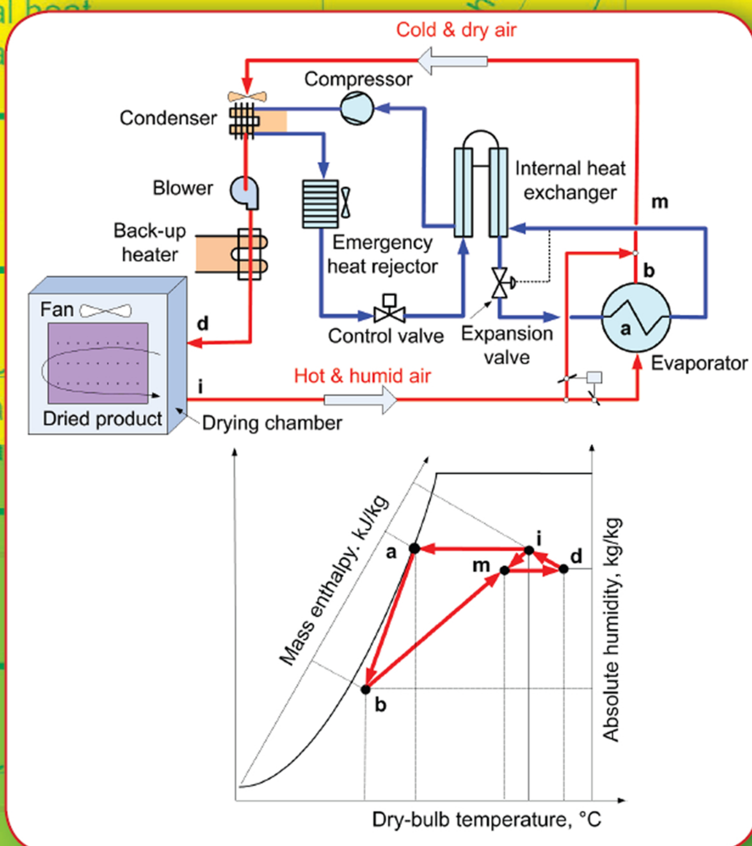
ADVANCES IN DRYING SCIENCE AND TECHNOLOGY

ADVANCES IN HEAT PUMP-ASSISTED DRYING TECHNOLOGY



edited by Vasile Minea

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HEAT PUMP-ASSISTED DRYING TECHNOLOGY

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Vasile Minea

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EDITED BY

Vasile Minea

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Series Preface

It is well known that the unit operation of drying is a highly energy-intensive operation encountered in diverse industrial sectors such as agricultural processing, ceramics, chemicals, minerals processing, pulp and paper, pharmaceuticals, coal polymer, food, forest products industries, and waste management. Drying also determines the quality of the final dried products. The need to make drying technologies sustainable and cost-effective via application of modern scientific techniques is the goal of academic as well as industrial R&D activities around the world.

Drying is a truly multi- and interdisciplinary area. Over the past four decades, the scientific and technical literature on drying has seen an exponential growth. The continuously rising interest in this field is also evident from the success of numerous international conferences devoted to drying science and technology.

This new series entitled "Advances in Drying Science and Technology" is designed to provide authoritative and critical reviews and monographs focusing on current developments as well as future needs. It is expected that books in this series will be valuable to academic researchers as well as industry personnel involved in any aspect of drying and dewatering.

The series will also encompass themes and topics closely associated with drying operations, such as mechanical dewatering, energy savings in drying, environmental aspects, life cycle analysis, technoeconomics of drying, electrotechnologies, and control and safety aspects.

Arun S. Mujumdar
McGill University, Québec, Canada

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Preface

This book, *Advances in Heat Pump-Assisted Drying Technology,* reviews recent innovations and system improvements proposed by academic and industry R&D communities. They focus on various aspects ranging from technological advancements in heat pumping in general to optimal dryer–heat pump coupling and control strategies, system modeling and simulation, and *in-field* long-term experiences.

Drying of solids is one of the most common, complex, and energy-intensive processes existing in many industrial sectors such as food, agricultural, pulp and paper, pharmaceutical, ceramic, and wood. It is a mix of fundamental sciences and technologies; it is also based on extensive experimental observations and operating experience.

The chapters in this book are written by recognized researchers throughout the world who are experts in various types of heat pump-assisted drying systems. It emphasizes several new design concepts and operating and control strategies that can be applied to improve the energy efficiency and environmental sustainability for drying processes.

This book is intended to serve both the practicing engineer involved in the selection and/or design of sustainable drying systems and the researcher as a reference work that covers the wide field of drying principles, various commonly used drying equipment, and aspects of drying in important industries.

The main aim of this book is to contribute to the increasing number of successful industrial implementations of heat pump-assisted dryers.

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Acknowledgments

I gratefully acknowledge Dr. Arun S. Mujumdar for commissioning a new series of books entitled "Advances in Drying Science and Technology" as a valuable working tool for academic researchers and industry people involved in various drying technologies. Thanks to Dr. Arun S. Mujumdar, heat pump-assisted drying technique has been included in this series of books as one of the most energy-efficient and economical drying technologies.

I express many thanks for the support received from the contributing authors and for their constant efforts to enhance the scientific and technological content of different topics associated with heat pump-assisted drying of agro-food, lumber, and other valuable industrial products. The technical content of each chapter has been improved thanks to the valuable assistance, comments, and suggestions made by peer reviewers, who are internationally recognized experts in drying and industrial heat pump technologies.

I greatly appreciate the support of several publishers and companies that granted copyright permissions to use figures and tables. A special mention for Professor Dr. Hans-Jürgen Laue from IZW e. V. (Germany), who, as the operating agent of the International Energy Agency Heat Pump Technology's (IEA HPT) Annex 35/13 International Project on Industrial Heat Pumps, graciously permitted liberal use of material from the Annex's publications and final report. Also, journals such as *Drying Technology* and *International Journal of Refrigeration*, as well as publications of IEA HPT Centre (i.e., *Newsletters*), have been invaluable sources of information for this specialized book.

I also thank the publisher, CRC Press, for its sustained involvement, assistance, patience, and strong support throughout the process. Specifically, I would like to mention Allison Shatkin, Senior Editor, Books, Material Science & Chemical Engineering, and Laurie Oknowski, Project Coordinator, Editorial Project Development at Taylor & Francis Group for their courteous, professional, and helpful support, even when there were delays.

Finally, on behalf of the book's contributors, I warmly acknowledge the support and patience of their family members during the preparation and correction of the manuscripts, which sometimes continued during periods of special events such as childbirth, university exams, summer vacations, and holidays.

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Series Editor

Arun S. Mujumdar is an internationally acclaimed expert in drying science and technologies. In 1978, he was the founding chair of the International Drying Symposium (IDS) series and has been the editor-in-chief of the *Drying Technology: An International Journal* since 1988. The fourth enlarged edition of his *Handbook of Industrial Drying*, published by the CRC Press, has just published. He is a recipient of numerous international awards including honorary doctorates from Lodz Technical University, Poland, and University of Lyon, France.

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Editor

Vasile Minea is a PhD graduate of civil and mechanical building engineering from the Bucharest University, Romania. He worked as a professor at that university for more than 15 years, teaching various courses such as HVAC systems for civil, agricultural, and industrial buildings, as well as thermodynamics, heat transfer, and refrigeration. During this period, his R&D work focused on heat exchangers, heat pump and heat recovery systems, development and experimentation of advanced compression–absorption/resorption heat pump concepts, as well as on the usage of solar energy for comfort cooling processes and industrial cold and ice production. Since 1987, Dr. Minea has been working as a scientist researcher at the Hydro-Québec Research Institute, Canada. His research activity mainly focuses on commercial and industrial refrigeration, heat recovery and geothermal heat pump systems, low-enthalpy power generation cycles, and heat pump drying. During the past 15 years, he collaborated with the Canadian and American heat pump drying industry and R&D drying community in developing laboratory- and industrial-scale experimental prototypes. Drying of various products such as vegetables, agricultural and biological products, and wood has been theoretically and experimentally studied, and results have been published in several drying conference proceedings and in prestigious journals such as *Drying Technology* and the *International Journal of Refrigeration*.

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1 Advances in Industrial Heat Pump Technologies and Applications

Vasile Minea

CONTENTS

1.1 INTRODUCTION

Depletion of fossil fuels and increasing requirements for the environment protection have prompted academic and industrial R&D communities to develop and promote new, more efficient heating and cooling systems, as heat pumps recovering industrial waste heat (Srikhirin et al. 2001), combined or not with renewable energy sources, such as solar (Nguyen et al. 2001) and/or geothermal energies.

This chapter summarizes recent R&D advancements in heat pump technology and applications, including those reported for industrial drying. The review of R&D advancements refers to new components, such as compressors, working fluids, and heat exchangers, and advanced heat pumping cycles and control methods aiming at enhancing the system's overall energy performances, whereas new industrial applications mainly focus on heat pump integration with various energy sources, such as waste heat and solar energy, and industrial processes such as drying, evaporation, and distillation.

1.1.1 World Energy Context

In 2008, the total world energy supply was 143 851 TWh (corresponding to about 15 TW of energy power), of which oil and coal combined represented over 60% (Figure 1.1a). Industrial users (agriculture, mining, manufacturing, and construction) consumed about 37%, personal and commercial transportation (20%), residential (heating, lighting, and appliances) (11%), and commercial buildings (lighting, heating, and cooling) (5%) of the total world energy supply. The rest, 32%, was lost in energy transmission and generation (IEA 2014) depending on the energy source itself, as well as the efficiency of end-use technologies.

Also in 2008, the world electricity generation was 20 181 TWh, of which more than 60% has been produced by using coal/peat and natural gas as primary energy sources (Figure 1.1b). Refrigeration, heat pump, and air conditioning industries consumed about 10%–15% of this total electric energy production (IEA 2014).

On the other hand, global CO_2 emissions came from electrical power generation (40%), industry (17%), buildings (14%), and transport (21%) energy consumptions (IEA 2014).

Such a world energy context opens up opportunities for developing alternative renewable and clean energy sources, such as solar, wind, hydrogen, water hydrokinetic, nuclear, ambient air, and geothermal. In addition, the considerable global energy use and CO_2 emissions could be reduced, especially in industry, if best available technologies were to be developed and applied worldwide (IEA 2015a).

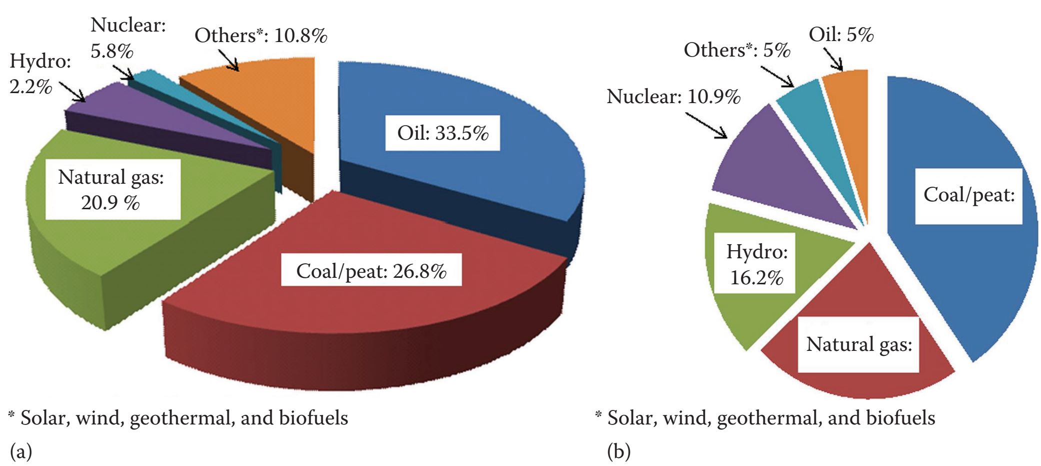

FIGURE 1.1 World energy context in 2008: (a) Total energy supply and (b) total electricity generation by fuel. (From IEA, Key world energy statistics, 2014, http://www.iea.org/publications/freepublications; accessed May 15, 2015.)

Among these technologies, industrial heat pumps offer opportunities to recover and reuse waste and/or process heat for heating or preheating, or for building space and domestic hot water heating, and space cooling. They can significantly reduce primary electrical and fossil energy, and reduce power demand and greenhouse gas emissions in energy-intensive industrial processes such as drying, evaporation, distillation, and washing. However, despite such advantages, relatively few industrial heat pumps are currently installed in industry (IEA 2015a).

1.1.2 Classification of Heat Pumps

Heat pumps are heat recovery devices that allow to recover free energy from ambient air or ground, or from industrial waste heat at relatively low temperatures and, simultaneously, to supply heat at higher temperature levels for domestic, commercial, or industrial usage.

This chapter refers only to the industrial heat pump systems listed in Table 1.1. Mechanical vapor compression heat pumps use electrical- or gas-driven compressors to compress synthetic, natural, or mixed refrigerants according to sub- or supercritical reverse Rankine-type thermodynamic cycles. Absorption, heat transformers, and compression–resorption heat pumps use two-component mixtures such as ammonia–water (NH_3/H_2O) and lithium–bromide (LiBr) as working fluids. They replace the traditional electrical- or gas-driven compressors by thermocompression processes. Mechanical vapor recompression heat pumps, which are among the most extensively applied systems in manufacturing industries, use a compressor or a high pressure blower to increase the pressure of the working fluid (generally, low pressure steam) in evaporation and/or distillation industrial processes. Thermal vapor recompression are mostly refrigeration machines without moving parts that recompress waste motive vapor from industrial boilers by using steam ejectors in order to provide cooling effects. Chemical heat pumps are systems that utilize organic or inorganic substances with relatively high thermochemical energy storage densities as well as reversible chemical reactions to upgrade the temperature of recovered thermal energy to higher temperature levels by absorbing (via endothermic reactions) and releasing heat (via exothermic reactions). Solid-state heat pumps such as thermoelectric, magnetocaloric, and thermoacoustic heat pumps are cooling or heating devices based on Peltier, magnetocaloric, and thermoacoustic effects. They eliminate conventional compressors and ozone-depleting or toxic working fluids, and generally include any moving components.

TABLE 1.1
Classification of Heat Pumps

Type	Variant	Working Fluids (Pairs)	Driven Energy
Mechanical vapor compression	Subcritical Supercritical	Refrigerants (synthetic, naturals)	Electricity Gas, oil
Absorption	Heat pump Heat transformer Compression-resorption	NH_3-H_2O H_2O-LiBr New pairs	Gas, oil Waste heat Solar Hybrid
Mechanical vapor recompression	Semi-open	Water vapor	Electricity
Thermal vapor recompression	Ejector	Water vapor Refrigerants	Steam Waste heat
Chemical	Heat pump Heat transformer	Gas/solid Liquid/solid	Waste heat Solar
Solid-state	Thermoelectric Magnetic Thermo-acoustic	Electrical current	Waste heat Solar

1.1.3 Industrial Heat Pumps' Market Outlook

The number of industrial heat pumps implemented throughout the word in recent years is relatively low. This situation is attributed, among other factors, to lack of technology and process integration knowledge, low awareness of plants energy consumptions, relatively long payback periods (>5 years) and new requirements for high-pressure and temperature applications (compressors, lubricants, and refrigerants).

In Canada, among 339 questioned industrial plants (lumber drying; milk, cheese, and poultry processing; sugar refining; pulp production; and textile) in four Canadian provinces, only 7.7% use one or more industrial heat pumps for process and/or waste heat recovery. Specific barriers are related to low prices of natural gas and oil versus electricity costs and to the fact that, historically, many incentives were based on product quality and/or environmental concerns rather than energetic and/or economic (IEA 2015a). In Denmark, the industrial utilization of heat pumps is still limited today. The most important barriers are their rather low economic advantages, as well as lack of knowledge and in-field experiences (IEA 2015a). In France, even mechanical vapor closed-cycle compression (e.g., in breweries, meat processing, dairies, and lumber drying) and mechanical vapor recompression industrial heat pumps (e.g., in sugar plants) were largely used in the 1980s and 1990s; the actual market is far to be fully developed, eventhough the development potential is considered to be very high. As a specific barrier, the lack of specialized engineering companies is pointed out (IEA 2015a).

In Germany, machinery, automotive, food, and chemical industries show a high potential for low-temperature industrial heat pump applications up to 80°C. For high-temperature industrial heat pumps (i.e., up to 140°C), a huge potential has been found in food (pasteurization, sterilization, drying, and thickening), paper, textile, and chemical industries (polyethylene melting and rubber production). Natural refrigerants such as ammonia and CO_2 are frequently used as working fluids, and both electrically driven and gas-engine heat pumps are used. However, lack of documented successful applications of industrial heat pumps is noted as a specific barrier to persuade customers to implement heat pumps in Germany (IEA 2015a).

In Japan, industrial heat pumps are already adopted in greenhouse horticulture and hydroponic cultures, as well as in drying of agricultural, fishery, and lumber products, and food processing plants (washing). Heat pumps with ability of producing water at around 100°C, for coating and drying process at 120°C and steam, are under development. Mechanical recompression vapor heat pumps are increasingly used in beer factories for molt boiling and alcohol distilling processes. However, in Japan, there is still a need to develop higher efficient equipment (compressors and heat exchangers), especially for operating at temperatures over 100°C, so that heat pumps can become competitive in terms of lifetime cost with conventional heating systems (IEA 2015a). In Korea, the global heat pump market has grown rapidly in recent years, but the spread of industrial heat pump utilization still lags behind in market development. The main reason is the low price of natural gas that is one of the lowest in most OECD countries. For example, the price of electricity for domestic consumers is only 43% of that paid by UK domestic consumers (IEA 2015a). Finally, in the Netherlands, recent developments of heat pumps focused on higher heat delivery temperatures and lifts. Eight of the most representative applications still running in the Netherlands are mechanical vapor recompression, one thermal vapor recompression, and one large mechanical vapor compression heat pump. Promising markets for industrial heat pumps in this country include chemical (distillation), food (dairy), refrigeration, paper and pulp, and agriculture (drying) industries (IEA 2015a).

1.2 SUBCRITICAL MECHANICAL VAPOR COMPRESSION HEAT PUMPS

1.2.1 Generalities

Most of industrial heat pumps work in the heating mode only according to the nonreversible subcritical Rankine reverse thermodynamic cycle (Figure 1.2a). The main components are compressor (reciprocating, scroll, screw, etc.), expansion device (thermostatic or electronic valve,

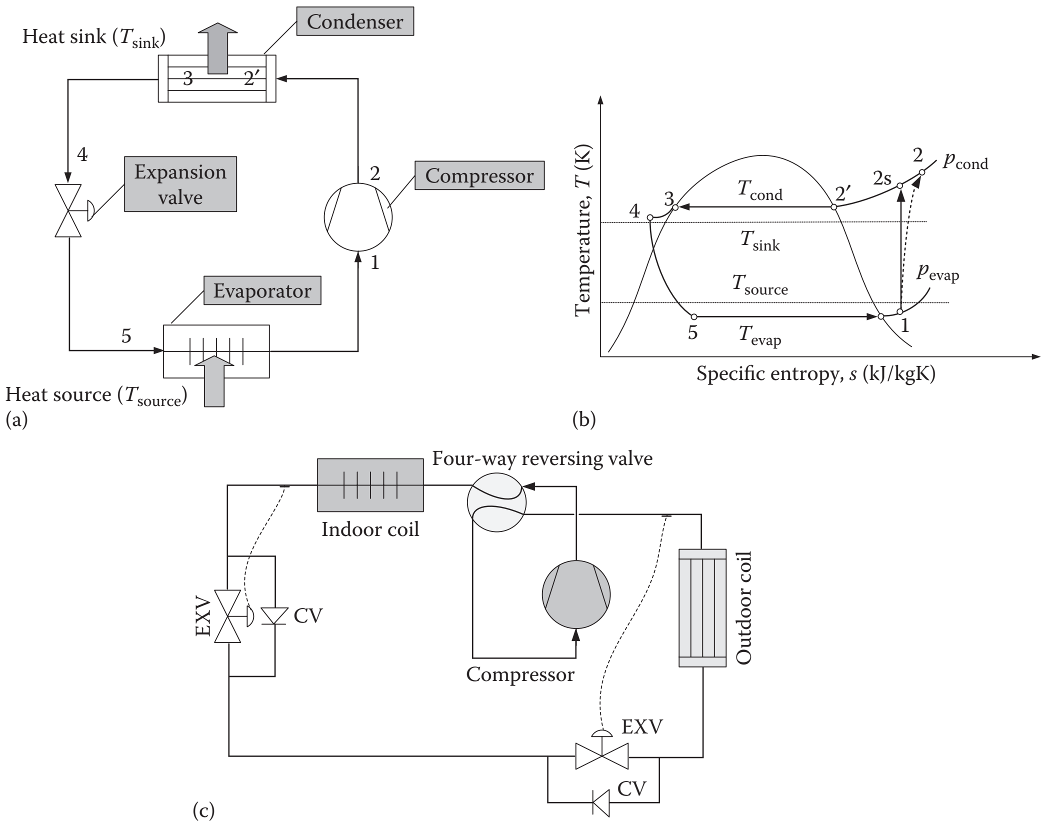

FIGURE 1.2 Schematic representation of a subcritical heat pump. (a) Nonreversible—operating in the heating mode only; (b) reversible—operating either in heating or cooling modes; and (c) thermodynamic cycle in *T–s* diagram. cond., condensing; CV, check valve; evap., evaporating; EXV, expansion valve; p, pressure; s, entropy; T, temperature.

orifice or capillary tube), and at least two heat exchangers (condenser and evaporator). Such a heat pump transfers heat from a low-temperature heat source to a higher temperature (warmer) heat (sink) source. To accomplish such a process, the heat pump uses the physical properties of a volatile working fluid (refrigerant), as well as some amount of external electrical (or fossil) primary energy to run the compressor and auxiliary equipment as blowers and/or fluid circulating pumps.

It can be seen that the entire subcritical thermodynamic process represented in the *T–s* diagram (Figure 1.2b) occurs below the critical point of the refrigerant being used. Heat absorption occurs by evaporation of the refrigerant at low pressure, and heat rejection takes place by condensing the refrigerant at a high pressure, but below that of the refrigerant critical point.

In the compressor, the refrigerant at state 1 (slightly superheated vapor) is adiabatically (theoretical process 1–2s) or polytropically (actual process 1–2) compressed up to the superheated states 2s (or 2), respectively. The electrical energy input is converted to shaft work to rise the pressure and temperature of the refrigerant. By increasing the vapor pressure, the condensing temperature is increased to a level higher than that of the heat source (T_{source}). In the condenser, the refrigerant is first desuperheated from superheated states 2s (or 2) to saturated vapor (state 2′) and then undergoes a two-phase condensation at constant temperature (T_{cond}) and pressure (p_{cond}) (process 2′–3). Before leaving the condenser, the saturated refrigerant is subcooled (process 3–4) in order to reduce the risks of flashing within the expansion valve (EXV). During all desuperheating, condensation, and subcooling processes, heat is rejected by the condenser to the heat sink medium (gas or liquid). After the condenser, the EXV expands the refrigerant at a constant enthalpy in order to reduce its pressure at a level corresponding to an evaporating temperature (T_{evap}) below the heat source temperature (T_{source}) (process 4–5). This device controls the refrigerant flow into the evaporator in order to ensure its complete evaporation and maintain a given superheat in order to avoid the liquid refrigerant to enter the compressor. However, excessive superheat may lead to overheating of the compressor. The refrigerant then enters the evaporator in a two-phase state (5), absorbs (recover) heat from the heat source thermal carrier and undergoes change from liquid-vapor to saturated vapor at constant pressure (p_{evap}) and temperature (T_{evap}). The saturated vapor is finally superheated slightly up to state 1 before entering the compressor. At this point, the cycle restarts.

By using a four-way reversible valve (Figure 1.2c), the subcritical heat pump may reverse the flow of refrigerant from the compressor through the outdoor or indoor coils in order to provide either heating or cooling, for example, to a building. In the heating mode, the outdoor coil acts as an evaporator, whereas the indoor is a condenser. The refrigerant flowing through the evaporator extracts thermal energy from outside air, water, or ground and changes its state from liquid to vapor. After compression, the refrigerant supplies heat to the indoor air or water to heat. In the cooling mode, the cycle is similar, but the outdoor coil is now the condenser and the indoor coil becomes the evaporator.

The most used subcritical nonreversible or reversible mechanical vapor compression heat pumps are the air- and ground-source heat pumps. Air-source heat pumps (see Figure 1.2a and b) extract heat from the ambient air or industrial waste gases and transfer it to building or industrial heating processes. Ground-source heat pumps extracts heat directly from the soil or from a water source (e.g., groundwater, river, lake, and sea) and transfer it to the building indoor air, to a water heating circuit (floor heating being the most efficient), or into a hot water tank for use as building and/or process hot water taps. These systems mainly use solar energy stored in shallow underground between 2 and about 200 m depth. To extract heat from the ground at very low temperatures (generally, between −5°C and 10°C during the heat pump normal operation) are used horizontal or vertical closed-loop ground heat exchangers (ASHRAE Handbook 2011). In the heating mode, an antifreeze mixture (brine) circulating, for example, through a vertical ground heat exchanger (Figure 1.3a) extracts heat from the ground (acting as a heat source), whereas the heat pump condenser, located inside the building, rejects it into the building's heating air acting as a heat sink medium. In the cooling mode (Figure 1.3b), the cycle is reversed, and the sensible and latent heat recovered from the building is rejected to the ground.

1.2.1.1 Design Outline

As could be seen from Figures 1.2 and 1.3, subcritical mechanical vapor compression heat pumps include two heat exchangers, that is, evaporator and condenser, and a compression device (compressor).

Optimum design of evaporator and condenser heat exchangers depends on their respective thermal capacities that are function of the operating temperature ranges, and on refrigerant flow rates. The theoretical thermal capacities of the evaporator and condenser (kW) can thus be calculated, for example, as functions of the refrigerant flow rate ($\dot{m}_R$, kg/s) and the refrigerant-side specific enthalpy (h, kJ/kg) changes (Figure 1.2b):

$$\dot{Q}_{evap} = \dot{m}_R \left(h_1 - h_5\right) \tag{1.1}$$

$$\dot{Q}_{cond} = \dot{m}_R \left(h_2 - h_4\right) \tag{1.2}$$

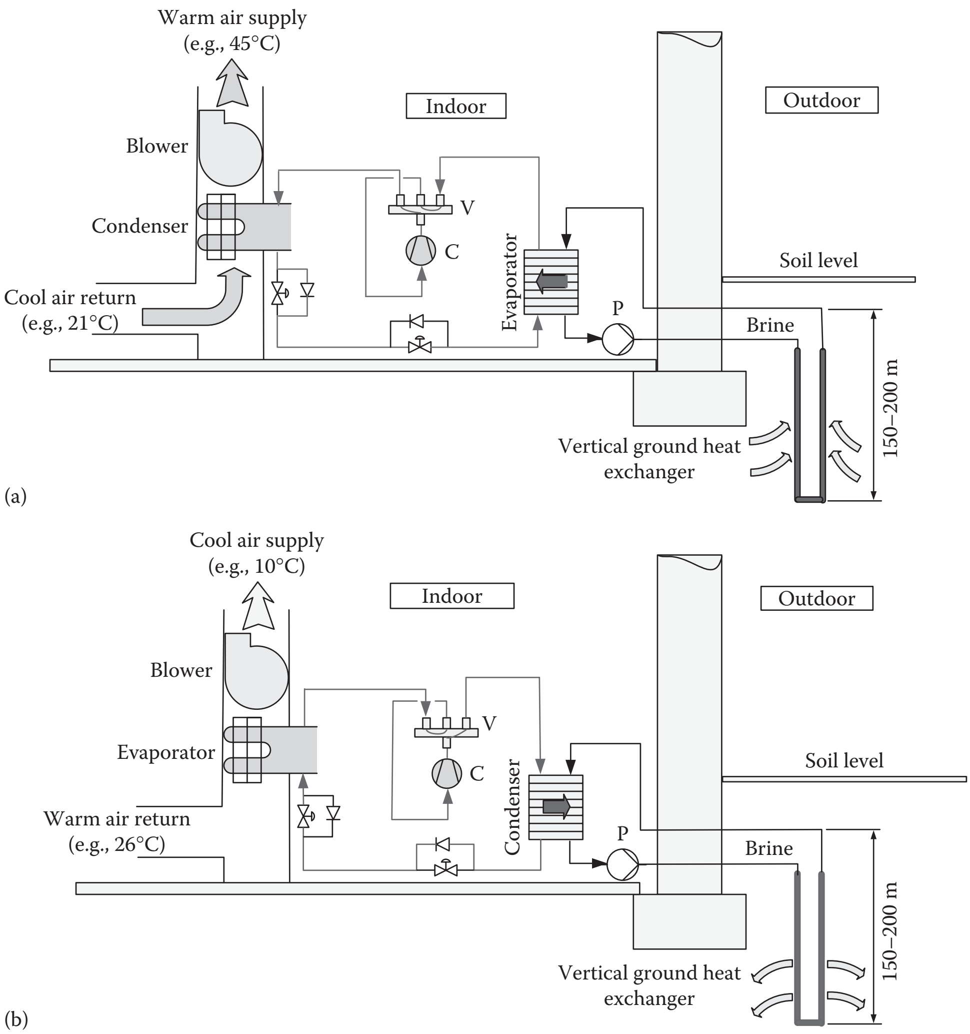

FIGURE 1.3 Schematic representation of a ground-source heat pump. (a) in the heating mode and (b) in the cooling mode. C, compressor; P, brine pump; V, 4-way reversible valve.

The isentropic efficiency of the actual compression process 1–2 versus the ideal (adiabatic) process (1–2s, where $s_1 = s_{2s}$), is defined as follows (Figure 1.2b):

$$\eta_s = \frac{h_{2s} - h_1}{h_2 - h_1} < 1 \tag{1.3}$$

Finally, the compressor theoretical electrical power input (kW) can be determined by the following energy conservation expression:

$$\dot{W}_{compr} = \dot{m}_R \left(h_2 - h_1\right) = \dot{Q}_{cond} - \dot{Q}_{evap} \tag{1.4}$$

1.2.1.2 Performance Indicators

In the heating mode, a mechanical vapor compression heat pump based on the ideal Carnot cycle operates between two heat reservoirs having absolute temperatures T_{source} (K) (heat source) and T_{sink}

(K) (heat sink), respectively (Figure 1.2b). The heating coefficient of performance (COP) for such an ideal (Carnot) cycle is the maximum theoretical efficiency defined as follows:

$$\mathrm{COP}_{\mathrm{Carnot}}^{\mathrm{heating}} = \frac{T_{\mathrm{source}}}{T_{\mathrm{source}} - T_{\mathrm{sink}}} \approx \frac{T_{\mathrm{cond}}}{T_{\mathrm{cond}} - T_{\mathrm{evap}}} \tag{1.5}$$

where:

T_{cond} is the condensing temperature (K)
T_{evap} is the evaporating temperature (K)

The heating COP of an actual (real) subcritical mechanical vapor compression heat pump is defined as the ratio between the condenser useful (supplied) thermal power output ($\dot{Q}_{\mathrm{cond}}$) and the electrical power input at both compressor and blower ($\dot{W}_{\mathrm{compr+blower}}$):

$$\mathrm{COP}_{\mathrm{subcritic}}^{\mathrm{heating}} = \frac{\dot{Q}_{\mathrm{cond}}}{\dot{W}_{\mathrm{compr+blower}}} \approx 1 + \frac{\dot{Q}_{\mathrm{evap}}}{\dot{W}_{\mathrm{compr+blower}}} < \mathrm{COP}_{\mathrm{Carnot}}^{\mathrm{heating}} \tag{1.6}$$

where $\dot{Q}_{\mathrm{evap}}$ and $\dot{Q}_{\mathrm{cond}}$ are defined by Equations 1.1 and 1.2, respectively.

In practice, the actual $\mathrm{COP}_{\mathrm{subcritic}}^{\mathrm{heating}}$ of mechanical vapor compression heat pumps varies between 40% and 60% of the maximum $\mathrm{COP}_{\mathrm{Carnot}}^{\mathrm{heating}}$ and depends on the difference (temperature lift) between the condensation (or heat sink) and evaporation (or heat source) temperatures: the smaller the difference, the higher the COPs. For example, air-to-air (or air-to-water) heat pumps operating in mild climates may achieve $\mathrm{COP}_{\mathrm{subcritic}}^{\mathrm{heating}}$ up to 4.0, but at ambient temperatures below approximately −8°C, their $\mathrm{COP}_{\mathrm{subcritic}}^{\mathrm{heating}}$ may drastically drop.

Similarly, in the cooling mode, the performance of a subcritical mechanical vapor compression heat pump can be described by the cooling COP:

$$\mathrm{COP}_{\mathrm{subcritic}}^{\mathrm{cooling}} = \frac{\dot{Q}_{\mathrm{evap}}}{\dot{W}_{\mathrm{compr+blower}}} \approx \frac{\dot{Q}_{\mathrm{evap}}}{\dot{Q}_{\mathrm{cond}} - \dot{Q}_{\mathrm{evap}}} < \mathrm{COP}_{\mathrm{Carnot}}^{\mathrm{cooling}} \tag{1.7}$$

where

$$\mathrm{COP}_{\mathrm{Carnot}}^{\mathrm{cooling}} = \frac{T_{\mathrm{sink}}}{T_{\mathrm{source}} - T_{\mathrm{sink}}} \approx \frac{T_{\mathrm{evap}}}{T_{\mathrm{cond}} - T_{\mathrm{evap}}} \tag{1.8}$$

represents the cooling COP of the equivalent ideal Carnot cycle.

In the United States and Canada, the heat pump's performance in the cooling mode is commonly described by instantaneous energy efficiency ratio (EER) or seasonal energy efficiency ratio (SEER), both expressed in Btu/Wh. The EER ratio is calculated by dividing the heat pump cooling capacity (expressed in Btu/h) by the compressor plus blower and circulating pumps power inputs (Watts) at a given set of rating conditions. The SEER ratio is defined as the cooling energy (Btu) provided by the heat pump during a given season (summer, year) divided by the total electrical energy consumed by the compressor plus blower and pumps during the same period of time, expressed in Wh) (ASHRAE 2013).

Note: 1 Btu/h = 0.2931 W.

1.2.1.3 New Industrial Applications

An electrically driven (subcritical) mechanical vapor compression heat pump with HFC-134a as the refrigerant has been applied to recover waste heat from water chillers and air compressors of a meat processing plant in Austria (Figure 1.4). The temperature lifts varied between 30°C and 55°C in order to supply about 50 m^3/day of hot water for process cleaning and space heating (IEA 2015b).

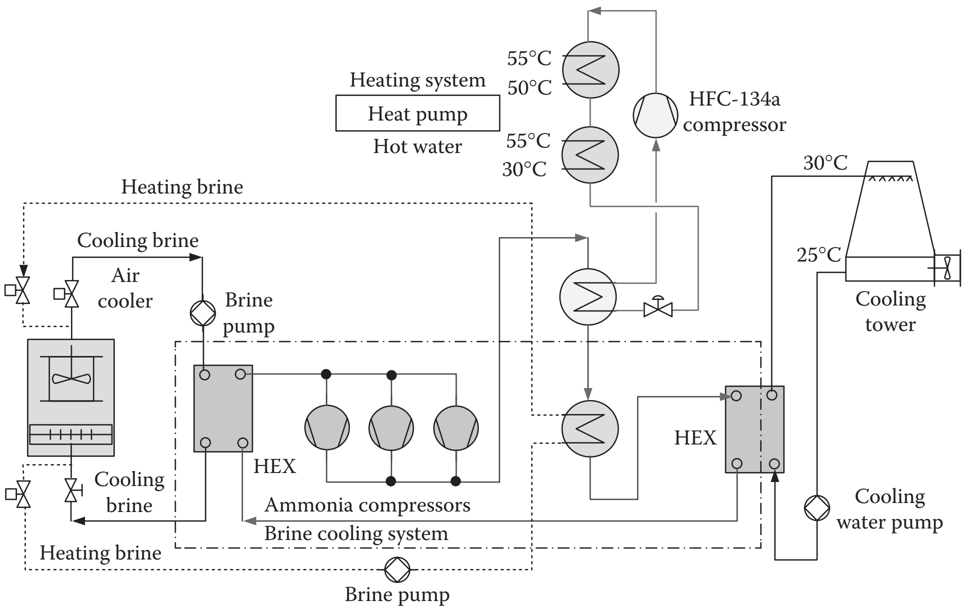

FIGURE 1.4 Process flow sheet of the subcritical mechanical vapor compression heat pump implemented in a meat processing plant in Austria. (From IEA, Industrial energy-related systems and technologies Annex 13, IEA Heat Pump Program Annex 35, Application of Industrial Heat Pumps, Final Report, Part 2, 2015b; redrawn and reprinted with permission from IEA HPT Annex 13/35 operating agent.)

Another 260-kW (thermal power supplied) (subcritical) mechanical vapor compression heat pump system has been installed in 2011 in a German metal forming and surface treatment plant (Figure 1.5). The heat pump recovers 180 kW of thermal power by cooling down from 27°C to 22°C, the cooling water required by five CO_2 laser cutting machines that run continuously. At the same time, the heat pump supplies process hot water at 65°C via one or several stratified hot water storage tanks (IEA 2015b).

Three 1.25 MW (thermal power) subcritical mechanical vapor compression heat pumps with twin-screw compressors and HFC-134a as the refrigerant have been implemented (2003) in a (tomatoes) greenhouse in the Netherlands (Figure 1.6). In the winter heating mode, the heat pump

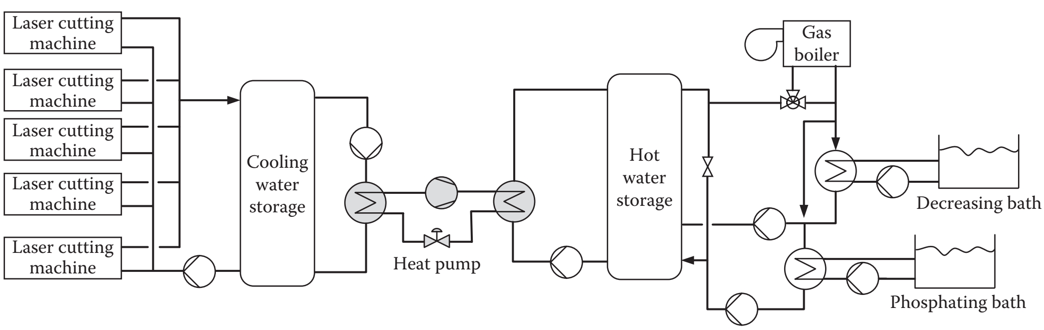

FIGURE 1.5 Subcritical mechanical vapor compression heating and cooling heat pump integrated in a metal processing plant in Germany. (From IEA, Industrial energy-related systems and technologies Annex 13, IEA Heat Pump Program Annex 35, Application of Industrial Heat Pumps, Final Report, Part 2, 2015b; redrawn and reprinted with permission from IEA HPT Annex 13/35 operating agent.)

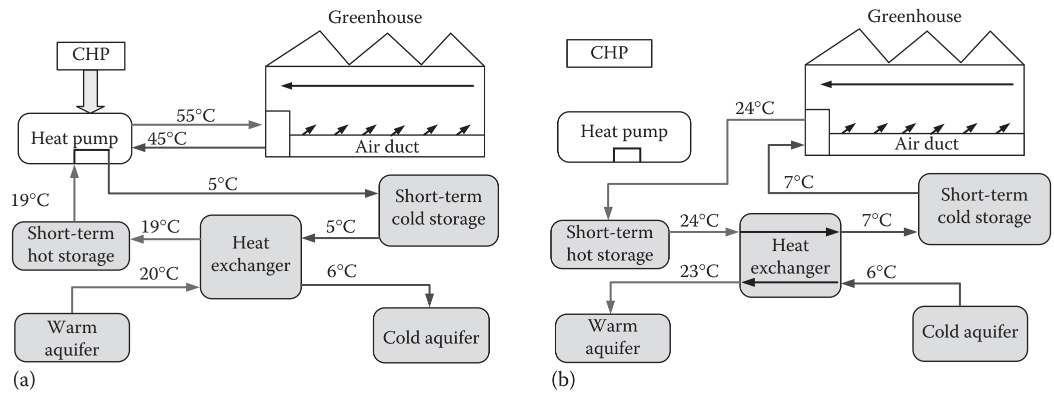

FIGURE 1.6 Mechanical vapor compression heat pump implemented in a commercial greenhouse in the Netherlands. (a) Winter heating mode and (b) summer cooling mode. CHP, combined heating and power plant. (From Raaphorst, M., Optimale teelt in de gesloten kas—Teeltkundig verslag van de gesloten kas bij Themato in 2004. http://www.hdc.org.uk/sites/default/files/research_papers/PC%20256%20final%20report%202007.pdf, 2005; IEA, Industrial energy-related systems and technologies Annex 13, IEA Heat Pump Program Annex 35, Application of Industrial Heat Pumps, Final Report, Part 2, 2015b; redrawn and reprinted with permission from IEA HPT Annex 13/35 operating agent.)

recovers heat from groundwater (240 m^3/h at 20°C) and delivers hot air to the greenhouse at temperatures up to 55°C (Figure 1.6a). Backup heating is provided by combined heat and power (CHP) gas-fired engines. In the summer cooling mode, the heat pump does not work and the excess heat is rejected to the groundwater (Figure 1.6b). The reported simple payback period was relatively high (14.9 years), but the energy cost savings were estimated at 29% and the reduction of CO_2 emissions, at between 40% and 60%. In addition, the system provided better temperature and humidity interior conditions, higher CO_2 concentrations inside the greenhouses, higher crop production (about 17% of annual increase) and quality, and reduced by 80% pesticide use (IEA 2015b).

Two subcritical mechanical vapor compression heat pumps with HFC-134a as the refrigerant have been installed in Japan for heat recovery within industrial cutting and washing processes (Figure 1.7). In conventional systems, the cutting water is cooled by a chiller up to 20°C, while the washing liquid is heated by electric or hot steam boilers to around 60°C. The implemented heat pumps eliminate both water chiller and electric heaters by recovering heat (30 kW) from the cutting

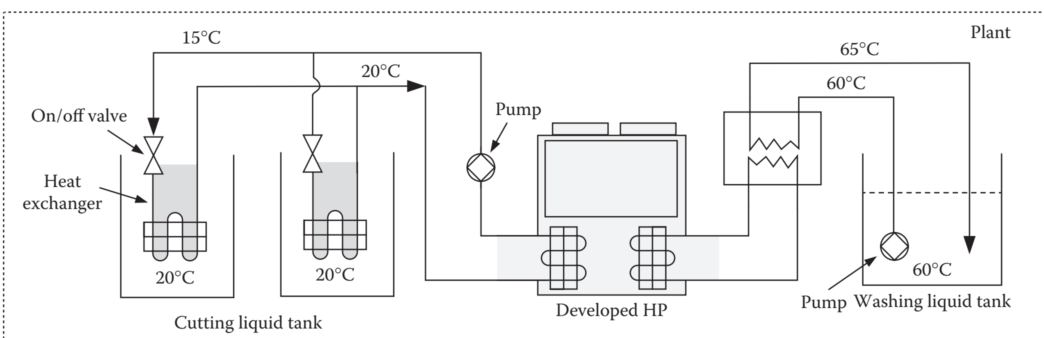

FIGURE 1.7 Subcritical mechanical vapor compression heat pump installed for industrial cutting and washing processes in Japan. (From IEA, Industrial energy-related systems and technologies Annex 13, IEA Heat Pump Program Annex 35, Application of Industrial Heat Pumps, Final Report, Part 2, 2015b; redrawn and reprinted with permission from IEA HPT Annex 13/35 operating agent.)

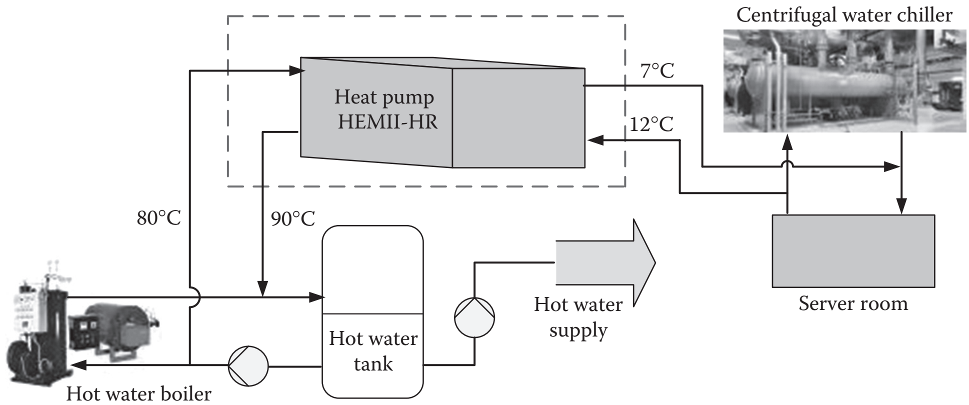

FIGURE 1.8 Subcritical mechanical vapor compression heat pump implemented in the server room of a Korean Internet Data Centre. (From IEA, Industrial energy-related systems and technologies Annex 13, IEA Heat Pump Program Annex 35, Application of Industrial Heat Pumps, Final Report, Part 2, 2015b; redrawn and reprinted with permission from IEA HPT Annex 13/35 operating agent.)

liquid to keep it at 20°C and, simultaneously, delivering heat (21.8 kW) at 60°C for heating the washing liquid. As a result, the system global COP, accounting for both simultaneous cooling and heating effects, was of about 5 (IEA 2015b).

An energy saving system using a subcritical mechanical vapor compression heat pump has been implemented to recover waste heat from water coming at 12°C from the cooling system of a server room in a Korean Internet data center (Figure 1.8). The heat pump supplies hot water at 90°C for industrial processes and cleaning (IEA 2015b).

A dual-energy source subcritical mechanical vapor compression heat pump has been developed for cold and very cold climates (Figure 1.9) (Minea 2011). In such climates, the heating performance of conventional air-source heat pumps sharply drops at outdoor temperatures below −8°C. As a result, conventional heat pumps use add-on electrical heaters installed in the duct work of forced hot air systems. They operate whenever additional heat is required and the heat pump is out of operation for significant periods of time during the winter. Moreover, when outdoor temperatures fall below −12°C, most electrical grids may achieve peak power demand loads at relatively high costs. Using fossil fuels as backup heating energy sources may raise issues such as insufficient space for incorporating the supplementary heaters inside residential buildings (Guilbeault 1987).

The new developed add-on concept integrates a fossil energy source (propane, oil, and natural gas) within the refrigeration circuit of an air-source heat pump (Figure 1.9). The indoor unit includes a variable speed compressor (C), a suction accumulator (SA), a four-way reversing valve (RV), a finned indoor coil with air blower, an expansion valve EXV2 with bypass and a check valve CV2. The outdoor cabinet contains a finned coil with air fan as well as expansion valve EXV1 with bypass and check valve CV1. An add-on cabinet, also located outdoor, includes a small gas-fired furnace with a compact combustion gas-to-refrigerant heat exchanger. It preheats, vaporizes, and superheats the refrigerant in the backup heating mode by using propane as a combustible. Two additional solenoid valves (SV1 and SV2) make it possible to bypass the outdoor coil and to supply low-pressure refrigerant liquid to the add-on heat exchanger via a capillary tube installed upstream of SV2. Finally, the check valve CV3 allows the refrigerant vapor leaving the add-on coil to bypass the four-way reversible valve and to flow, via the SA, to the compressor suction line in the backup heating mode.

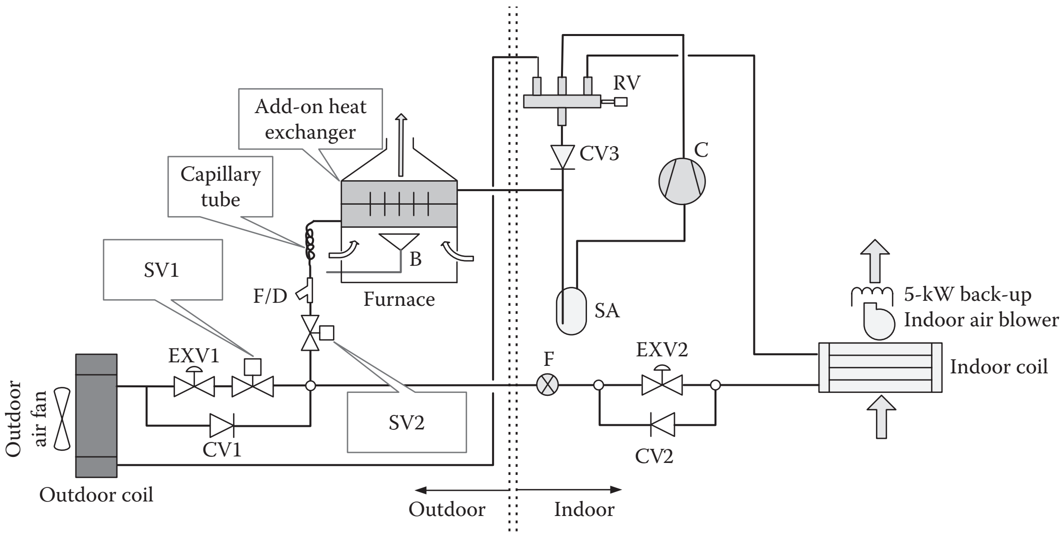

FIGURE 1.9 Schematic of the dual-energy source heat pump. B, burner; C, variable speed compressor; EXV, expansion valve; F, refrigerant flow meter; F/D, filter-drier; RV, 4-way reversible valve; SA, suction accumulator; SV, Solenoid valve. (From Minea, V., Dual-energy source heat pump, in *10th IEA Heat Pump Conference*, May 16–19, Tokyo, Japan, 2011; reprinted with permission from IEA HPP Centre.)

1.2.2 Subcritical Mechanical Vapor Compression Heat Pump-Assisted Dryers

Drying is an energy-intensive operation consuming between 9% and 25% of national energy of the developed countries (Mujumdar 1995). Such a process may consume up to 70% of the total energy in wood drying industry, 50% in the manufacturing of finished textile fabrics and over 60% from farm corn production (Mujumdar 1987). Consequently, improving the energy efficiency of drying equipment in order to reduce and/or recover a part of energy losses, mostly because of the moist air venting (representing about 85% of existing industrial dryers), is one of the most relevant objective of R&D activities throughout the world (Chua et al. 2002).

Among other methods aiming at reducing global energy consumption (electrical and fossil) in the drying industry there are heat pump-assisted dryers. These systems generally integrate air-to-air subcritical mechanical vapor compression heat pumps, acting as simultaneous dehumidifiers and heating devices, and slightly modified conventional drying enclosures (chambers). They recover sensible and latent heat by condensing moisture from a part of the hot and humid drying air and supply it back to the dryer by heating the same air stream. Such a process may accelerate the drying cycles, preserve the quality of dried products, and reduce the overall energy consumption.

1.2.2.1 Energy Efficiency

Energy performances of heat pumps used as dehumidification and heating devices in drying processes can be characterized by their COPs ($COP_{drying}^{heating}$) defined as the total heat supplied to the dryer by the heat pump's condenser (Q_{cond}) (kWh) divided by the compressor and blower electrical energy consumption ($E_{compr+blower}$) (kWh) during each drying cycle:

$$COP_{drying}^{heating} = \frac{Q_{cond}}{E_{compr+blower}} = \frac{Q_{evap} + E_{compr+blower}}{\dot{W}_{compr+blower} * \tau} \quad (1.9)$$

where:

$\dot{W}_{compr+blower}$ is the electrical power input of the heat pump compressor and blower (kW)
τ is the drying time