CYCLES AND REFRIGERATION

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Summary

In the refrigeration process, energy is removed as heat from a low temperature region to a high temperature region. Refrigeration's largest overall application is the prevention or retardation of microbial, physiological, and chemical changes in foods. Although several principles can be applied to heat removal, the vapor compression cycle is the basis for most refrigeration systems. In these systems, a fluid called refrigerant absorbs and releases energy in one or multiple thermodynamic cycles. Since vapor cycles in real cooling systems deviate from ideal cycles, the efficiency of a refrigeration system is often evaluated by the Coefficient of Performance. Major components of simple mechanical refrigeration systems include the condenser, expansion valve, evaporator, and compressor.

1. Introduction

It is known that heat flows in the direction of decreasing temperature, that is, from high-temperature to low-temperature regions. The reverse process, however, cannot occur by itself. The transfer of energy as heat from a low-temperature region to a high-temperature, one requires special devices called refrigerators or heat pumps. In most refrigeration systems, a fluid called the refrigerant absorbs energy as heat from the cold space and releases it to the surroundings. During the different processes occurring in a refrigeration system, the refrigerant alternates between a vapor and liquid state, changing its pressure and temperature and returning to its initial state in the cycle.

A system contains energy (E, measured in Joules) in numerous forms, such as internal energy (U), caused by the motion of molecules and intermolecular forces; potential energy (PE), resulting from the system's elevation on a gravitational field; and kinetic energy (KE), due to the system's motion relative to a given frame. Other forms of energy include chemical, nuclear, and magnetic energy. The first law of thermodynamics states that the net energy change in a system is equal to the addition of energy entering and leaving the system (see *Food Engineering Thermodynamics*). In other words, a system cannot create or destroy energy on its own. Equation (1) shows that the net change in energy of a given system depends on the amount of energy entering and leaving the system.

$$\underbrace{E_{in} - E_{out}} = \underbrace{\Delta E_{system}} \qquad (1)$$

Where

$\underbrace{E_{in} - E_{out}}$ = Change in internal (ΔU), kinetic (ΔKE), potential (ΔPE) energies

ΔE_{system} = Net energy entering and leaving the system

Energy is transferred from and to a system as heat (Q) due to the difference in temperature or work (W) associated with a force and a displacement. In refrigeration systems where the refrigerant flows in a controlled volume, mass flow, known as flow work (W_{flow}), is another important way to transfer energy. The flow work in a controlled volume is defined as the product of pressure (p) times the volume (V). Ideal refrigeration systems transfer energy from one point to another without a net change of energy in the system $(\Delta E = 0)$. In other words, $E_{in} = E_{out}$.

$$E_{in} - E_{out} - Q - W - W_{flow} = 0 \qquad (2)$$

In refrigeration systems, changes in kinetic and potential energy can be depreciated $(\Delta PE \cong 0; \Delta KE \cong 0)$. Enthalpy (H) is an important property, defined when considering a flowing system (e.g., refrigeration system), as the sum of flow work (W_{flow}) and internal energy (U) in a given control volume ($H = W_{flow} + U$).

In refrigeration cycles, energy is transferred (Q) from a cold point to a hot point as heat.

The second law of thermodynamics indicates that this process cannot be done without the addition of work (W). During the process, a working fluid (the refrigerant) changes its enthalpy state in a cycle wherein the net energy balance (ideally) is zero. In this way, an equation can represent the different states of energy in an ideal cycle:

$$Q - W - \Delta H = 0 \quad (3)$$

Pressure-enthalpy diagrams (Figures 2 and 4) and temperature-entropy diagrams are commonly used to represent property changes occurring in a given refrigerant during a thermodynamic cycle, such as the refrigeration cycle.

2. Vapor Compression Cycles

In an ideal simple, compressible, mechanical vapor system, such as the one shown in Figure 1, the refrigerant flows into an evaporator as a liquid/vapor mixture (2). While absorbing heat (Q) from the food, the refrigerant increases its enthalpy and completely vaporizes into a saturated gas state (3). The saturated vapor refrigerant enters into a compressor (3→4), where through the addition of work (W), increases in temperature and pressure to a superheated vapor state (4). After compression, the refrigerant enters the condenser where it discharges energy as heat (Q) to the surroundings. In this process (4→1), the refrigerant condenses from superheated vapor to a saturated liquid state and lowers its temperature. To complete the cycle, the saturated liquid refrigerant (1) enters an expansion valve where an abrupt drop in pressure and temperature occurs and some liquid refrigerant changes to gas (1→2); the liquid/gas mixture (2) then re-enters the evaporator completing the cycle. A pressure-enthalpy diagram is useful for observing how the properties of a given refrigerant change during the refrigeration cycle (Figure 2).

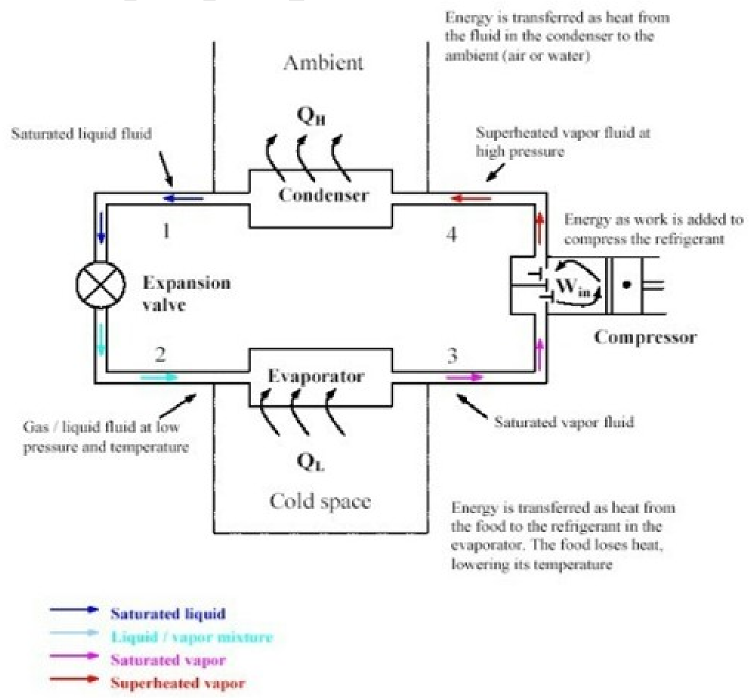

Figure 1. Diagram of a simple compressible mechanical vapor cycle. (Q) is energy

transferred as heat, (W) is energy transferred as work.

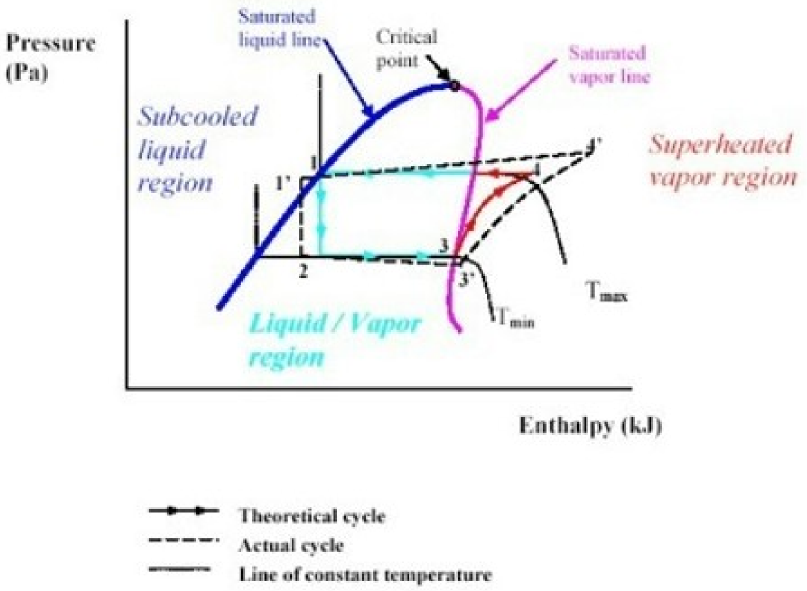

Figure 2. Simple compressible vapor Pressure–enthalpy diagram. (T_{min}) is minimum temperature, (T_{max}) is maximum temperature.

Deviations from ideal cycles may occur in real systems. The path 1'→ 2→ 3'→ 4' in Figure 2 shows the actual deviations in a simple vapor compressible cycle. Many causes explain such differences: the refrigerant after condensation may be subcooled (1') while remaining in the condenser or, as in many systems, the receiver tank is placed between the condenser and the expansion valve. In an ideal cycle, vapor refrigerant leaving the evaporator enters into the compressor in a saturated vapor state, while in actual cycles superheating occurs during evaporation (3'). Actual compression is not isoentropic (3'→ 4'), and pressure loss (4'→ 1', 2→ 3') along with heat loss may occur in the system.

2.1. Coefficient of Performance

The efficiency of refrigeration systems is usually expressed in terms of coefficient of performance (COP_R), which relates the amount of energy as heat extracted from the refrigerated space (cooling effect) with the amount of energy as work required by the system in a cycle.

$$COP_R = \frac{Q_L}{W_{in}} \tag{4}$$

where Q_L is the amount of energy for heat (kJ) removed from the cooled space by the evaporator, and W_{in} is the amount of energy for compression work (kJ) required by the system. Since $W_{in} = Q_H - Q_L$, in other words, the difference between the energy as heat extracted from the cooled space (Q_L) and the energy as heat released to the surroundings

(Q_H), the COP_R can be expressed as

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{(Q_H/Q_L)-1} \qquad (5)$$

Performance of a refrigeration system is deeply affected by temperature, which should be maintained with the evaporator (T_L) in the cold space, and by the temperature of the surroundings (T_H), where the condenser releases energy (Q_H). In this way, the COP of actual refrigeration systems is evaluated based on the maximum theoretical COP a system working with the same temperature difference can achieve.

A reversible cycle, the Carnot refrigeration cycle (or reversed Carnot) has the highest coefficient of performance that a refrigerator operating between two given temperature limits can have. The thermodynamic processes occurring in the reversed Carnot cycle follow: (1 - 2) Isoentropic (constant entropy) compression; (2 - 3) Isothermal (constant temperature) compression; (3 - 4) Isoentropic expansion; and (4 - 1) Isothermal expansion. Energy as heat is extracted from the colder space during process (4 - 1), rejected to the hotter surroundings during process (2 – 3), and then work is applied to the system during process (3 – 4). The fluid that absorbs and rejects heat during compression and expansion is an ideal gas. The reversed Carnot, an ideal cycle, is the most efficient refrigeration cycle, to which other cycles are compared in terms of efficiency. The COP for a reversible refrigeration cycle, such as the Carnot cycle, is defined by

$$COP_{R,rev} = \frac{1}{(T_H/T_L)-1} \qquad (6)$$

where T_L is the cold absolute temperature (K) and T_H the surroundings or external absolute temperature (K). Any device operating at higher COP than a reversible refrigerator violates the basic thermodynamic laws and therefore is not possible.

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Biographical Sketches

Gustavo V. Barbosa-Cánovas received his B.S. in Mechanical Engineering at the University of Uruguay and his M.S. and Ph.D. in Food Engineering at the University of Massachusetts-Amherst. He then worked as an Assistant Professor at the University of Puerto Rico from 1985-1990, during which he was granted two National Science Foundation (NSF) awards for research productivity. Following this, he went to Washington State University (WSU) where he is now a Professor of Food Engineering, and Director of the Center for Nonthermal Processing of Food (CNPF). Dr. Barbosa-Cánovas chaired the Organizing Committee for the 1997 and 1999 Conference of Food Engineering (CoFE). In addition, he is one thea editors of the journal *Food Science and Technology International* which is published by SAGE, as well as for the journal *Innovative Food Science and Emerging Technologies*, published by Elsevier Science, and the Food Engineering theme in the Encyclopedia of Life Support Systems (EOLSS) to be published by UNESCO. Dr. Barbosa-Cánovas is the Editor-in-Chief of the Food Engineering Book Series published by Kluwert Academic and Plenum Publishers (KAPP), as well as of the Food Preservation Technology Book Series published by CRC Press. He has chaired and organized several technical sessions at the American Institute of Chemical Engineers (AIChE) and at Institute of Food Technologists (IFT) annual meetings, edited 12 books on Food Engineering topics, and authored, among others: *Dehydration of Foods* (Chapman and Hall), *Nonthermal Preservation of Foods* (Marcel Dekker), *Food Engineering Laboratory Manual* (Technomic), and *Engineering Properties of Biological Materials* (ASAE). Dr. Barbosa-Cánovas is also part of the editorial board for four technical journals, including the *Journal of Food Engineering*, *Journal of Food Process Engineering*, *Journal of Food Science and Technology* (LWT), and the *International Journal of Physical Properties of Foods*. He is an International Consultant for the United Nations' Food Agriculture Organization (FAO), an Associate Researcher for the United Nations' PEDECIBA (a special program to develop basic sciences), and a consultant for several major food companies in the United States.

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