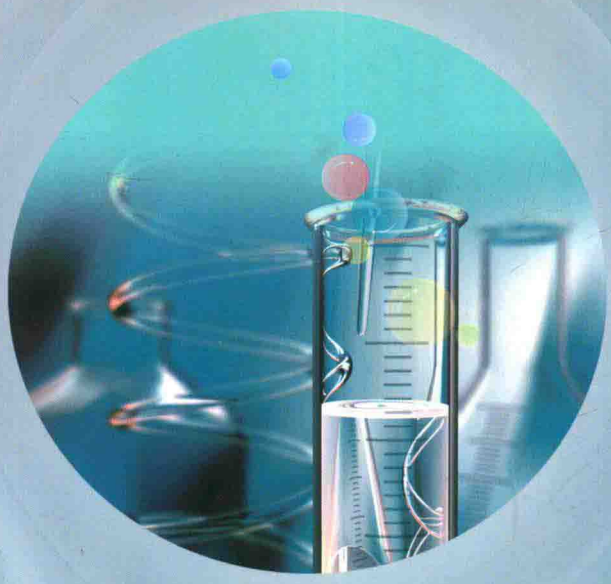
国家级精品课程教材

Experiment of Chemical Engineering Principle

化工原理实验

钟 理 主编



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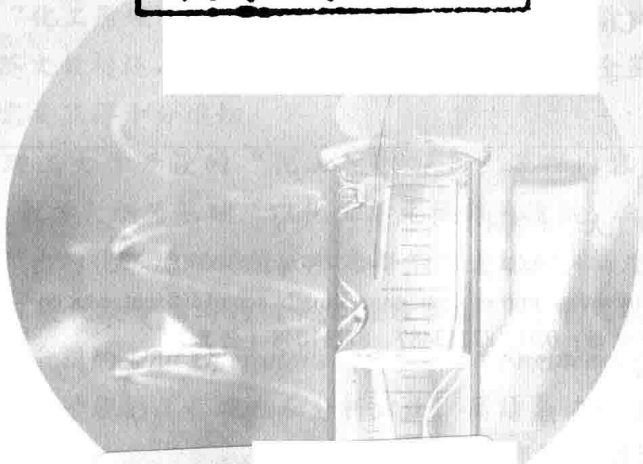

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内容提要

本书是为适应教育部在全国高校深化教学改革，使我国高等教育与国际接轨，在高校开展全英教学的背景下编写而成的。本书以化工单元操作过程实践性课程——化工原理实验为背景，参考美国的教科书 *Unit Operations of Chemical Engineering* 以及我国面向21世纪的教材《化工原理》，并结合我国国情，基于教育部本科生“化工原理实验”教学大纲及课程内容要求编写。教材编写过程强调理论与实际及工程观相结合，注重知识综合运用，全书既包括常规验证性实验，如雷诺实验、流体机械能转换实验等，又增添一些演示实验，如电除尘实验、旋风分离实验等，力求覆盖化工类单元操作实验基本原理、基本设备、测试仪表和方法等。每个实验后附有一些思考题，供学生实验过程中及撰写实验报告时思考。本书是国内首部用英文编写的化工原理实验教材，适合作为高等院校化工、食品、环境、制药、化工机械、生物化工、高分子材料、应用化学、冶金等相关专业的本科全英化工原理实验教材，也可作为化工及相关领域科技人员的参考用书。

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前　言

“化工原理实验”是化学工程学科最重要的核心课程之一，化工原理的工程实践教学已有近1个世纪的历史。1923年，美国麻省工学院教授W. H. 华克尔等出版了第一部关于化工单元操作的著作*Principle of Chemical Engineering*，化工原理是以该书的理论为基础发展起来的，化工原理实验作为其配套的工程实践性课程，具有很强的工程实践性。随着20世纪70年代化学工程学与其他学科的交叉渗透，出现了许多新的学科，涉及单元操作的化工原理课程与其他学科如生物工程、食品工程、材料科学与工程、制药工程、环境工程、能源工程、精细化工及应用化学等领域相互重叠，成为大化工类最重要的学科基础课程之一。为了适应21世纪高级化工技术人才的培养，本书根据化工类专业人才培养方案和教学内容体系要求以及不同学科发展需要编写而成，在编写过程中力求覆盖单元操作的基本实验原理、实验方法、实验装置、测试仪表等，注重理论与工程实际相联系。教材内容满足教育部本科生“化工原理实验”教学大纲要求。

当前，我国高等教育与国际接轨，采用英文教材、开展全英教学是高等教育改革趋势，也是质量工程建设的重要内容。华南理工大学从1996年开展“化工原理”双语和全英语教学以来，已编（改）写出版了英文版的“化工原理”理论教学用书，然而，作为“化工原理”教学过程中最重要的实践性环节及教学内容——化工原理实验，国内英文教材还是空白，编写《化工原理实验》全英教材，以适应化工原理全英语教学需要显得十分迫切。

本书以华南理工大学开设的“化工原理实验”课程内容和教育部高等学校“化工原理实验”教学大纲为基础，以化工单元操作为主线，结合华南理工大学化工类本科生多年开出的化工原理实验，参考与借鉴老健正、梅慈云编著的《化工原理实验指导》和伍钦教授等编写的《化工原理实验》等中文教材，以及美国大学化工类本科生广泛采用的*Unit Operations of Chemical Engineering*一书进行编写。编写过程力求突出实验过程的工程观点和分析方法，简洁易读，便于学生的学习。在每个实验后面附有一定的思考题，供学生开展实验、撰写实验报告时思考和解答。针对科技英文教材难点，对某些英文专业词汇给出中文解释；对一些较难的句子，给出相应的注释（Notes），以便于学生阅读和理解。本书内容与结构基于华南理工大学“化工原理实验”教学大纲，分为“化工原理实验Ⅰ”和“化工原理实验Ⅱ”两部分，“化工原理实验Ⅰ”与“流体力学与传热”理论教学相配套，“化工原理

实验Ⅱ”与“传质与分离工程”理论教学相匹配。它们主要包括如雷诺实验、流体机械能转换实验、管道阻力实验、离心泵实验、过滤实验、传热实验、蒸馏实验、吸收实验和干燥实验等化工原理验证性实验。为了增加学生的感性认识，增设了一些演示实验，如电除尘、旋风分离器分离气固混合物、边界层演示实验等。本书附录附有化工原理实验常用的物性数据以及单位换算等，供学生撰写实验报告时查阅。

本书可作为化学工程、石油化工、生物工程、食品工程、环境工程、制药工程、材料、纺织、冶金、化工装备及控制工程、应用化学、精细化工、轻工造纸等学科的化工原理实验全英教材，也可供从事化学工程及相关领域教学、科研、设计和生产单位的工程技术人员参考。

本书在编写过程中得到了华南理工大学教务处及华南理工大学出版社的大力支持，谨在此表示衷心感谢。

鉴于编者水平所限，书中难免存在疏漏与不足，希望读者不吝指正，使本教材在使用过程中不断得到改进和完善。

编　者

2016 年 5 月

Contents

Chapter 1

Introduction to Basic Knowledge of Experiments

Figure 1-1 shows the photo of oil-refinery's model, which covers different unit operations and devices of chemical engineering, such as fluid transportation and measurement attained by pipelines, pumps, blowers or flow rate meters, heat transfer achieved by exchangers, mass transfer realized by tower equipment as well as drying accomplished by dryers. Any chemical engineering plant can consist of various unit operations and equipment. Experiments of chemical engineering principle let students know, understand and study the basic principle, method and process of each unit operation and equipment so as to foster and develop engineering views and practice capacity of students through experiments.

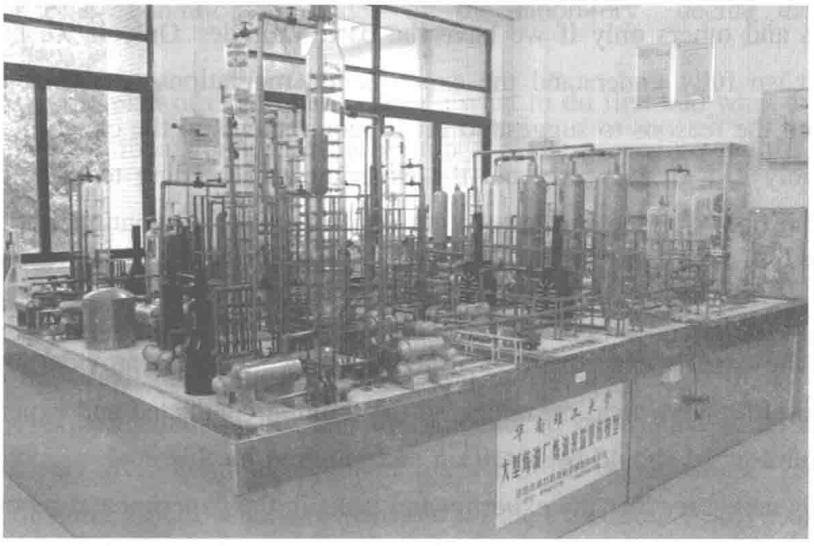

Fig. 1-1 Photo of oil-refinery's model.

Ⅰ. Basic Attitude to Carry Out the Scientific Experiments

When the experiments of chemical engineering or other scientific experiments are carried out, the staff and operators in the lab at first need to have one essential attitude—seeking truth from facts.

"Seeking truth from facts" we say here is that the phenomena, data and laws

observed in the experiments are honestly recorded, and they are treated as firsthand materials or information. Scientific inference or deduction must be based on the phenomena, data, laws observed in the experiments, and scientific theories and conclusions are examined by the experimental data. Therefore, the data and information recorded should be those actually observed and never be those edited (编造), revised (修改) or misrepresented (歪曲) in any reasons. For example, a datum is 100 which is based on the theoretic calculation, but it is 90 measured actually in the experiments. How to do? Value 90 should be recorded at first, then the reasons have to be found out. No other data could be used perfunctorily (敷衍地) to replace it.

The phenomenon, data, law observed in the experiments directly may be not accurate, and may be wrong sometimes, but whether these are correct or not can only be checked by doing the experiments repeatedly. We can never change or cancel any datum or record because it is different from those in the books or it is not in agreement with the result calculated based on theory. It is severe to treat the experimental observation; it is never casual (随便地) to record some datum or perfunctory to change it.

We emphasize the point that experiments can provide the useful and significant data for ourselves and others only if we have the basic attitude. Only if we have this basic attitude, can we fully understand the experimental regulations of chemical engineering principle, and the reasons to suggest so many requirements to the experimental research; can we actively (主动地) carry out the experiments according to these requirements, and obtain the right training to improve our experimental skill continuously.

Ⅱ. Basic Knowledge to Conduct Experiments

All steps in the experiments are for a primary aim which is to provide an experimental report with useful or practical meaning, so the training conducted and experimental basic knowledge introduced should be based on and required by this goal.

So, it is necessary that the experimental tasks in the experimental report, the results observed in the experiment are described by the chart, formula, word. The discussion results are showed tersely (简练地) and clearly to make the readers to be absolutely clear. In addition, the following requirements must be complied with:

- The data must be reliable, the data should be recorded seriously.
- It is responsible for the experiments, the preparation should be made well before the experiments and it is concentrated to do the experiments.
- The experimental plans should be thought of severely and explained honestly for readers to check whether they are reasonable or not.
- The experimental record should be possibly checked and the experimental date,

place, condition and relevant persons should be described clearly.

In order to make a qualified report, each step, problem and concrete (具体) requirement in the experimental process are proposed as follows.

1. Preparation for experiments

(1) Read the textbook, and know the goal and requirements of the experiments.

(2) According to specific requirements (具体要求) of the experiment, study the operations and theoretical foundations (理论基础) of the experiment, analyze what kinds of data should be measured and estimate the variable regularity (变化规律) of the data.

(3) Go to the scene (现场) to see the process of the equipment, the structure of main equipment, and the variety of the meters as well as the place of their installation, check whether the equipment is suitable for the experiment, and try to know the start method and application of the equipment (but it is not started and operated without permission, in case of the damage of equipment and other accident happening).

(4) According to experimental tasks and the scenic conditions (现场状况) of equipment or other conditions provided by the laboratory, decide the data to be measured.

(5) Make the plan of experiment, decide what to do first and what to do next, and understand the operational condition, the startup (启动) procedure and the adjustment of the equipment.

2. Organization of experiments

The experiments in this course are finished by the cooperation of a couple of students, so the organization must be done well during the period of experiments. To guarantee the experimental quality and the students to be trained at all aspects, there should be not only division but also cooperation within the organization. There is a leader in each experimental group, who is responsible for the execution (执行) of experimental plan, and for contact and command of each person in this group. The experimental plan should be discussed in the group to make everyone know, to make every member be in charge of particular work (including to operate the experiment, record the experimental data and observe phenomena and so on), and take turns (轮换) at right time [the turns cannot be taken in the experiment for high operation requirement (高操作要求), and the training can be conducted in exercise (演习中)].

3. Measurement of the experimental data

(1) The data which will affect the experimental results or will be needed in the

process of data should be measured, including the condition of atmosphere, the relevant sizes of the equipment, material properties and operation data.

(2) Not all the data need to be measured directly. Some data can be deduced by other data or found in the handbooks, so there is no need to measure them. For instance, to get the viscosity and density of water, only the temperature needs to be measured, and the viscosity and density can be found in the handbooks according to the temperature.

4. Read the data and record

(1) Make the recording form in advance before the experiments (the whole recording form is listed for recording just some datum). The name, the symbol and unit of every physical quantity should be recorded in the form. Every student should have an experimental notebook and not a piece of paper to record the data in order to guarantee that the data are complete and that proper presentation (条理) is clear in case of confusion.

(2) The experimental data must not be started to read until the phenomenon is stable during the period of experiments. When the experimental conditions change, operators should wait for a moment and then read the data since it takes some time to be stable (some experiments may need to take a long time to be stable), and the meters generally is held back (滞后). Do not measure data at once when the experimental conditions change. If such data are used to make a report, the conclusion is not reliable.

(3) Read the data twice at least under the same conditions. Only if the two data are almost the same, can the operation conditions be changed so as to observe the experiment and to read data under another condition.

(4) Every datum should be rechecked when it is recorded, in case that a wrong datum is read and recorded.

(5) The record of data should reflect really the accuracy of meters. In general, the next number behind the minimum scale (最小分度) of meter needs to be recorded. For example, the minimum scale of thermometer (温度计) is 1℃ and if the temperature is 24.6℃ at that time (当时), 25℃ cannot be recorded. If the temperature is exactly 25℃, 25.0℃ should be recorded and 25℃ should not be recorded because there exists the accuracy (精确度). The last number (末位数字) in recording data is evaluated (估计). If 25℃ is recorded, it represents that the temperature may be 24℃ or 26℃, or its error is ±1℃. 25.0℃ represents the temperature is between 24.9℃ and 25.1℃ at that time, and its error is ±0.1℃. But 24.58℃ cannot be recorded by the above thermometer because it is beyond the accuracy of the thermometer.

(6) The record of data should be based on the actual ones in the experiments. For

instance, the required (规定) temperature of water is 50.0℃, while the actual temperature of water is 50.5℃ during the period of reading it, 50.5℃ should be recorded. If the datum is stable and is not changeable, it should be recorded as usual instead of leaving blanks. If some data fail to record (漏记录), the relevant space (相应的空格) should be left.

(7) If abnormal phenomena and conditions happen or some evident errors occur in the experiments, they should be marked in the remarks column (备注栏).

5. Notices during the period of experiments

It is wrong that some students just record the data and ignore other things in the experiments. In addition to recording data during the period of experiment, the following should also be noted.

(1) The students who are in charge of the operation must watch out for (密切注意) the change of the meters and adjust them at any time to ensure that the whole process is going in the required condition so as to decrease the difference between the operational and required conditions of experiments as much as possible. What is more, the students who are in charge of the operation cannot leave without notice.

(2) After reading the data, operators should compare them with the previous data, and also compare them with other relative data, and analyze whether the data are reasonable or not. Once finding out that something is not reasonable, operators should have a discussion with the others in the group to find the cause, and work out what is wrong, which comes from operators' knowledge or from the measurement of data, so as to find and solve the problems in time (及时).

(3) The phenomena in the experiments need to be observed carefully, especially some irregular phenomena, operators should cherish (抓紧) time to study why they occur.

6. Processing of experimental data

(1) Under the same condition, if there are several stable data which fluctuate a little bit (有点波动), operators should take their average and then process the data. It is not necessary to take their average after individual process (逐个处理) for saving time.

(2) When the data are processed, some data which are not meaningful should be given away (舍弃) according to the rule of significant digits (有效数字). The accuracy of data is determined by the accuracy of the measuring meters, and it cannot be increased due to the increase of digit place (位数) during the period of calculation, but decreasing digit place arbitrarily (任意地) is not allowed because it reduces the original

accuracy of the data.

(3) During the period of processing data, if the process is too complicated and there are too many experimental data, the form list (列表) is generally used and the same project is processed together. This processing way is not only simple but also time-saving.

(4) It is necessary that a group of data can be used as an example to list the calculative process so as to check.

(5) During the period of processing data, the sum up of constants (常数归纳) can be used to induce all constants in the formula (将计算公式中所有常数归纳) and treat them as a constant. For example, Re of fixed pipe is calculated when the flow velocity changes, since, $Re = \frac{du\rho}{\mu}$, $u = \frac{V}{\frac{\pi}{4}d^2}$, then $Re = \frac{4\rho V}{\pi d\mu}$, and d, ρ and μ do not change in the experiment, so they can be treat as a constant. Let $B = \frac{4\rho}{\pi d\mu}$, then $Re = BV$. First B value is found in calculation, and then V value is inserted, finally Re can be found. In this way the speed of calculation can be greatly increased.

7. Writting of experimental report

A good report must be written simply and clearly, so it is required that the data are complete, the explanation is clear and the conclusion is correct. There are discussion and analysis in the report, and the formulas (公式) and graphs (图) obtained are in the well-defined condition. It is not required that the pattern and style of report are all the same but it should generally include the following:

(1) Title of report (it is needed to be simple and clear).

(2) Name of reporter and the partners.

(3) Task of experiment.

(4) Principle of experiment.

(5) The explanation of the equipment [including the picture of the flow process (流程) and the kinds and specifications (规格) of main equipment and meters].

(6) Record of experimental data (including the recording table of original data you read directly and the recording table after processing and calculating).

(7) Processing of data and example for the calculation. A group of data (note where they are from) are quoted (引用) and the process of calculation for this group of data is listed as calculation example.

(8) Experimental results. A conclusion of this experiment is suggested clearly and definitely (明确地) according to the experimental task. It can be expressed by graphs,

empirical equation (经验公式), or listing table (列表), and the experimental conditions should be indicated for all of those.

(9) Analysis and discussion. The experimental results are estimated and evaluated, the error and its reason are analyzed, and the problems found in the experiment should be discussed. Improvement and suggestion of experimental methods and equipment may be written and incorporated (归并) into this part.

(10) Answer the thinkable questions (思考题).

Ⅲ. Analysis of Experimental Error and Processing of Data

There always exists some difference between the data of experimental measurement and actual data due to different reasons [even though the instrument (仪器) is quite accurate, just the approximate values (近似值) can be measured]. This difference in values represents the error. For estimation and analysis of measurement error, it is significant for evaluating the experimental results and the design plan, and it is what we should master skillfully.

basic concepts of measurement error

1. Accurate value and average value

A physical quantity of any object to be measured (被测量对象) always has a definite objective accurate value (一定的客观真实值)—accurate value (真值), but the accurate value cannot usually be measured directly. The definition of accurate value is given in the field of experimental science: the average of infinite (无限的) observable values is called accurate value. Because the times of experimental measurement are limited, the average of definite observation values is close to the accurate value, which is called the optimal value (最佳值). The indicating value coming from the more advanced instrument (高一级仪表) is used as accurate value during the period of experiment.

2. Absolute error and relative error

(1) Absolute error: when the measured value x is minus the accurate value A, the remainder (余量) obtained, Δx, is absolute error. That is

$$\Delta x = x - A \tag{1-1}$$

(2) Relative error: it is defined as the accuracy judging some measured value, the relative error δ is used to express it as follows:

$$\delta = \frac{\Delta x}{x} \times 100\% \tag{1-2}$$

3. Characteristics and classification of error

(1) The systematic error: It is referred to the error caused by unfound (未被发现) factors during the period of the measurement or experimental process. The influenced results of these factors always deviate in the one direction. Their amount and symbol (大小和符号) are completely the same in the same group of experiments. They change according to a fixed law as the conditions change. For example, the zero place (零位) of mercurial thermometer is 0.2℃ higher than usual, if the thermometer is used to measure the temperature many times, the reading data will be 0.2℃ higher than usual every time.

(2) Stochastic (随机的) error or chance error (偶然误差): It is referred to the error when the same amount is measured under the same condition, the absolute values are variable, sometimes big or small, without the fixed law and are unpredicted (无法预测), but they have compensable (抵偿性) error. If some amount is accurately measured for a lot of times, it is found that the stochastic error completely obeys the statistical laws, the error amount (大小), positive or negative, is totally determined by the probability. Hence, as the times of measurement increase, the arithmetic mean (算术平均值) of stochastic error approaches to zero. Therefore, the arithmetic mean of many measurements will be close to the accurate value.

(3) Fault error (过失误差) or careless error (粗差): It is caused by the operational mistake and it often seems that the error is very great. It can be avoided only through careful operation since the fault error is often caused by operators. Hence, this kind of error should be deleted in the data processing.

Processing of experimental data

1. Concepts of significant digits

During the period of measuring or processing experimental data, it is important to use several significant digits to express the experimental result. It is wrong to think the more digits after decimal point (小数点) are, the more accuracy is, or the more digit places kept by calculation results are, the more accuracy is. The digit places taken by measurement should correctly reflect the available accuracy (可能达到的精度) of the meters used and the measurement methods.

When the measured value is recorded, one estimated digit should generally be kept. For instance, the reading of differential manometer (微压差计) is 125.7 mmHg*, the

* 1mmHg = 133.32Pa, the same below.

front three digits (前三位数) 125 is accurately known, and 0.7 is estimated. In order to clearly express the accuracy of data and to easily carry out calculation, the data read can be written as index number (指数). The decimal point is added after the first significant digit, the level of digit value is determined by 10 power (10 的幂次方). For example, 125.7mmHg was read just now, it can be recorded as (1.257×10^2) mmHg. It represents 4 significant digits. In the meantime, even though last place of significant digits (有效数字末位) is zero, it must be recorded. For instance, the reading of differential manometer is exactly 125.0 mmH_2O*, it can be recorded as (1.250×10^2) mmH_2O.

If some value or datum is not directly measured, that is, the value or datum must come from the intermediate calculation, the calculation can be conducted based on the calculation law of significant digits.

(1) Calculation of addition (加法运算): In all digits, the digit which has the least places of decimal (小数位数最少) is used as standard, and other digits have one more place than this.

For example: $60.4 + 2.02 + 0.222 + 0.0467 \rightarrow 60.4 + 2.02 + 0.22 + 0.05 = 62.69$.

(2) Calculation of subtraction (减法运算): The process of significant digits is the same as operation of addition when the difference between subtraction digits (相减的数) is great. If the difference between subtraction digits is close, some significant digits (若干有效数字) will be lost in this way. Hence, in addition to keeping required significant digits, the calculation methods or measurement ways should be improved so that the subtraction of two close digits does not occur.

(3) Calculation of division (除法运算): In all digits, the digit which has the least places of significant digit (有效数字位数最少) is used as standard, and other digits and product or quotient (积或商) should have one more significant digit than it.

For example: $603.21 \times 0.32 \div 4.011 \rightarrow 603 \times 0.32 \div 4.01 = 48.1$.

(4) Average of calculation (计算平均值): If there are four or more digits to take average, the place of significant digit in the average value can increase one.

(5) Calculation of power and root (乘方与开方运算): The final result of calculation keeps one more place of significant digit than original digits.

For example: $25^2 = 625$, $\sqrt{4.8} = 2.19$.

(6) Calculation of logarithm (对数运算): The places of significant digit before and after taking logarithm should be equal.

For example: $\lg 2.345 = 0.3701$, $\lg 2.3456 = 0.37025$.

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* $1mmH_2O = 9.81Pa$, the same below.

2. Experimental data processing

Most data of the experiments of chemical engineering principle are measured indirectly, and the procedure of processing experimental data generally is as follows: first, the results measured directly are listed in a table according to appearing sequences (出现或前后顺序), then the middle results, measured indirectly and their error are calculated. All calculation results are listed in the table. Finally, all results are expressed by charts according to the experimental requirement, or are shown by empirical equations (经验公式).

(1) Drawing (绘制) of experimental curves.

The advantage demonstrating experimental data by the charts is to directly be perceived (直观清晰), to conveniently be compared (便于比较) and to easily watch out the points of limiting value (极值点), the turn points (转折点), periodicity (周期性), the changing rate and the other characteristics. Experimental curves also help us to find the mathematical model.

When the charts are drawn according to the experimental data, the following should be considered:

①Choice of coordinate system (坐标系): The coordinate systems generally used in chemical engineering majors have the rectangular coordinate, logarithmic coordinate, semi-logarithmic coordinate and so on. The coordinate system is chosen according to the relation between the data or the functions to be predicted. If it is a linear function, the rectangular coordinate is used. If it is a power function, the logarithmic coordinate is chosen so as to make the chart be linear. The semi-logarithmic coordinate is selected for an index function. The semi-logarithmic coordinate can be chosen if the difference between digit levels of the smallest and largest values for self-variable and induced-variable is too great.

For example, for the function of $y = ae^{bx}$, y is used as the logarithmic coordinate, and x as semi-logarithmic coordinate of straight line scale (直线分度), since

$$\ln y = \ln a + bx \tag{1-3}$$

And for the parabolic curve of $y = ax^b$, the double logarithmic coordinate (log-log-coordinate) should be used, as shown in Figure 1-2, since

$$\lg y = \lg a + b\lg x \tag{1-4}$$

where Equation (1-4) is linear.

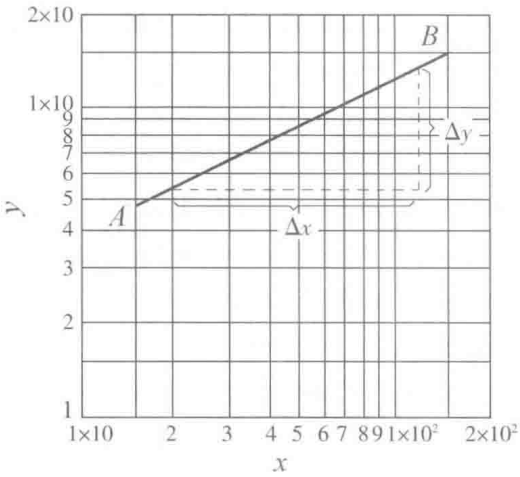

Fig. 1-2 Double logarithmic coordinate.

It is clearly seen that the digit value shown is the accurate value in the logarithmic coordinate, and the origin is one and not zero. Because the logarithms of 1, 10, 100, and so on, are respectively 0, 1, 2, and so forth, the distance of every order (数量级) is the same in the coordinate paper. Since it is the value of accurate digit scale, the digit value of scale is not used directly to carry out the calculation when the slope (坡度, 斜率) of straight line is found. And its logarithm should be used to conduct the calculation. Suppose the slope is K, so

$$K = \frac{\lg y_2 - \lg y_1}{\lg x_2 - \lg x_1} \tag{1-5}$$

②Scale (分度) of coordinates: It should approximately be in accordance with (与……相符) the significant digits of experimental data, and the most suitable scale is to make the coordinate readings of experimental curves and data have the same places of significant digits. Besides that, the ratio between the axis of abscissa (横坐标) and the axis of longitudinal coordinate (纵坐标) is not surely in accordance, and should be chosen according to the actual condition, to make the slope of experimental curves be between 30° to 60°. Such the reading of curve coordinates has higher accuracy.

(2) Determination of empirical equations.

The method of empirical equations is also called the method of mathematical models. It directly describes the relationship between self-variable and induced-variable of process or phenomena, and it is also an important method, especially in the wide application of computers at present.

The comparison way of charts is usually adopted. That is, the experimental curves are drawn by experimental data and are compared with the typical (典型的) curves to