S. C. Kaushik · S. K. Tyagi ·
V. Baiju

Solar Cooling

Basics and Advances

Springer

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Foreword

It gives me immense pleasure to congratulate Dr. S. C. Kaushik and his learned colleagues in writing a comprehensive book on solar cooling system which is also the need of the time. The book, 'Solar Cooling: Basics and Advances' is based on extensive research done by the authors and is presented systematically and coherently for the sake of reader's convenience. The book would be of great use for the solar scientists, engineers, students and researchers in the field of Applied Thermal Engineering and HVACR System. Some novel concepts of Solar Cooling have been analyzed and presented which are not common. I have great appreciation of the authors for their pain staking efforts and once again congratulate them for the book.

Prof. M. S. Sodha
Padmashree and SS Bhatnagar
Awardee; Former Vice Chancellor,
Lucknow University; DAAV Indore
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Preface

Solar energy is one of the most abundant sources of energy which is not only freely available but also free from harmful gaseous pollutants and can be used for a number of useful applications and cooling is one of them. The production of cooling using solar energy is known as solar refrigeration and airconditioning in which solar photovoltaic cells could be used to generate electricity to run the vapour compression refrigeration (VCR) system and/or solar thermal collector to generate heat to run sorption refrigeration systems and thermoelectric/thermoacoustic cooling systems.

Although there are number of books of solar energy and several books on refrigeration and air conditioning published separately, so far, but none on solar cooling systems. This is because this topic has been confined only to presentations and discussions in various conferences, workshops and research publications in Journals of repute. The authors have realized this gap in the available literature and proposed a unique book on basics and advances in solar cooling systems which is of great interest to solar scientists and practicing engineers, especially, the young researchers in the field of solar energy and thermal engineering.

This book is mainly based on the research work carried out by the authors covering the basics of solar energy, solar energy options and potential for cooling, solar energy collector, solar energy storage, solar operated vapour compression, vapour absorption and vapour adsorption systems, desiccant cooling systems, thermoelectric cooling systems, alternative cooling systems, hybrid cooling systems, and economic consideration in solar cooling systems. Further, the relevant research papers, review articles, and technical reports available in the literature were also consulted for the completeness of the book.

The content of this book has been divided into 12 chapters starting from basics of solar energy to economics of solar cooling. The first chapter presents the basic concept of thermodynamics and thermodynamics systems viz., heat engine and refrigeration cycle and psychrometry while the second chapter deals with the solar energy options and potential for cooling. Chapter 3 presents the solar collector options and different types of solar collections and solar energy storage options and types of energy storages are presented in Chap. 4.

In Chap. 5, the vapour compression refrigeration and their solar cooling options is presented while vapour absorption and vapour adsorption cooling systems also known as heat-driven cooling system are presented in Chaps. 6 and 7 respectively. The desiccant cooling systems are given in Chap. 8 while the thermoelectric cooling system is presented in Chap. 9. On the other hand alternate cooling system options and hybrid cooling systems are presented in Chaps. 10 and 11 respectively. Finally, the economic considerations in solar cooling systems are given in Chap. 12 while the relevant references are given at the end of the book.

The book would be of great interest to scientists and practicing engineers for the design of solar cooling systems.

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Kerala, India V. Baiju

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- Energy experts in the scientific community and various organizations whose work have been consulted, referred and used in writing this book.
- Last but not the least the family members (wife and children) for their high patience, cooperation and everlasting moral support.
- And above all, the Almighty God for giving intellect and strength to write this book with wisdom.

S. C. Kaushik
S. K. Tyagi
V. Baiju

About This Book

This book presents the concept of solar cooling and applications of solar energy for the operation of different types of cooling systems such as:

- Vapour compression (refrigeration) system
- Vapour absorption system
- Vapour adsorption system
- Desiccant cooling system
- Thermoelectric cooling systems
- Alternative cooling systems
- Hybrid cooling systems

Further, this book provides the technical and economic consideration for solar cooling options and finally, equips the readers with key techniques associated with various solar cooling options and their potential for real-life applications.

This book will appeal to the broad readership particularly Energy Engineers viz. graduate students, engineers, and scientists working in the area of solar refrigeration systems.

Contents

About the Authors

Prof. S. C. Kaushik former Emeritus Professor and Head, Centre for Energy Studies, IIT Delhi received his Ph.D. in Plasma Science from IIT Delhi after his distinguished First Position in Master's degree in electronics. His research fields include the activities in Plasma Science and Thermal Science and Engineering; Energy Conservation and Heat Recovery, Solar Refrigeration and Air-conditioning, Solar Architecture, and Thermal Storage and Power Generation. He has made significant contributions in these fields as evident by his over 600 research publications in Journals of repute at National and International levels having more than 21000 citations so far. He has guided 72 Ph.D. Theses and 120 M.Tech Projects and has authored several books. Dr. Kaushik has also been the Post-doctoral Fellow at Queensland University, Brisbane, Australia, Visiting Professor at LES-IIM-UNAM, Mexico and Madam Curie Visiting Fellow of European Commission, Paris, France.

As per, DST-Elsevier survey report-2015, Prof. Kaushik was ranked No.1 Academic Research Performer in India in Energy and he was conferred the Bharat Ratna-Dr. A. P. J. Abdul Kalam Gold Medal Research Award (2017) from GEPRA (India) and received the Outstanding Research Faculty Award (2018) from Careers360—an educational counselling academic publisher. Dr. Kaushik has also been recognized among top 1% Global Scientists from India in Energy through an Independent Study conducted by Stanford University Scientists in 2020 and Elsevier in 2021 and 2022 respectively.

Dr. S. K. Tyagi is presently working as Associate Professor at Department of Energy Science and Engineering (formerly Centre for Energy Studies), Indian Institute of Technology Delhi since April, 2017. Earlier he was working as Director/Scientist-E at Sardar Swaran Singh National Institute of Renewable Energy, Kapurthala. He has also worked as Assistant Professor at SMVDU, Katra (J&K) during Nov, 2008–March, 2011. Dr. Tyagi has worked as Invited Scientist at Korea Institute of Energy Research, South Korea, and Post-Doctoral Fellow, Hong Kong and China during 2002–2008. He has more than 25 years of research experience and expertise in the area of Renewable Energy including solar thermal and biomass related fields. He has made a significant contribution in RD&D activities and having more than 250 publications of repute. He has also guided 12 Ph.D. Theses and 18 M.Tech. and B.Tech. projects, edited four books, 12 Book Chapters and one Special Issue of Biofuels Journal and filed four Patents. Dr. Tyagi has been recognized among top 2% Global Scientists from India in Energy through an Independent Study conducted by Stanford University Scientists in 2020, Elsevier in 2021 and 2022 respectively. He has organized four Conferences and two Training Programs, while attended several others and delivered more than 30 invited talks, globally. He has taken up several R&D projects worth 15 Million INR (as PI and Co-PI) funded by different agencies including Indian Industry. He is also member of several reputed professional societies.

Dr. V. Baiju is currently working as Assistant Professor, Department of Mechanical Engineering, TKM College of Engineering, Kollam, Kerala. He did Post Doctoral programs in the area of solar cooling systems from IIT Delhi. He established an Energy Research Centre at TKM College of Engineering with indigenous systems of solar vapour adsorption, desalination, etc. He has more than fifty articles in the area of solar cooling systems, solar vapour adsorption cooling systems in particular. Currently he is supervising five research scholars and other funded projects in the area of solar cooling and applications. He has 15 years of teaching and research experience in the field of refrigeration and airconditioning.

Chapter 1
Introduction: Basic Concepts

Solar energy is one of the most abundant source of energy, which is freely available in nature. The most significant advantage of solar energy as related to other types of energy is that it is clean and can be delivered without ecological issues such as pollution, greenhouse effect and global warming, even if the associated costs are a little higher. Moreover, solar power costs have steadily declined over the last few decades. Solar energy received on the earth's surface is amounting to approximately 10,000 times the world's present yearly energy consumption. It makes solar energy as one of the promising renewable energy sources. So the utilisation of solar energy and its technologies have received much attention.

The above said attractive features of solar energy make it as a viable alternative to the traditional energy sources and spread its presence in all engineering areas. Solar energy is beneficial for power generation in remote areas; it can be utilised for electric power generations using photovoltaic cells or through thermal energy using a turbine. The major solar energy applications are found in domestic and industrial heating processes. For domestic purposes, solar energy can be used for cooking, water heating, solar lamps, etc. In chemical industry the applications are found in the distillation of saline water and other chemical compounds. Water pumping and drying of fruits are the common applications in agriculture sector. Other purpose of solar energy includes the power source for vehicles, satellites, sea vessels, aircraft, street lights, watches and calculators etc.

There are number of useful and unique applications of solar energy and cooling is one of them. The production of cooling using solar energy is known as solar refrigeration. The conventional vapour compression refrigeration (VCR) system uses a substantial amount of high-grade energy (electricity), and nearly 40% of global CO_2 emissions are produced from this power generation. At the same time, leaking of CFCs from those devices have a significant environmental impact, such as ozone depletion. By replacing the traditional VCR system with solar cooling technology, great relief can be achieved on environmental issues. Solar energy can be used to

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provide cooling in various ways, including PV-assisted VCR systems, solar absorption systems, solar adsorption systems, and thermoelectric cooling. Whether the cooling is solar-assisted or electrically operated, the working of the refrigeration system is nearly identical. This chapter provides a brief overview of the refrigeration system as well as basic thermodynamics applicable to the refrigeration system.

1.1 Basic Thermodynamics

Thermodynamics is the branch of science that deals with energy in the form of heat and work and their transformation. There are wide variety of applications of thermodynamics, such as in day to day life, heat transfer equipment, power plants, IC engines, turbines, compressors, heat pump and refrigeration is one of them. Refrigeration is the science that deals with the production and maintenance of the temperature of a space or a product below that of the surroundings for either comfort or preservation. In other words, refrigeration is the process of removing heat from a space at a temperature lower than its surrounding temperature. Devices that produce refrigeration are called 'refrigerators', and the cycles on which they operate are 'refrigeration cycles'. According to the Clausius statement of the second law of thermodynamics, heat flows in the decreasing direction of temperature spontaneously, that is, from higher temperature regions to lower temperature regions without external work. This heat transfer process occurs in nature without any devices. But for the reverse process, the transfer of heat from a low-temperature region to a high-temperature requires power-consuming devices called refrigerators. The working fluid used for achieving the refrigeration is called refrigerants (Kaushik 1989). There are two basic laws of thermodynamics that are important from the subject point of view: (i) first law of thermodynamics and (ii) second law of thermodynamics.

1.1.1 First Law of Thermodynamics

The first law of thermodynamics was formulated by Joule in the nineteenth century, based on the repetitive experiments. The first law defines a useful property called energy. The first law of thermodynamics is also called the law of conservation of energy. According to this law, the total energy of the system is constant; energy can be transformed from one form to another, but cannot be created or destroyed. If Q is amount of heat supplied to the system by its surroundings and W is work done by the system then, according to the first law of thermodynamics, the net heat transfer to the system is equal to the net work done by the system in a cycle.

$$\oint dQ = \oint dW \tag{1.1}$$

1.1.2 Second Law of Thermodynamics

The inadequacy of the first law to identify whether the process can take place or not is remedied by introducing the second law of thermodynamics. Satisfying the first law alone does not guarantee that the process will take place in real. In short, a process will take place if it satisfies both the first and second law of thermodynamics.

The second law of thermodynamics has two statements, as explained below.

(a) Kelvin-Planck statement
(b) Clausius statement

(a) Kelvin-Planck Statement
According to Kelvin-Planck statement, it is impossible to construct a cyclically operating device that receives heat from a single reservoir and produce a net amount of the work (Fig. 1.1).

This means that the complete conversion of heat energy into work is impossible, that is, an engine with 100% efficiency is impossible to construct. This indicates that a heat engine must exchange heat with a low-temperature sink and a high-temperature source.

(b) Clausius Statement
As explained in the previous sections, heat always flows from a body at higher temperature to another body at lower temperature (Fig. 1.2) spontaneously. According to

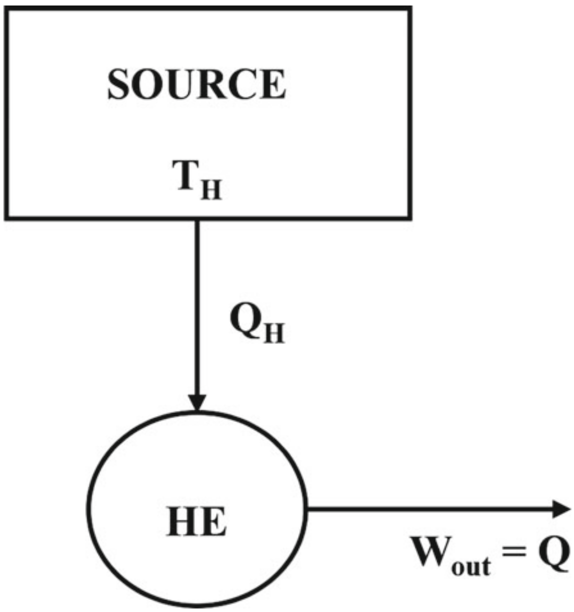

Fig. 1.1 Schematic representation of a heat engine (HE) (which is impossible according to the Kelvin-Planck statement)

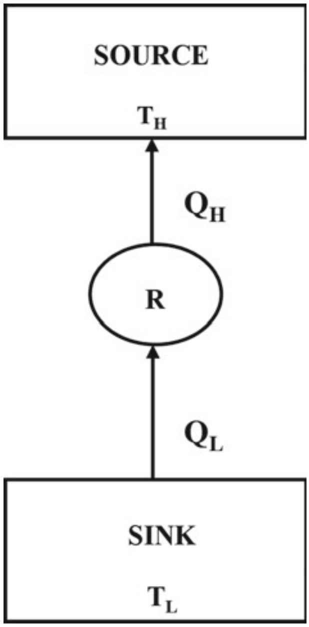

Fig. 1.2 Schematic representation of a refrigerator (R) (which is impossible according to the Clausius statement)

the Clausius statement, "It is impossible to construct a device that operates on a cycle and produces no effect other than the transfer of heat from lower temperature to higher temperature body". This means that the transfer of heat from the body at a lower temperature to a higher temperature does not take place naturally. For this to happen, the device is to be powered by an external agency. For example, house hold refrigerator cannot work if it is not powered by an external source such as an electric motor coupled to a compressor.

Both Kelvin-Planck and Clausius statements are formulated based on the experimental observations and cannot be proved until now, nobody conducted an experiment that contradicts the first and second laws of thermodynamics.

1.1.3 Thermodynamic Systems

The thermodynamic system may be defined as the space confined by definite boundaries within which the thermodynamic processes take place. Anything outside of such boundaries is referred to be surroundings, while both system and surroundings are referred to as universe. Boundaries may be fixed (storage tank for compressed air) or movable (cylinder piston arrangement for enclosing gas). Thermodynamic systems are classified into three types: (i) Open system (ii) Closed system and (iii) Isolated system.

(i) **Open system:** In open system, mass of the working substance crosses the boundary of the system during the process. Here the boundary is taken as imaginary and it allows transfer of energy as well as matter.

(ii) **Closed system:** Closed system is referred to as the system having fixed mass, and the boundary does not allow the mass transfer. However, the possibility of energy transfer is there through the boundary.

(iii) **Isolated system:** In this type of system, there is no energy or mass transfer, across the system boundary. As a result, there is no interaction between the system and the environment since it is fully isolated. The schematic of different types of thermodynamics systems are shown in Fig. 1.3.

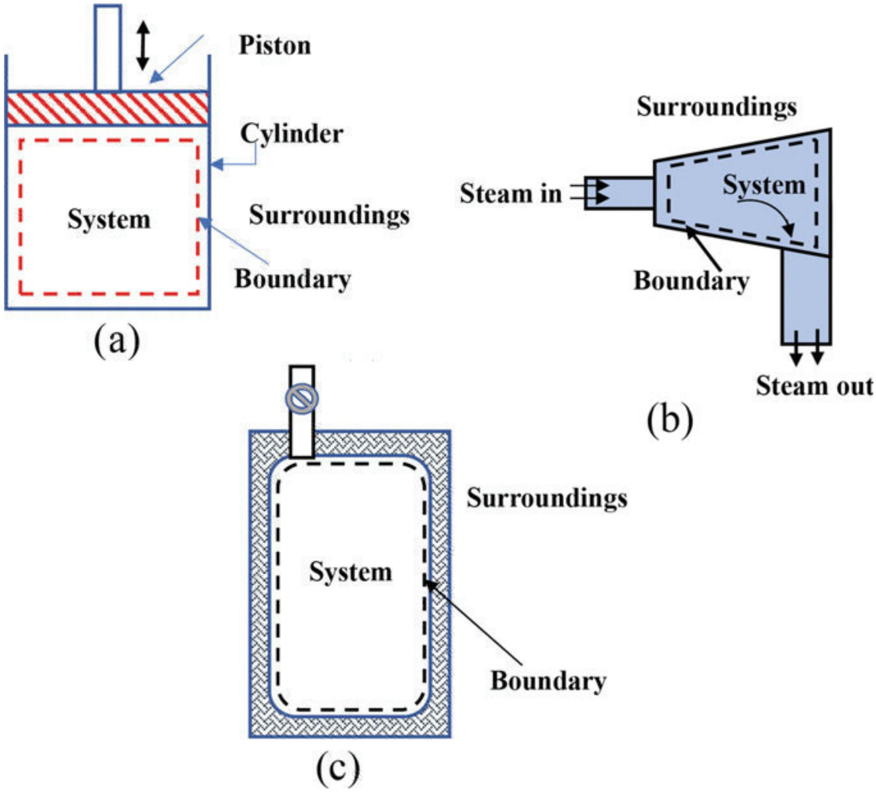

Fig. 1.3 Schematic of thermodynamic systems **a** open system **b** closed system and **c** isolated system

1.1.4 Thermodynamic Properties

Specific Heat (C)

The amount of heat required to raise the temperature of 1 kg of a substance by 1 °C is called specific heat of that substance, i.e.

$$Q = mCdT \tag{1.2}$$

where m is the mass (in kg), C the specific heat and dT the temperature difference (C: J/kg K).

Two types of specific heats are:

(i) Specific heat at constant volume (C_v)

$$C_v = \left.\frac{\partial u}{\partial T}\right)_v \tag{1.3}$$

where u is the internal energy (J/kg) and T is the absolute temperature (K).

(ii) Specific heat at constant pressure (C_p)

$$C_p = \left.\frac{\partial h}{\partial T}\right)_p \tag{1.4}$$

where h is the enthalpy.

Enthalpy (H)

Enthalpy (H) is the total heat content of the system. It is the sum of internal energy (U) and pressure volume (PV) work.

The enthalpy of a substance is a property since it consists of the sum of property and product of the two other properties, i.e.,

$$\begin{aligned} H &= U + PV \\ h &= u + pv \text{ (specific, for } m = 1\,\text{kg)} \\ dh &= du + d(pv) \\ d(pv) &= pdv + vdp \end{aligned} \tag{1.5}$$

At constant pressure, $vdp = 0$

$$\begin{aligned} dh &= du + pdV \\ pdV &= RdT \\ dh &= du + RdT \\ du &= mC_v dT \\ dh &= C_v dT + RdT \end{aligned} \tag{1.6}$$

$$dh = (C_v + R)dT$$
$$dh = C_p dT$$
$$C_p = C_v + R \tag{1.7}$$

The total enthalpy is given by

$$H = mC_p dT \tag{1.8}$$

Thermal Reservoir

Thermal reservoir is a body with ability to store or supply large quantity of heat without appreciable change in its temperature. Source is a thermal reservoir which supplies heat and sink is the reservoir that absorbs heat energy.

Heat Engine

The conversion of other forms of energy into work is ambitious, whereas, the conversion of work into other energy forms is easy. It requires a special device. A heat engine is a cyclic device that converts heat energy into mechanical work. It receives energy as heat from a high-temperature reservoir and part of the energy received is converted into useful work and remaining is rejected into the sink (Fig. 1.4).

$$W_{\text{out}} = Q_{\text{in}} - Q_{\text{out}} = Q_H - Q_L \tag{1.9}$$

where Q_{H} is the heat input to the heat engine, Q_{L} the heat rejected to the surroundings and W_{out} the work produced by the heat engine.

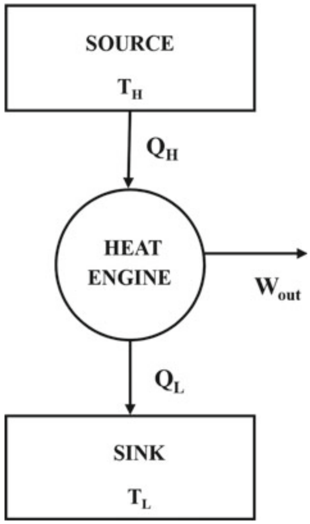

Fig. 1.4 Schematic of a heat engine (HE)

1.1.5 Thermal Efficiency

A part of net heat supplied to the system (Q_{in}) is used for converting into the useful work and the remaining (Q_{out}) is exhausted to the surroundings. Since Q_{out} is never equal to zero, the network output of the engine is always less than the amount of heat input. The fraction of heat input converted into useful work (W) is a measure of performance of a heat engine, known as the thermal efficiency and given as below:

$$\text{The efficiency, } (\eta) = \frac{\text{Work output}}{\text{Heat input}} \tag{1.10}$$

$$\eta = \frac{W_{out}}{Q_{in}} \approx 1 - Q_{out}/Q_{in} < 1 \tag{1.11}$$

1.1.6 Refrigerator and Heat Pump

In nature, heat always transfers from a greater temperature region to a smaller temperature. The reverse process, however, cannot occur naturally, that is, the transfer of heat from lower temperature to higher temperature requires some special device called as the heat pump or refrigerator.

Refrigerator

A refrigerator is a cyclic device which is used for maintaining a system at temperature lower than the surrounding temperature. Figure 1.5 shows the schematic of a refrigerator.

As can be seen from Fig. 1.5, it is a cyclic device, which absorbs heat from a low-temperature reservoir to a high-temperature reservoir when the work is performed on the body.

Let Q_L be the heat extracted from the system and Q_H be the heat rejected to the surroundings.

Then W_{in} is the work input to the device, given as (Cengel et al. 2011):

$$W_{in} = Q_H - Q_L \tag{1.12}$$

Heat Pump

A device which transfers heat from a lower temperature space/body to a higher temperature space/body with the aid of an external agency is called a heat pump. The objective of both refrigerator and a heat pump are different. The objective of the refrigerator is to maintain a space at a lower temperature than the surroundings (space cooling), while a heat pump is used to maintain a space at a higher temperature than that of surroundings (Fig. 1.6). In other words, a heat pump is employed in the cold

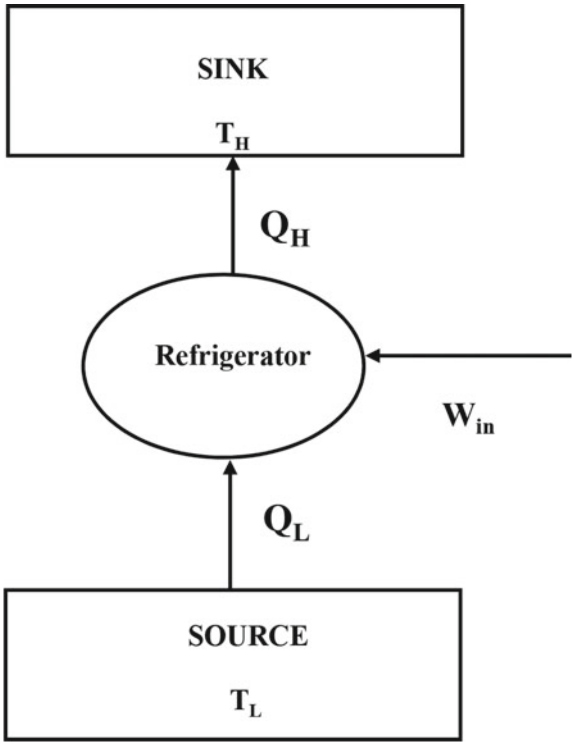

Fig. 1.5 Schematic of a refrigerator (R)

regions to heat up the space for maintaining the thermal comfort, while the refrigerator is employed at both hot and cold climate to preserve something including but not limited to medicines (vaccines), food products, fruits, vegetables, and so on.

1.1.7 Coefficient of Performance (COP)

The performance of the refrigerators and heat pump is usually expressed as the ratio of cooling or heating produced to work input known as coefficient of performance (COP) given as below;

$$\text{COP} = \frac{\text{Desired effect}}{\text{Work input}} \tag{1.13}$$

For a refrigerator, the desired effect is the cooling load or refrigerating effect and the performance (COP_R) is given by:

$$\text{COP}_\text{R} = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L} \tag{1.14}$$

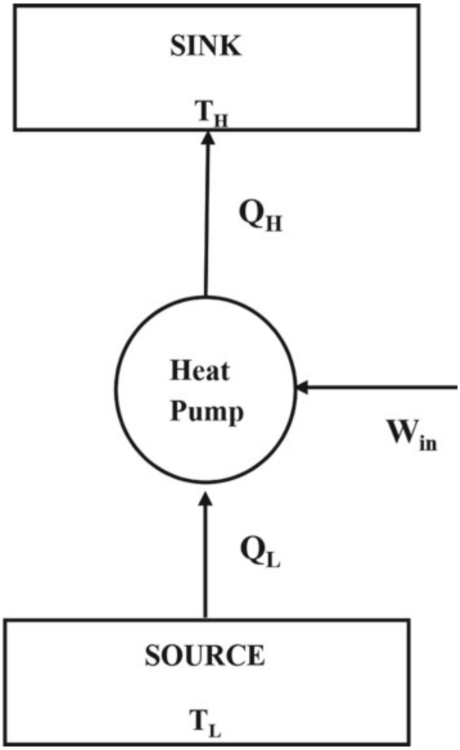

Fig. 1.6 Schematic of a heat pump (HP)

The value of COP_R can be greater than unity. This shows that the amount of heat extracted from the refrigerated space can be more than the work spent on it. The efficiency of a heat engine is always less than unity. This is one of the reasons why the performance of a refrigerator and heat pump is expressed in terms of COP rather than efficiency to avoid the oddity.

Similarly the coefficient of performance of heat pump is given by:

$$COP_{HP} = \frac{Q_H}{(Q_H - Q_L)} = \frac{T_H}{(T_H - T_L)} \tag{1.15}$$

where, the desired effect is heating load and Q_H is the heat supplied to the (heating) space and Q_L is the heat extracted from the ambient (surroundings), while W is the work supplied to the machine.

COP_{HP} is always greater than COP_R.
Using Eqs. (1.14) and (1.15), we have:

$$COP_R = \frac{Q_L}{(Q_H - Q_L)} \quad (1.16)$$

Adding 1 on both sides,

$$\begin{aligned} COP_R = & \frac{Q_L}{(Q_H - Q_L)} + 1 = \frac{(Q_L + Q_H - Q_L)}{(Q_H - Q_L)} \\ = & \frac{Q_H}{(Q_H - Q_L)} = COP_{HP} \end{aligned} \quad (1.17)$$

Therefore,

$$COP_{HP} = COP_R + 1 \quad (1.18)$$

In other words, the COP of a heat pump is always more than unity, while COP of a refrigerator may be greater than or equal to unity.

1.2 Psychrometry

Psychrometry is a branch of science, which describes the study of properties of moist air. The moist air is a combination of dry air and water vapour present in it.

1.2.1 Terms Used in Psychrometry

(a) *Dry air*: It contains N_2, O_2 etc. and does not contain water vapour in it.
(b) *Moist air*: The atmospheric air which contains water vapour and dry air.
(c) *Saturated air*: It contains the maximum amount of water vapour at a particular pressure and temperature.
(d) *Dry-bulb temperature* (t_{db}): It is the actual temperature of moist air recorded by an ordinary thermometer with a dry bulb.
(e) *Wet-bulb temperature* (t_{wb}): The wet bulb temperature represents the temperature of air recorded by a thermometer when its bulb is covered with a wetted wick (cloth) and is exposed to moving air (e.g., the temperature felt when skin is wet). The device used for measuring humidity is called a psychrometer. The psychrometer consists of two thermometers, viz. wet-bulb thermometer and dry-bulb thermometer.
(f) *Wet-bulb depression* (*WBD*): It is the difference between dry-bulb temperature and wet-bulb temperature:

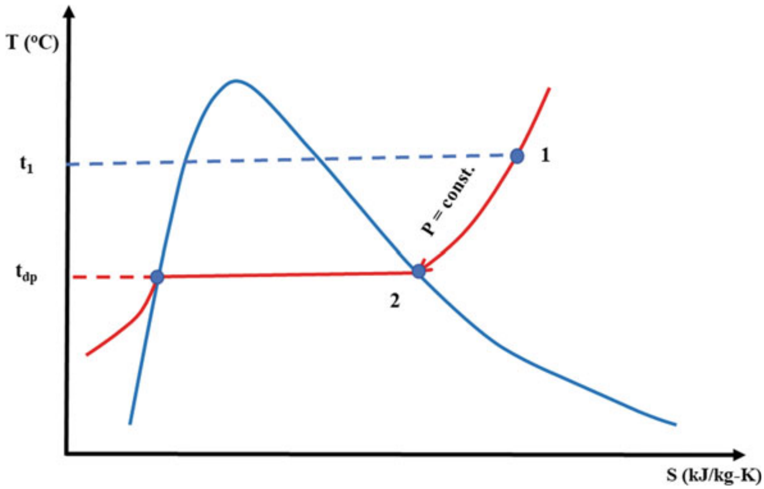

Fig. 1.7 Thermodynamic state of water vapour in moist air

$$\text{WBD} = t_{\text{dbt}} - t_{\text{wbt}} \tag{1.19}$$

(g) *Dew point temperature* (t_{dp}): The dew point temperature is the temperature at which the water suspended in atmospheric air starts condensing when it it is cooled at constant pressure. The horizontal line drawn from the corresponding state to the saturation line represents the dew point temperature in the chart. The dew point temperature lines are shown in the Fig. 1.7 along the saturated relative humidity lines. When an unsaturated quantity of air is cooled isobarically, the temperature of the mixture will decrease to the saturation temperature, t_{dp} of the water vapour and the water. The water vapour begins to condense at this point. The temperature t_{dp} is called as the dew point temperature.

(h) *Dew point depression* (DPD): It is the difference between dry-bulb temperature and dew point temperature:

$$DPT = t_{\text{db}} - t_{\text{dp}} \tag{1.20}$$

(i) *Specific humidity or humidity ratio* (ω):
The ratio of mass of water vapour to the mass of dry air present in moist air is defined by the specific humidity or humidity ratio (ω).

$$\omega\ (\text{kg of water vapour/kg of dry air}) = m_{\text{v}}/m_{\text{a}} \tag{1.21}$$

we have,

$$PV = mRT \tag{1.22}$$

for water vapour,

$$P_v V = m_v R_v T$$

for dry air,

$$P_a V = m_a R_a T$$

$$R_v = \frac{R_u}{M_v} = \frac{8314}{18} = 462\,\mathrm{J/kg\,K} (\mathrm{M_v} = 18, \mathrm{M_a} = 28.87)$$

$$R_a = \frac{R_u}{M_v} = \frac{8314}{28.97} = 286.9\,\mathrm{J/kg}\,K$$

so,

$$\omega = \frac{m_v}{m_a}$$

$$\omega = \frac{(P_v V)(R_a T)}{(P_a V)(R_v T)} \tag{1.23}$$

$$\omega = \frac{(P_v R_a)}{P_a R_v} \tag{1.24}$$

i.e.,

$$\omega = 0.622 \times \frac{P_v}{P_a} \tag{1.25}$$

According to Dalton's law of partial pressure, total pressure P_t is equal to the sum of the partial pressure of dry air P_a and partial pressure of water vapour P_v.

$$P_t = P_a + P_v$$

or

$$P_a = P_t - P_v \tag{1.26}$$

hence,

$$\omega = 0.622 \times \frac{P_v}{P_t - P_v} \tag{1.27}$$