普通高等教育“十一五”国家级规划教材

Refrigeration Technology

（制冷技术）

Ze-Zhao Hua Hua Zhang Bao-Lin Liu Shen-Yi Wu
华泽钊 张 华 刘宝林 邬申义 编著

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内 容 简 介

本书为高等教育“十一五”国家级规划教材，是国内第一本有关制冷技术的英文教材。本书详细地阐述制冷的基本技术，介绍了近20多年来制冷技术的重要发展，也适当地介绍国内外制冷行业的动态。全书共13章，包括4个部分。第1部分主要介绍制冷的范畴、应用、发展历史和国内外的学术组织和刊物。第2部分系统叙述制冷原理，讨论制冷循环的热力学分析、使工质降温的基本方法(包括流体制冷工质和固体制冷工质)、气体制冷循环、机械驱动和热驱动的蒸汽压缩制冷循环、蒸汽压缩制冷的循环分析。第3部分详细介绍制冷用的工质，讨论了制冷循环对工质的要求，工质的物理、化学和制冷的特性；某些制冷工质破坏臭氧层和增强温室效应的机理和程度，新的环境友好的制冷工质；同时也介绍了湿空气学与空气处理过程。第4部分介绍蒸汽压缩制冷循环的主要部件和设备，包括压缩机、冷凝器、蒸发器和流量控制部件。

本书可作为制冷、动力、建筑空调等专业的英语教材，也可供制冷、空调、动力等公司、企业的技术人员参考。

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Preface

Refrigeration technology is closely linked with the national economy and people's lives. It is widely used in building air-conditioning, artificial environment, food refrigeration and freezing, cryobiology and cryomedicine, natural gas industry, iron and steel industry, aerospace etc.

Over the past 20 years, China's refrigeration industry has been developing rapidly. China has now become a major manufacturing country of refrigeration machinery (the exports of refrigeration and air-conditioning industry being ranked the first in the world). Some of the Chinese refrigeration enterprise groups, such as Bingshan Group, Moon Group, Haier, Gree, Xinfei, Hisense, Changhong, etc. have become world famous, with their products exported to many areas of the world. The international brand name refrigeration enterprises, like American Carrier and York, Japanese Daikin, Hitachi and Sanyo, Danish Danfoss, German Bitzer, etc. have one after another set up their manufacturing, marketing and R&D bases in China.

Accordingly, over the past 20 years, refrigeration specialty in China's universities has also been developed rapidly. There were only 10 universities with the authority to grant bachelor's degree of refrigeration in 1986, and the number had come up to about 100 in 2008. The number of universities granting master and doctor degrees of refrigeration had risen from 6 and 3 in 1986 to 50 and 20 in 2008, respectively. Several thousands of students graduating each year from these degree programs are working in the refrigeration field. As these graduates are expected to have a global vision as well as a comprehensive understanding of refrigeration concepts and methodologies in English.

In 1995, we compiled an English handout of "Principle and Technology of Refrigeration" so that our students could have English reading material and younger scientists and technicians could have an English reference book. In 2006, the Chinese Ministry of Education approved our application and included the book "Refrigeration Technology" in the list of National Higher Education "Eleventh Five-Year" State-level Planning Textbooks (Guide No. B080522).

Few textbooks from European and American universities are suitable for our teaching purposes in China, as they do not have refrigeration specialty in their education systems. There are two well written books of refrigeration. One is "Principles of Refrigeration" edited by W. B. Gosney (Cambridge University Press, London, UK, 1982); the other is "Refrigeration and Air Conditioning" (2nd edition) edited by W. F. Stoecker and J. W. Jones (McGraw-Hill Book Company, New York, USA, 1982). However, these two books were published some 26 years ago in 1982. The landscape of the field has since changed dramatically. First of all, environmental protection sets a challenging prerequisite to the refrigerant technology. The refrigerants of CFC and HCFC, which

had been widely used successfully for more than 50 years, were found decades ago to have the effect of undermining the ozone layer in stratosphere of earth atmosphere. In 1987, 24 countries signed the Montreal Protocol to phase out CFCs. Before the issue was settled, the Kyoto Protocol in 1997 brought up another issue - prevention of global warming, which requested that refrigerants should have very low greenhouse effect and refrigeration systems should greatly reduce energy consumption and CO_2 emission.

In the last 20 years, refrigeration technology has also had considerable development in other aspects. Gifford-McMahon refrigerator, pulse tube refrigerator and auto-cascade vapor compression mixture refrigerator have been extended to the cryogenic temperatures and achieved at a practical level; as thermo-electric refrigeration is concerned, some new materials having higher values of "the figure of merit" are being explored; thermal demagnetization and optical refrigeration, which were only used at very low temperature in the past, are now expected to be used for general purposes at room temperature; the emergence of many new designs of compressor, condenser and evaporator increases the efficiency of the refrigeration system, and reduces its energy consumption; the inverter driven compressor and the electronic expansion valve have made the refrigeration system operation more effective and enhanced its safety index.

Under the circumstances mentioned above, the present book is written to first of all elucidate the basic principles of refrigeration technology and also to address the overall situation of domestic and oversea refrigeration industries, together with the important development of refrigeration technology in recent years.

The book contains 4 parts and 13 chapters. Part 1, with Chapter 1 only, is the Introduction, which covers the scope and the applications of refrigeration, its historical development, and the relevant domestic and international academic organizations and publications. Part 2, with 5 chapters, concerns the principles of refrigeration, focusing on thermodynamic analysis of refrigeration cycle, the methods of decreasing temperature (including the fluid refrigerants and solid refrigerants), cycle analysis of vapor compression refrigeration. Part 3, including 3 chapters, discusses the working substances for refrigeration, including the requirements of refrigerants, the properties of refrigerants, environmental friendly refrigerants and also psychrometry and air handling processes. Part 4, with 4 chapters, is about the equipment for refrigeration cycles, including compressor, evaporator, condensing equipment and flow control devices.

Since English is not the authors' native language, a number of high-quality original materials, such as the two books mentioned above, were referenced to guide the writing process. All these materials, as well as other important literatures, were given as references at the end of each chapter. We make the special mention here in the hope of being understood and supported by those who read and use the book.

Ze-Zhao Hua Hua Zhang Bao-Lin Liu Shen-Yi Wu
August, 2008
in Shanghai University of Science and Technology

前　言

制冷技术与国民经济联系密切，与人民生活息息相关；在建筑空调、人工环境、食品冷冻和冷藏、低温生物和冷冻医疗、天然气工业、钢铁工业、航空航天以及科学技术的其他领域应用十分广泛。

近20年来，我国的制冷工业呈现了飞速发展的局面，我国已经成为世界上制冷机械的生产大国，制冷空调行业产值居世界第一。我国的一些制冷企业集团，如冰山、冰轮、海尔、格力、新飞、海信、长虹等已经成为世界知名企业，产品远销世界各地；国际名牌的制冷企业，如美国的开利、约克、特灵，日本的大金、日立、三洋，丹麦的Danfoss，德国的Bitzer等，纷纷在我国建立生产、销售或研发基地。

相应地，近20年来我国制冷专业的高等教育也获得了快速发展。具有制冷学士学位授予权的高校，从1986年的10多所，发展到2008年的100多所；具有制冷硕士学位授予权的高校，从1986年的6所，发展到50所；具有制冷博士学位授予权的高校，从1986年的3所，发展到20所。每年有数千名本科生和研究生从学校毕业投入这一行业工作，他们应当是具有全球视野、熟悉制冷专业英语知识的行业新兵。

为了让学生手头有本英文教材，让年轻科技人员有较合适的英文案头书，我们于1995年编写了英文版“制冷原理与技术”讲义，2002年编写了《制冷技术》（英文版）内部教材。2006年初，教育部将我们申报编著的*Refrigeration Technology*列入了普通高等教育“十一五”国家级规划教材（指南号：B080522）。此外，本教材在编写过程中还得到上海市重点学科项目（项目编号：S30503）和上海理工大学的大力支持。

由于教育体制的不同，欧美国家的多数大学没有设置制冷专业，因此适用于作教材或主要教学参考的英文书籍很少。曾经有两本英文版的有关制冷方面的书籍是写得很好、适合于作教材的。其中一本是英国剑桥大学出版社1982年出版、伦敦大学制冷工程教授W. B. Gosney撰写的*Principles of Refrigeration*（Cambridge University Press，London，UK，1982）；另一本是美国McGraw-Hill Book Company出版、美国伊利诺伊大学机械系教授W. F. Stoecker和J. W. Jones撰写的*Refrigeration and Air Conditioning*（Second edition）（McGraw-Hill Book Company，New York，USA，1982）。但这两本书都是在1982年出版的，迄今已有26年。在这20多年来情况发

生了巨大的变化。首先是环境保护对制冷剂提出了令人震惊的要求，如已经顺利地广泛使用了50多年的、最常用的工质CFC和HCFC被发现会破坏同温层中的臭氧层，1987年的蒙特利尔议定书规定要限期淘汰；此事未了，1997年的京都议定书又提出了防止全球变暖的问题，要求新制冷剂的温室效应很小，要求大大降低制冷系统的能耗和CO_2的排放。

在这20多年内，制冷技术的其他方面也有了长足的发展。G-M、脉管气体制冷机和自动复叠式混合工质制冷机已经扩展到低温的温区，并达到了实用阶段；在热电制冷方面，正在探索高性能指数的材料；过去只能用于极低温度的磁制冷和光制冷，现在有望用于一般常温的场合；许多新型压缩机、冷凝器和蒸发器的设计使制冷系统效率提高，能耗降低；变频电机技术的成功及推广、电子膨胀阀部分地替代热力膨胀阀，使制冷系统运行更加安全有效等。

基于上述的这些情况，我们编著了这本书，希望在讲清制冷技术基本原理的前提下，适当地反映近年来制冷技术的重要发展，同时也介绍国内外制冷行业的动态。全书共13章，包括4个部分。第1部分，即第1章引言，介绍制冷的范畴、应用、发展历史以及国内外的学术组织和刊物。第2部分为制冷原理（共5章），分别讨论制冷循环的热力学分析、使工质降温的基本方法（包括流体制冷工质和固体制冷工质）、气体制冷循环、机械驱动和热驱动的蒸汽压缩制冷循环、蒸汽压缩制冷的循环分析。第3部分为制冷用的工质（共3章），分别介绍：制冷循环对工质的要求，工质的物理、化学和制冷的特性；某些制冷工质破坏臭氧层和增强温室效应的机理和程度，新的环境友好的制冷工质；湿空气学与空气处理过程。第4部分为蒸汽压缩制冷循环的主要部件和设备（共4章），分别对压缩机、冷凝器、蒸发器和流量控制部件进行了讨论和分析。

本书的编写分工为：华泽钊执笔第1～4章和第7～9章；张华执笔第5、6章和13章；刘宝林执笔第10、11章和12章。本书的主审是现在英国诺丁汉大学建筑环境学院任教的邬申义博士。他在该校担任制冷技术课程的教授，有丰富的教学经验，对此项工作也非常热心和仔细，对本书的专业和英语水平的提高，作出了积极的贡献。上海理工大学的研究生李蒙、刘美静、尹航、石巧慧、戎森杰、郝保同、谭月普、苏东桃等参加了本书部分工作。

还有两个情况需要说明：为力保此书的文字质量，我们在编写时参考了一些英语写作质量高的材料，如前面提到的1982年分别在英国和美国出版的两本书，以及其他的许多材料，凡参考引用处我们都作了标注，希望得到有关方面的理解和支持；另外，近20年来，国内的一些企业、研究所和大

学在制冷技术方面做了大量创新的工作，取得了卓越的成就，本书并未将这些内容全收罗进来，只是选取其中有关技术基础的少数部分，这是因为本书主要是用作大学教材，只能讲述一些重要的、具有基础性的专业内容，因此希望得到国内同行的理解和支持。

华泽钊 张华 刘宝林 邬申义

2008年8月

于上海理工大学

作者简介

华泽钊：1962年清华大学热能工程专业本科毕业；1965年清华大学工程热物理专业研究生毕业。随后到上海理工大学任教。1968年开始制冷与低温的教学和研究，1980～1983年在美国麻省理工大学做博士后研究；1986年被国务院学位委员会批准为我国首批低温与制冷博士点导师；2003年被评为首届国家级教学名师。

张华：1989年上海理工大学制冷专业本科毕业，1989～1996年在西安交通大学攻读制冷专业硕士和博士学位。1999年在上海理工大学完成博士后研究后在该校任教，为本科生和研究生讲授制冷原理和制冷压缩机等课程。2002年被评为教授，2006年被聘为制冷及低温工程专业博士生导师。

刘宝林：1990年山东工业大学热能动力工程本科毕业；1993年山东工业大学工程热物理专业研究生毕业；1996年获得上海理工大学制冷与低温工程博士学位，并开始制冷与低温的教学和研究。2001～2004年在美国密西根州立大学和亚利桑那大学做博士后研究；2006年被批准为低温与制冷博士点导师。

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Part II The Principles of Refrigeration

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Part I Introduction

Chapter 1 Introduction to Refrigeration

1-1 A Sample of Refrigeration System——Split Room Air Conditioner

A residential air conditioning system is used here to explain the basics of refrigeration. Residential air conditioning systems, whether window unit, split unit or central system, are considered to be high-temperature refrigeration, and is used for comfort cooling.

If the outside air temperature is about 35℃ in the summer, and the room temperature is to be maintained at about 26℃, the heat flows naturally from the warm outside environment into the room. An air conditioning system, a kind of refrigeration systems, is used to pump heat from the inside to the outside of the house. This takes energy that has to be supplied.

Fig. 1-1 is a diagrammatic sketch of a split air conditioner, which comprises two units: an outdoor unit and an indoor unit, which are placed outside and inside the building respectively. They are connected to each other by means of small copper tubing.

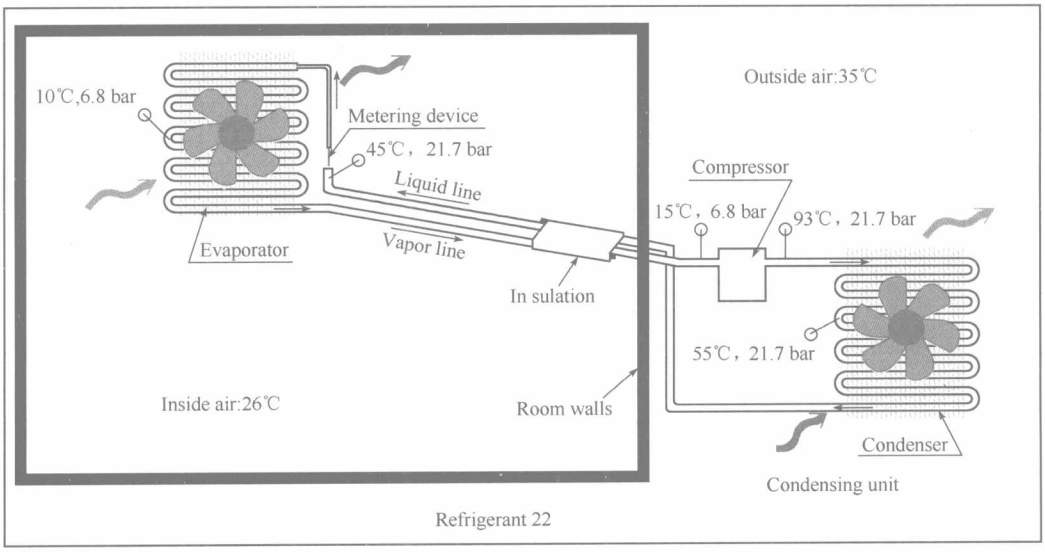

Fig. 1-1 Cooling room air by a split air conditioner

The outdoor unit, which is also called condensing unit, consists of a compressor and

a condenser. The indoor unit is an evaporator, which is installed on the wall in the room to be cooled.

There are 4 main components in the spilt refrigeration system: a compressor, a condenser, a metering device (throttling device, decreasing temperature device), and an evaporator. Any components beyond them are called accessories.

The working media inside the refrigeration system is called refrigerant. Suppose the refrigerant R22 is used here in the split air conditioner, and the vaporizing temperature of R22 is 10℃ and 55℃ at pressure 6. 8bar and 21. 7bar respectively.

The compressor is a vapor compression device which uses pistons or some other parts to compress the refrigerant R22 vapor from 6. 8bar and 21. 7bar, and send it to the condenser. The compressed vapor is superheat, the temperature which is about 93℃, higher than its saturation temperature 55℃.

The condenser is a heat exchanger which removes heat from the hot compressed refrigerant vapor and allows it to condense into liquid. The outside air being sucked through the condenser coil and fins is at 35℃, and the heat of superheated refrigerant vapor will be rejected into the outside air stream.

The liquid refrigerant from the condenser is then routed to the metering device, which is a capillary tube in the split air conditioner. The capillary tube is a copper tube with a very small calibrated inside diameter, which restricts the refrigerant flow. And the pressure of refrigerant drops from 21. 7 to 6. 8bar.

The evaporator is a heat exchanger which removes heat from the warmer room air to the refrigerant and allows the refrigerant to evaporate into vapor. The refrigerant R22 will evaporate at 6. 8bar and 10℃ inside tube of the evaporator. The room air of 26℃ is sucked through the evaporator coil and fins, which is cooled by the evaporating refrigerant vapor through the fins of the evaporator.

The refrigerant is then routed back to the compressor to complete the cycle. The refrigerant is used over and over again absorbing heat from the inside and rejecting heat to the outside of house.

1-2 Definition and Scope of Refrigeration

1. Definition of refrigeration

Literally, the word "refrigerate" is *to make or keep cool or cold; to preserve food, biologicals, etc. by keeping cold and freezing*, as defined in *Webster's New World Dictionary*.

Scientifically, there are several similar definitions of "refrigeration", such as the follows:

"Refrigeration"*is used to maintain a chamber at a lower temperature than those of its surroundings* (in *The Penguin Dictionary of Physics*).

According to ASRE (American Society of Refrigeration Engineering), refrigeration is defined as *the science of providing and maintaining temperatures below that of surroundings*.

The science and art of refrigeration is concerned with the cooling of bodies or fluid to temperatures lower than those available in the surroundings at a particular time and place, as written by W. B. Gosney[1].

Refrigeration may also be defined as *the artificial withdrawal of heat, producing in a substance or within a space a temperature lower than that which would exist under the natural influence of surroundings*.

2. Refrigeration and heat pump

The places, where surroundings are at the temperatures lower than the required condition, have to be heated up. The similar machinery as refrigerator which performs the heating process is called a *heat pump*. The main difference between the refrigeration system and heat pump system can be physically conceived of from the fact that in the former there is pumping of heat out of the system into the surrounding as against pumping of a heat from surrounding into the system in the latter case. Thus a refrigeration system can be used as a heat pump, just by reversing the direction of operation as shown in Fig. 1-2.

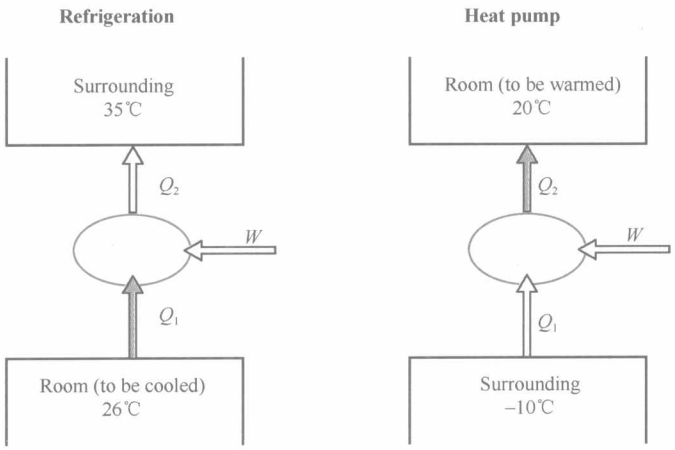

Fig. 1-2 Refrigeration and heat pump

In *Dictionary of Physics*, heat pump is defined as a device for heating building, in the form of a heat engine driven in reverse. Refrigeration is also defined as a form of heat pump.

As early as 1852, Lord Kelvin (Thomson) pointed out that the refrigerator can be used as a heat machine. If one places the evaporator of a split air conditioner out of doors and the condenser inside a building, the heat discharged into the building is greater than the work supplied to drive the machine.

3. Refrigeration and air conditioning

The definition of comfort air conditioning is "*the process of treating air to control simultaneously its temperature, humidity, cleanliness, and distribution to meet the comfort requirements of the occupants of the conditioned space*"[2].

Refrigeration can offer cooling, dehumidifying, and also heating (by heat pump) for air conditioning. Refrigeration has also many other applications than air conditioning, as shown in Fig. 1-3.

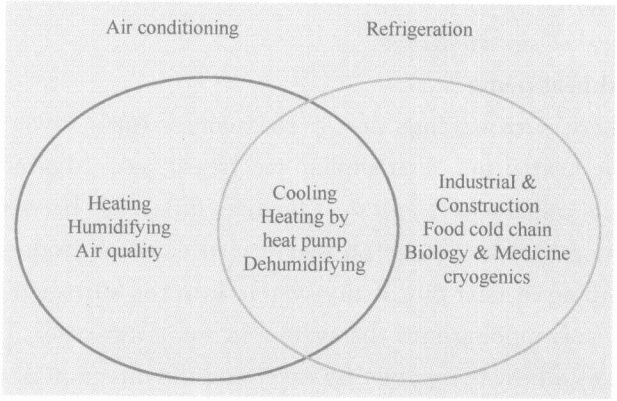

Fig. 1-3 Relationship of the refrigeration and the air conditioning fields

4. Refrigeration and cryogenics

In principle, refrigeration is concerned with all the temperature regions below the surroundings, down to absolute zero degree 0K.

The word "Cryo" from Greek, "kryos", means cold, frost. The Greek word "genos" means origin or creation. And "Cryogenics" is a branch of science and technology that deal with the production of very low temperatures and their effect on the properties of matter.

"Very low temperature" has different meaning for different things and situations. For example, for the weather service, $-30℃$ is very low temperature; while, for the physicists it means temperature close to 0K, at which the temperature has significant effect on the properties of substances.

Nevertheless, there is some agreement that cryogenics is concerned with temperatures below about 120K, approximately, which is a little above the normal boiling point of liquefied natural gas. The concept was adopted at the 13rd Congress of the International Institute of Refrigeration.

Today, the scope of cryogenics covers cryogenic engineering, low temperature physics, cryoelectronics, cryobiology, cryomedicine and others.

1-3 Main Applications of Refrigeration

Refrigeration has applications embracing a huge range of fields we all encounter in

our daily life, particularly in the food, health and indoor environment fields. Refrigeration plays an essential role in sustainable development.

For convenience of study, refrigeration applications may mainly be grouped into several general categories: ①comfort air conditioning, ②industrial air conditioning, ③food preservation and food cold chain, ④industrial and construction process, ⑤air liquefaction and separation, ⑥cryomedicine and cryobiology, ⑦rocket propellant and cryo-electronics, ⑧superconductivity and low temperature physics.

1. Comfort air conditioning

Comfort air conditioning applies not only in domestic, office, and commercial building, but also in automobile, train, ship, and airplane. Comfort air conditioning is one of the largest applications of refrigeration.

There are mainly three kinds of air conditioners (AC) for domestic, office, and commercial building: window air conditioner, split system air conditioner and central air conditioning system. The last one is also called "Chilled-water and Cooling-tower AC unit".

(1) Window air conditioner

A window air conditioner serves as a complete air conditioner in a small space. The unit is made small enough to fit into a standard window frame.

It contains a fan and a blower fixed in the same motor shaft as shown in Fig. 1-4. The blower blows the room air over the evaporator coil, and the fan blows the outside air over the condenser coil in the summer.

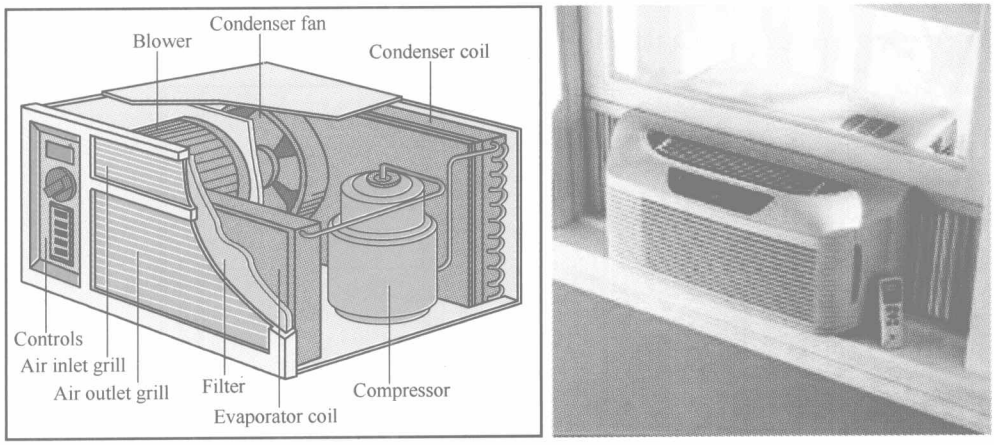

Fig. 1-4 Window air conditioner

(http://home.howstuffworks.com/ac.htm; http://www.nextag.com/window-air-conditioner/search-htm)

(2) Split-system air conditioner

A split-system air conditioner splits the system into two parts, evaporator unit and condensing unit, which are set up inside and outside of the building respectively.

Fig. 1-1 is a type of split-system air conditioner which is widely used in China, and