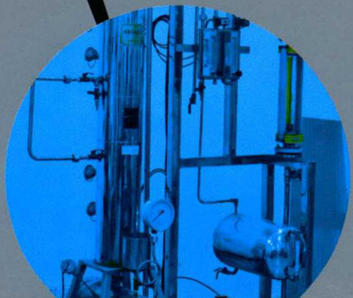
高等教育双语教学推荐教材

The Experiments of Unit Operations of Chemical Engineering

（化工单元操作实验）

■ 金万勤 居沈贵 等编著 ■ 王延儒 审校



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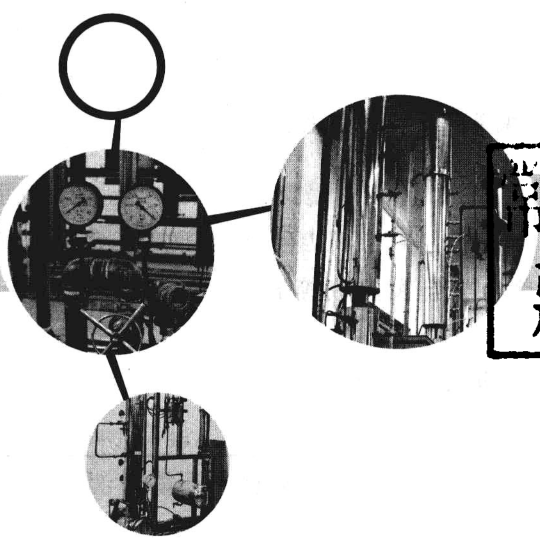

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本书作为高等学校化工原理双语课程配套的英文实验课教材，系统地讲解了化工原理实验的基本原理、基本要求以及实验的装置和流程（包括一些演示实验），并介绍了实验误差分析和实验结果的数据处理的方法，以及计算时需要用到的重要参考数据。

本教材适用于化工、轻工等工程应用类专业的本科生和研究生使用，也可以为从事相关领域的技术人员提供参考。

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前言

现代教育逐渐面向现代化、面向世界和未来，高校教育逐渐形成公共课程和专业课程双语化的发展趋势。双语教学已经成为了一种培养学生具有国际视野、国际交流和竞争能力的重要手段。双语教学不仅体现在用英语授课，还体现在老师与学生之间用英语进行交流和互动上，其中对专业词汇的掌握以及如何正确地表达尤其重要。作为化工专业的基础课程，化工原理课程强调学生对于理论和实践知识的共同掌握。然而目前专门描述基础的化工方面的英文版实验指导书非常匮乏，这给从事实验教学的老师在指导实验时带来了不便。本书作为化工原理双语课程配套的英文实验课教材，系统地讲解了化工原理实验的基本原理、基本要求以及实验装置和流程（包括一些演示实验），并介绍了实验误差分析和实验结果的数据处理的方法，以及计算时需要用到的重要参考数据。

本书共有五大部分。第一部分为化工原理实验的基本要求，以便学生对照这些要求正确进行实验；第二部分为化工原理实验，共有八个实验，分别为流体流动阻力测定实验、离心泵性能特性曲线测定实验、恒压过滤常数测定实验、对流给热系数测定实验、固体流态化实验、精馏实验、吸收（解吸）实验、干燥速率曲线测定实验；每个实验均介绍了实验目的、实验原理、实验装置流程、实验操作步骤、实验数据记录和处理、实验报告要求和思考题，以便指导学生预习实验的过程、正确操作；第三部分为化工原理演示实验，共有六个实验，分别为流体的压强及其测量演示实验、流体流型（雷诺数）演示实验、流体机械能分布及其转换演示实验、边界层演示实验、塔模型演示实验和流体绕流演示实验，以供学生观察有关实验，分析实验现象，加深对有关原理的理解；第四部分为实验误差分析和实验结果的数据处理，使学生了解造成实验误差的主要原因，分析计算中遇到的问题，掌握数据处理的正确方法，同时提高学生实验质量；第五部分为附录，附有常用的一些物理量和单位转换等，以便学生在开展实验实习和

数据计算时进行查阅。

本教材适用于化工、轻工、生工或者其他工程应用类专业的学生使用，其他专业的教学可根据自身的教学情况选择部分实验进行教学。教学过程中若能辅以外籍教师或有海外留学经历的专业教师进行指导为佳，学习本课程在教学的同时还能起到促进对专业英语的学习和交流等作用。

本书由金万勤、陈小强、暴宁钟、顾学红和居沈贵参与编写，并由王延儒进行审校，娄玥芸等学生进行了整合工作。在编著的过程中，得到了南京工业大学化学化工学院和材料化学工程重点实验室领导的大力支持，同时本书出版得到了江苏高校优势学科建设工程资助（PADD）在此编著者深表感谢。

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2013 年 1 月

Contents

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Basic requirements for the experiments

The experimenter should submit a qualified report satisfied the requirements of the course after he accomplishes the experiment. The report is requested to express the task and the results of the experimental observation described with tables, graphs, formula and words succinctly and explicitly, in order that, readers can be clear to understand. Besides that, those should be considered as below:

(1) The data must be reliable. The experimental plan should be thought over and over again before carrying out, so the preview is very important. The experimenter must concentrate his energy, observe the experimental phenomenon and record the original data seriously and correctly.

(2) The experimental records must withstand checks and trials. So the experimental conditions, time, place and the personnel should be illustrated.

In order to make a qualified experimental report in every step and every problem of the experimental process, there are specifications and requirements as below:

0.1 Previewing the experiment

(1) Read lab handouts, make sure to figure out the aim of the study and requirements.

(2) According to the specific task in the experiment, student should study the basic of experimental theory and the way to do the experiments. Whether the parameters needed to be directly measured should be analyzed. Estimating the variation trend of experimental data is also important.

(3) Observe and study the experimental process worksite, especially the main structure and installation of equipment and surveying instrument. Understand their measuring principle and method of use, and check the rationality of the whole experimental project.

(4) According to the experimental task and preview study, settle down the experimental scheme, make up the whole operating procedures.

0.2 Forming group and dividing work

Experimenters are usually divided into lots of small group with two people in each, so it is important to organize the groups well before the experiments start. Each group should have a head to be responsible for implementation of the experimental plan, contacting and discussing with the members to do their respective duties including operating instruments, recording data and observing phenomena, etc. In addition, taking turns of respective duty within the group is necessary.

0.3 Measuring the experimental data

All the data in the process that will affect the results must be measured. It includes atmospheric conditions, equipment dimensions, material properties and operation data, but not all data are directly measured. We do not need to measure the standard data previously discovered or derived from manual, such as density, viscosity, Specific heat, and other physical properties. For example, the physical properties of water are available and can be found in handbooks.

0.4 Reading and recording the experimental data

(1) Draw up the recording form before starting to the experiment. In the form, physical quantities including name, symbols and units should be recorded. Each experimenter should have an experimental recording book. Do not use informally a piece of paper or lab handout blank space to record. Ensure the integrity, clarity and accuracy of experimental data collected.

(2) The experimental data could not be recorded till the phenomenon is stable. Only after waiting a reasonable moment, experimenter can read the data and make a notice of the condition change. This is because the changed conditions destroyed the original and steady state. Establishing a steady state needs certain time (some experiment takes quite long time to achieve stability state). Usually instruments will show delay because of that phenomenon.

(3) Recheck each record immediately to avoid accidental recording error, their delay of datum indications.

(4) Experimental records must reflect the accuracy of the instrument. In general, experimenter should record the place below the minimum graduation of the instrument. For example, if the minimum graduation of a thermometer is 1℃, the current temperature reading is 20.5℃ or 19.5℃, 20℃ should not be recorded; and if it is just 20℃, 20.0℃ should be recorded.

(5) The records should be based on the experimental condition in situ.

(6) If it appears to be an abnormal condition and obvious data error in experiment, experimenters should illustrate in the remarks column.

0.5 Paying attention to the experimental process

Some experimenters know nothing regardless their respective duties in the experiment. Besides recording data in the experiments, the following tasks experimenter should be done:

(1) The operator must pay close attention to the instrument of indicating value change, and adjust at any time to ensure the whole operation process under the prescribed conditions and to reduce the gap between the operating conditions and the prescriptive operating conditions. The operating personnel must not leave their positions without authorization.

(2) After reading data, experimenters shall immediately compare it to the previous data and contrast to the relevant data to analysis if the mutual relationship between them is reasonable, and the change trend of the data is normal. If there is unreasonable situation,

experimenters should immediately explore the possible causes so as to solve problems in time.

(3) Observable appearance should also be paid attention to in the experimental process, especially when there are some unusual phenomena. The opportunity should be seized and the reason should be figured out about the abnormal one, finally obstacles can be overcome.

0.6 Managing the experimental data

(1) According to the significant figure arithmetic rules, some meaningless numbers should be rejected during data arrangement process. Accuracy of a digital is determined by the measurement sensitivity of the instrument itself, it will never be more exact by increasing the number of digits. Reducing number of digits is not permitted because it would reduce the accuracy.

(2) When dealing with a large number of complex experimental data, generally it is better to make a list of priorities by arranging the same project at a time. This type of arranging data process is a time-saving consolidation method.

(3) Example of detailed calculation should be given below the list of data for further inspection.

0.7 Preparing the report

A good experiment report must consist of brief and integral data, clear discussion and analysis of the formula or curve, definite conditions of the graph, and correct conclusions. The content of report generally includes:

(1) Report title.

(2) Name of the experimental group.

(3) Aim of the experiment.

(4) Theoretical basis of the experiment.

(5) Illustrations of experimental equipments (including process schematic diagram and the main equipment, instrument types and specifications).

(6) Experimental data. It should include all the data concerned with the experiment. The data are those after processing or be used to calculate. The original records could be attached to the appendix of the report.

(7) Data arrangement and calculation example, including references to explain the data sources and simplified formula to write the process. Data calculation results should be listed as a calculation example.

(8) Experimental results. According to the experiment task, conclusion of the experiments should be put forward clearly using the diagram, empirical formula or list. All of the experimental conditions should be marked clearly.

(9) Analysis and discussion. Assess the results of experiment, analyze the causes of error, and discuss the problems occurring in the experiments. Any suggestion made to the experiment method or the equipment can be written in this part.

1

Experiments in unit operations of chemical engineering

1.1 Fluid flow resistance test

1.1.1 Experimental purpose

(1) Know well the method of measuring resistance loss of fluid flowing through the straight pipe and valve, and the variation of energy loss in fluid flow by the experiment.

(2) Determine the relationship of straight pipe friction coefficient λ and Reynolds number Re, and subsequently compare the λ-Re equation with experiential formula.

(3) Determine the local resistance coefficient ξ of fluid flow through a valve.

(4) Learn the methods of using inverted U-shaped differential pressure gauge, 1151 differential pressure sensor, Pt 100 temperature sensor and rotameter.

(5) Observe the pipeline components consisting of pipes and valves, and understand the functional role of those parts.

(6) Apprehend the use of chemical experiment software library (MCGS configuration software and VB experiment data processing software system).

1.1.2 Basic principles

When fluid flows in the tube, as the existence of viscous shear stress and eddy current, it is inevitable to consume part of mechanical energy. The mechanical energy consumption includes fluid flowing through the frictional resistance and the local resistance caused by fluid movement direction changes in straight pipe.

1.1.2.1 Frictional drag

The fluid flows stably in a equidiameter horizontal pipe, resistance loss performs as the pressure drop. Namely

$$h_f = \frac{p_1 - p_2}{\rho} = \frac{\Delta p}{\rho} \tag{1-1}$$

Many factors influence the resistance losses, especially turbulent flow, which cannot be completely solved by the theoretical method. Experimental study of its regularity is the best way. In order to reduce the workload, making the experiment results of general significance, experimenters must use dimensional analysis method combined into number relational expression. According to dimensional analysis, the influence factors of the resistance loss are:

(1) Fluid properties: the density ρ, viscosity μ;

(2) Geometries of pipe: length l, diameter d, wall roughness ε;

(3) Flow conditions: velocity u.

Which can be expressed as:

$$\Delta p = f(d, l, \mu, \rho, u, \varepsilon) \tag{1-2}$$

A combination of the following non-dimensional type:

$$\frac{\Delta p}{\rho u^2} = \Phi\left(\frac{du\rho}{\mu}, \frac{l}{d}, \frac{\varepsilon}{d}\right) \tag{1-3}$$

$$\frac{\Delta p}{\rho} = \varphi\left(\frac{du\rho}{\mu}, \frac{\varepsilon}{d}\right)\frac{l}{d}\frac{u^2}{2} \tag{1-4}$$

If $\lambda = \varphi\left(\frac{du\rho}{\mu}, \frac{\varepsilon}{d}\right)$, the formula (1-1) turns into:

$$h_f = \frac{\Delta p}{\rho} = \lambda \frac{l}{d}\frac{u^2}{2} \tag{1-5}$$

In the formula, λ is friction coefficient. When it shows the laminar flow (viscous flow), $\lambda = 64/Re$; When it shows the turbulent fluid, λ is both the functions of Reynolds number Re and relative roughness factor ε, which shall be determined by the experiments.

1.1.2.2 Local resistance

There are usually two kinds of calculation methods for local resistance including the equivalent length method and the resistance coefficient method.

(1) Equivalent length method. Fluid flows through a pipe or valve, for the loss caused by local resistance, equivalent to the resistance losses where the fluid is flowing through with a length of pipe diameter and straight pipe, so the straight pipe length is called equivalent length, with symbols l_e. This way, one can use the straight pipe resistance formula for calculating local resistance losses. In the pipeline calculation, one can calculate the total length including the lengths of pipeline straight pipe fitting, valve. If the equivalent length such as line of straight pipe length is l, thus, in all kinds of local resistance equivalent length for the sum $\sum l_e$, the fluid flow in the line of total resistance losses $\sum h_f$ are

$$\sum h_f = \lambda \frac{l + \sum l_e}{d}\frac{u^2}{2} \tag{1-6}$$

(2) Resistance coefficient method. Calculation of local resistance by considering the fluid flowing through a pipe and the resistance of the valve with fluid loss in the pipeline kinetic energy coefficients is called the resistance coefficient method.

$$h_f' = \xi \frac{u^2}{2} \tag{1-7}$$

where, ξ—local resistance coefficient, non-dimensional;

u—average flow velocity in the small section of pipe flow, m/s.

Because the length between both sides of pipe from the pressure taps of straight pipe is short, compared to the local resistance, the friction resistance caused by that can be negligible. This value can be read by Bernoulli equation by adopting the pressure differential equation for reading program.

1.1.3 Experimental equipment and process

1.1.3.1 Experimental facility

The experiment device is shown in Figure 1-1. It is mainly made up with high slots, pipes with different diameters and materials, and various valves and fittings, rotor flow meters, etc. The first root is stainless steel smooth tube and the second root is galvanized iron pipes, applied to the determination of smooth tube and tube turbulent flow resistance. The third root is stainless steel tube with valve, which is used to the determination of local

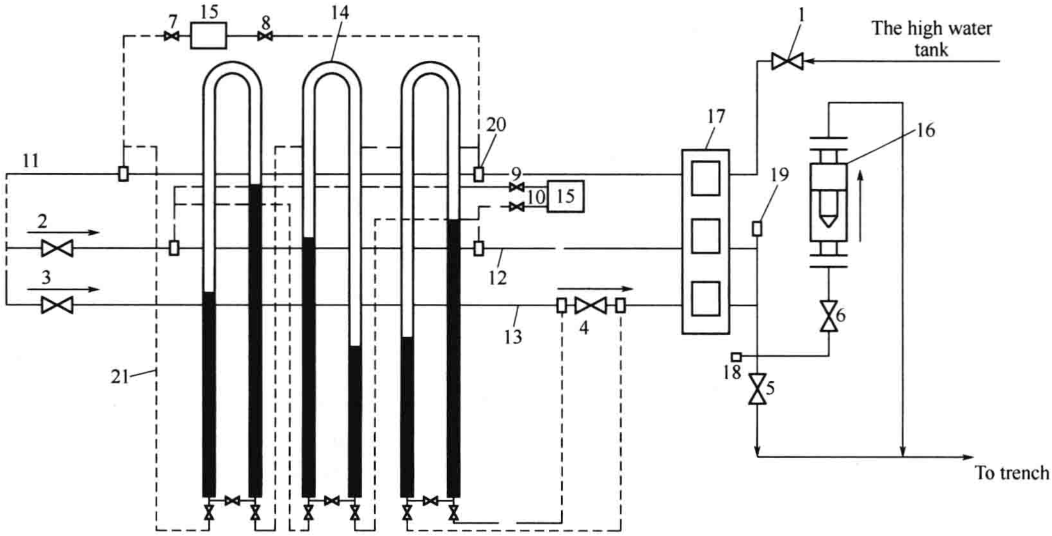

Figure 1-1 Schematic drawing of fluid flow resistance test device
1-feed valve; 2,3,5-globe valve; 4-gate valve; 6-flow regulator; 7～10-cock; 11-smooth tube; 12-rough tube; 13-stainless steel pipe; 14-inverted U-shaped differential gauge; 15-1151 differential pressure sensor; 16-rotameter; 17-the instrument box; 18-Pt 100 temperature sensor; 19-Pt 100 temperature sensor; 20-equalizing ring; 21-pressure measuring catheter

resistance.

The experimental medium is water, supplied by high water flow of the 25 m head through the experiment device. Water will flow into the pool through the underground pipeline, then turn back to the higher water level by pumping for recycling.

The water flow was tested by the rotor flow meter installed in the rear of equipment. The resistances of the gate valves and the straight section are measured, respectively, by inverted U-shaped differential gauge or 1151 differential pressure sensor and digital display instrument. The use method of inverted U-shaped differential gauge is described in section 4. 2. 1.

1. 1. 3. 2 Device structure size

Device structure size is shown in Table 1-1.

Table 1-1 Fluid flow resistance test device size

Name	Material	Pipe inner diameter/mm				Test length /mm
		Device number				
		(1)	(2)	(3)	(4)	
Smooth pipe	Stainless steel tube	32. 06	32. 05	32. 20	32. 10	2. 0
Rough tube	Galvanized iron pipe	36. 69	36. 68	36. 67	36. 63	
Local resistance	Stainless steel tube	26. 65	28. 60	28. 61	28. 62	—

1. 1. 4 Experimental steps and considerations

1. 1. 4. 1 Experimental procedures

(1) Know well with the experiment device system.

(2) Open inlet valve 1, water flows from the tank through the overflow device.

(3) Open exhaust air valves 2~6 after closing valves 5、6.

(4) When there is no flow in the pipe (zero flow), then three inverted U-shaped differential pressure gauges, as mentioned in the 4. 2. 1. 1 (4), are adjusted to the normal state of the measurement of differential pressure.

(5) Open the cocks 7~10 to drain the bubbles in catheter of manometer in 1151 differential pressure sensor, and then close the cocks. Open the data measuring instrument power of the 1151 differential pressure sensor, record the initial value (or calibration, calibration was carried out by the instructor).

(6) Close valve 2, open valve 6 and adjust the flow so that rotameter begins to show the values as $2m^3/h$, $3m^3/h$, $4m^3/h$, ⋯, $10m^3/h$, with largest rotor cross section corresponding to the high scale value. Measure the values at each flow rate (8~9 points), which is different depending upon the resistance of the smooth pipe and the rough pipe (differential pressure mmH_2O❶). Write down the values shown in the inverted U-shaped differential manometer and 1151 differential pressure sensor.

(7) Close valve 2, open valve 3, measure the local resistance of gate valve when it is fully open. Set rate of flow as $2m^3/h$, $3m^3/h$, $4m^3/h$ and measure three points corresponding to the pressure difference to obtain the average drag coefficient.

(8) Open system drain valve 5 at the end of the experiment to drain water from the system to prevent rust and freezing in the winter.

1. 1. 4. 2 Considerations

Opening and closing of the valves in the pipeline and the inverted U-shaped differential pressure gauge on the valve must be performed slowly with great care in order to avoid sudden surges due to compression and decompression that will cause damage to the instruments.

1. 1. 5 Experimental report

(1) Plot the experimental results of rough pipe on the λ-Re curve in the double logarithmic graph paper, collate with the related formula in teaching materials on the chemical principles, to determine the relative roughness and the absolute roughness of the pipe.

(2) Plot the experimental results of smooth pipe on the λ-Re curve in the double logarithmic graph paper, and calculate the error by the controlled Plato Dionysius equation.

(3) According to the experiment results on local resistance, find the average value of ξ when the gate valve is fully open.

(4) Analyze and discuss the experimental results.

1. 1. 6 Questions

(1) When doing exhaust work on the device, is it necessary to close the flow control valve of the flow tail? Why?

(2) How to test that the air was excluded within the test system?

(3) Can the λ-Re relationship measured with water as medium be used to apply to other fluids? If so, how to apply?

(4) On different devices with different diameters, can the λ-Re data obtained at different water temperature be associated with a curve?

❶ $1mmH_2O=9.80665Pa$.

(5) If there are glitches on the pressure taps and the edge of the hole or they were not installed perpendicularly, what influence can be observed on the static pressure measurement?

1.1.7 Examples of experimental data recording and data processing

Table 1-2 Data example of the fluid-flow resistance test experiment
Experimental device: 3# ; Tube length: l=2m; Temperature: 15 ℃

Number	Flow /(m^3/h)	Smooth tube differential pressure (caliber d=0.03220m) /mmH_2O	Rough pipe differential pressure (caliber d=0.03667m) /mmH_2O	Gate valve (fully open) resistance (caliber d=0.02861m) /mmH_2O
1	1.5	35	22	
2	2	57	38	11.5
3	2.5	85	54	18.0
4	3	117	73	26.0
5	3.5	160	96	
6	4	202	125	
7	4.5	246	157	
8	5	298	196	
9	5.5	352	229	
10	6	420	273	

Calculation results:

Table 1-3 Data example of the fluid-flow resistance test experiment

Test times	Flow/(m^3/h)	$Re_{\text{smooth tube}}$	$\lambda_{\text{smooth tube exp}}$	$Re_{\text{rough pipe}}$	$\lambda_{\text{rough pipe exp}}$	$\lambda_{\text{rough pipe cal}}$
1	1.5	1.46×10^4	0.0273	1.29×10^4	0.0318	0.0303
2	2	1.95×10^4	0.0250	1.73×10^4	0.0309	0.0286
3	2.5	2.44×10^4	0.0239	2.16×10^4	0.0281	0.0274
4	3	2.93×10^4	0.0228	2.59×10^4	0.0264	0.0266
5	3.5	3.42×10^4	0.0229	3.02×10^4	0.0255	0.0260
6	4	3.90×10^4	0.0222	3.45×10^4	0.0254	0.0255
7	4.5	4.39×10^4	0.0213	3.88×10^4	0.0252	0.0251
8	5	4.88×10^4	0.0209	4.31×10^4	0.0255	0.0248
9	5.5	5.37×10^4	0.0204	4.75×10^4	0.0246	0.0245
10	6	5.86×10^4	0.0205	5.18×10^4	0.0247	0.0243