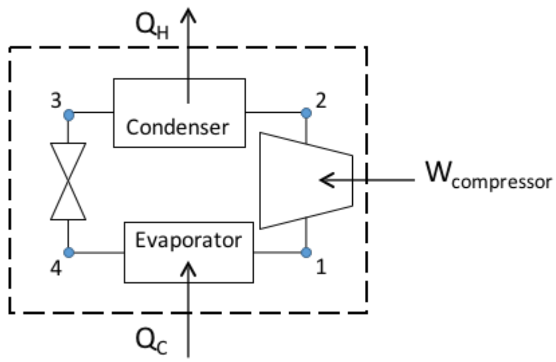
Consider the common kitchen refrigerator, an example of a vapor-compression refrigeration system. A refrigerator consists of a compressor, a set of heat exchanging pipes (coils) outside of the unit, an expansion valve, a set of heat exchanging pipes (coils) inside the unit, and refrigerant (a liquid that evaporates inside the refrigerator to create the cold temperatures).

The refrigerator operates by the following cycle.

- The compressor compresses the refrigerant gas. The compressed gas heats up as it is pressurized.
- The coils on the back of the refrigerator let the refrigerant dissipate its heat. The refrigerant condenses into liquid at high pressure.
- The high-pressure liquid refrigerant flows through the expansion valve. On one side of the expansion valve the refrigerant is high-pressure liquid and on the other side the refrigerant is at low pressure.
- The liquid refrigerant immediately boils and vaporizes, its temperature dropping to well below freezing. This makes the inside of the refrigerator cold, as the cold vapor flows through the coils inside of the refrigerator.
- The cold refrigerant gas is sucked up by the compressor, and the cycle repeats.

Analyzing Refrigeration Systems

We will analyze the components of a refrigeration system by applying the 1^{st} Law to each device in the cycle (compressor, condenser, throttle, and evaporator). For all devices we will assume steady state, steady flow (SSSF), one-dimensional (1D) flow, uniform flow, and a quasiequilibrium process. We will also neglect any changes in kinetic and potential energy.



Neglecting heat transfer with the surroundings, the rate at which work is consumed per unit mass of vapor passing through the compressor is:

$$W_{compressor} = \frac{\dot{W}_{compressor}}{\dot{m}} = h_1 - h_2$$

The sign of $W_{compressor}$ will be negative, following our sign convention that work is negative when it is done on the system by the surroundings.

The only work interaction for the condenser is flow work. Therefore, the rate at which heat is transferred per unit mass of vapor passing through the condenser is:

$$Q_{condenser} = \frac{\dot{Q}_{condenser}}{\dot{m}} = h_3 - h_2 = -Q_H$$

The sign of $Q_{condenser}$ will be negative, following our sign convention that heat transfer is positive when heat is transferred to the system from the surroundings.

The throttling process through the expansion valve is isenthalpic:

$$h_3 = h_4$$

The only work interaction for the evaporator is flow work. Therefore, the rate at which heat is transferred per unit mass of vapor passing through the evaporator is:

$$Q_{evaporator} = \frac{\dot{Q}_{evaporator}}{\dot{m}} = h_1 - h_4 = Q_C$$

The sign of $Q_{evaporator}$ will be positive, following our sign convention for heat transfer.

Refrigeration System Performance Parameters

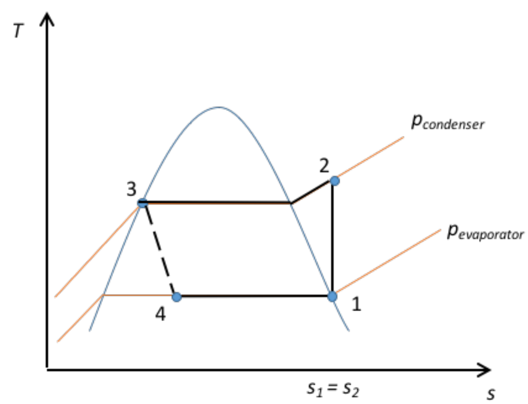
The objective of a refrigeration cycle is to remove energy Q_C from the cold reservoir. The coefficient of performance (COP) of a refrigeration cycle is given by:

$$COP_R = \frac{Q_C}{W_{cycle}} = \frac{Q_C}{Q_H - Q_C}$$

Ideal Refrigeration Systems

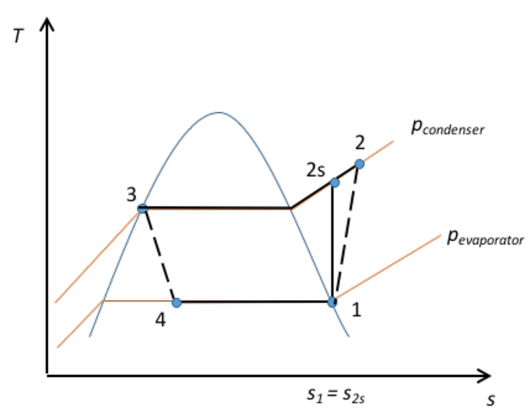
An ideal refrigeration system consists of reversible processes through the compressor, condenser, and evaporator. Note that the throttling process is not reversible.

Process	
1→2	Isentropic compression through the compressor from saturated vapor to the condenser pressure
2→3	Constant pressure heat rejection through the condenser to saturated liquid
3→4	Isenthalpic throttling process to the evaporator pressure
4→1	Constant pressure heat addition through the evaporator



Actual Refrigeration Systems

Analysis of an ideal refrigeration system assumed the compressor, condenser, and evaporator operated reversibly. We can also analyze refrigeration systems when given the isentropic efficiency of the compressor.



Example

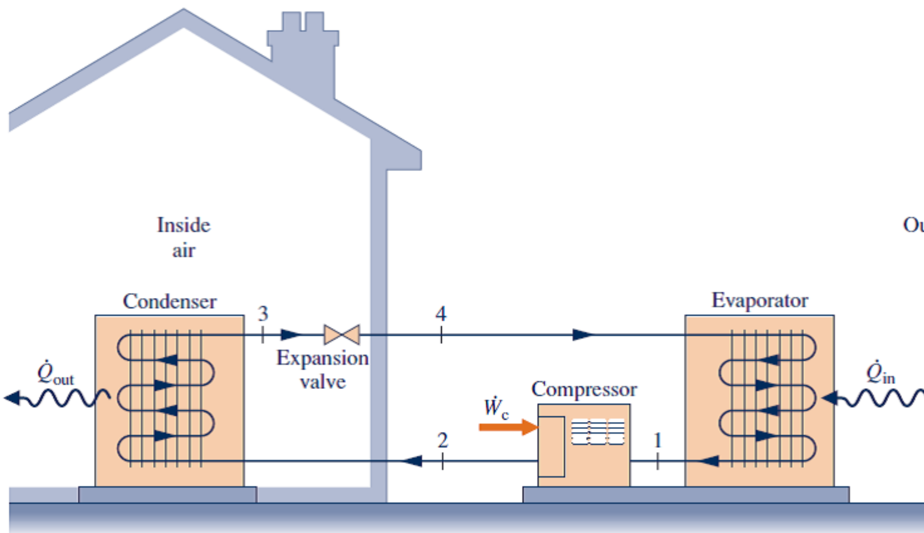
A vapor-compression refrigeration cycle operates at steady state with working fluid R134a. Saturated vapor enters the compressor at 2 bar. Saturated vapor leaves the condenser at 8 bar. The isentropic compressor efficiency is 80% and the mass flow rate is 7 kg/min. Find the compressor power (kW) and the coefficient of performance of the cycle.

Heat Pump Systems

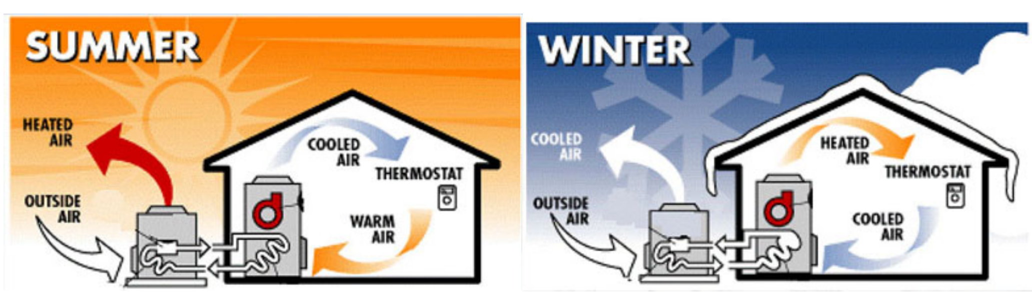
Vapor-compression heat pump systems are identical to refrigeration systems in composition and in analysis. Vapor-compression heat pump systems and refrigeration systems do differ in their objective:

- The objective of a heat pump cycle is to deliver energy Q_H to the hot reservoir (see picture below [1]).
- The objective of a refrigeration cycle is to remove energy Q_C from the cold reservoir.

Heat pump systems offer an alternative to furnaces and air conditioners in climates with moderate heating and cooling needs. The most common type of heat pump is the air-source heat pump, which transfers heat between your house and the outside air.



Air-source heat pumps can provide cooling in the summer and heating in the winter, by using a reversing valve (see picture below[2]). In the cooling mode, the outside heat exchanger becomes the condenser and the inside heat exchanger becomes the evaporator. In the heating mode, the outside heat exchanger becomes the evaporator and the inside heat exchanger becomes the condenser.



[1] (Moran, et al. 2011)
[2] (17ht)

Heat Pump System Performance Parameters

The COP of a heat pump cycle is given by:

$$COP_{HP} = \frac{Q_H}{W_{cycle}} = \frac{Q_H}{Q_H - Q_C}$$

Example

Refrigerant 134a is the working fluid in a heat pump that maintains the inside temperature of a building at 22˚C on a day when the outside temperature is 5˚C. Saturated vapor enters the compressor at -8˚C and exits at 50˚C, 10 bar. Saturated liquid exits the condenser at 10 bar. The refrigerant mass flow rate is 0.2 kg/s for steady-state operation. Find the compressor power (kW), the isentropic compressor efficiency, the heat transfer rate provided to the building (kW), and the coefficient of performance.

Numerical Answers to Examples

Page	Answer(s)
5	4.174 kW, 4.13
7	7.53 kW, 84%, 34.98 kW, 4.65