PILOT PLANTS AS A BASIS FOR THE DESIGN OF LARGE-SCALE EQUIPMENT*

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WHETHER it is a new chemical process, or a fresh venture into the production of an already established product, the design of a full-scale plant for a given output must be based on trial experiments on a semi-works scale. But a correlation between the pilot plant and the full-scale works is not a simple exercise in arithmetic; it involves a careful and rational interpretation of the various attendant physical and chemical factors. Failure to recognise this has led to frequent disappointments, and financial failures on account of the unexpectedly poor performances of large-scale plants after erection. On the other hand, there are cases where very favourable results have been obtained with a large-scale plant, although the pilot-scale experiments were discouraging and difficult. A classical example of this is provided in the initial experiments of C. M. Hall on the manufacture of Aluminium. It is rather poignant that such an element of risk should be incident just where the biggest outlay in capital is involved.

A systematic study of the vast experiences gained in this field and a thorough understanding of the fundamental principles involved have led to the modern science of chemical engineering design. It is now possible with the help of these theoretical methods and a set of basic experimental data to design various types of industrial equipment of any desired capacity and performance, as for example, evaporators, fractionating columns, settling tanks, heat exchangers, absorption towers, driers, etc. All these achievements are, however, mostly confined to processes which involve in the main physical operations only. They also largely run parallel with corresponding developments in other branches of engineering. In all cases, the required 'model' experiments for acquiring basic data for design are planned on the principle of similarity. According to this principle, one determines a single or more dimensionless parameters which are characteristic for the operation under consideration. The functional relationships involving these dimensionless numbers are then determined through the model-scale experiments. Now, whatever be the size of the plant, for conditions which result in the same value for the dimensionless parameters, the function of the plant is identical, and can be correlated in a linear scale ratio. Thus, for all cases of fluid flow, correlative results are obtained at equal Reynold's numbers $\frac{DU\rho}{\mu}$, where D is a linear dimension which determines the flow such as diameter for a pipe with circular cross-section, U is the linear rate of flow, ρ the density and μ the viscosity of the fluid. Wide use is made of this principle, for example, in aerodynamic studies on model planes suspended in wind tunnels. Here with the help of the scale models and highly compressed air the value of $D\rho$ in the Reynold's expression is kept constant and the results obtained with the models then translated for the full-scale prototypes at the prevailing atmospheric pressures. Similarly hydrodynamic experiments are performed with ship models in water tanks in order to obtain the necessary data for the final shipping designs. Such conditions of dynamic similarity are also successfully employed for the design of heat transfer equipment in chemical plants. Here the dimensionless expressions required have to include additional temperature factors, and a few of those commonly used in design practice are:

the Prandtl number $\frac{C\mu}{K}$ for evaluating temperature drop across films,

the Peclet number $\frac{DU\rho C}{K}$ for heat transfer in viscous oils in laminar flow, and

the Grashof number $\frac{D^3\rho^2 g\beta\Delta t}{\mu^2}$ for heat transfer under conditions of natural convection.

Here C is specific heat, K the thermal conductivity of fluid, β the volumetric

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coefficient of thermal expansion, and the other symbols have the usual significance.

When a unit operation includes a chemical reaction also additional factors such as energy of activation, reaction velocity, etc. must be taken into consideration for deriving the appropriate dimensionless numbers for pilot plant studies. The problem thus becomes more complex but all the same it will be useful to determine one or more such criterions for similarity so as to enable one to predict with reasonable certainty the effect of a change of scale.

Few systems are governed by a criterion of purely chemical similarity with respect to concentration, reaction rate, etc. Several physical factors are inevitably associated with the systems in which chemical reactions take place. Thus, materials must be transported to and from the reaction centres by diffusion or turbulent currents. Frequently considerable heats of reaction have to be suitably transferred to the surroundings from the interior in order that a system may be maintained at a desired reaction temperature. The conditions of dynamic similarity dictated by such physical factors are in general not compatible with corresponding conditions required for purely chemical similarity. For example fluid velocities required to give equal Reynold's number would not allow of equal reaction times in the large- and small-scale apparatus. A complete mathematical solution of this problem is beset with difficulties. However a solution can be approached by first considering systems under conditions in which one of the factors alone is predominant. Thus, for a process in which the chemical reaction velocity is sufficiently low to be determinative, factors of chemical 'resistance' are the most significant, and the "physical resistance" factors can be ignored. Hence for drawing up correlations, conditions of dynamic similarity will play a very much less prominent role compared to conditions of chemical similarity. On the other hand, if the physical resistance is much the greater of the two, then conditions for chemical similarity can be ignored and scale relations can be drawn for conditions of dynamic similarity only, as for example, the maintenance of the same degree of turbulent motion in both systems.

The first attempt on problems of this nature was made by Prof. Damkohler of Gottingen in 1936 (*Z. Elektrochem.*, 42, 846). Proceeding from fundamental equations expressing conservation of mass, heat, and momentum, he derived the following four characteristic dimensionless factors:

$$\text{I.}\quad \frac{\text{Number of molecules chemically changed}}{\text{Number of molecules supplied by turbulent currents}} = \frac{\nu_j U l}{C_j v}.$$

$$\text{II.}\quad \frac{\text{Number of molecules chemically changed}}{\text{Number of molecules supplied by diffusion}} = \frac{\nu_j U l^2}{C_j D_j}.$$

$$\text{III.}\quad \frac{\text{Chemical heat developed}}{\text{Heat removed by convection}} = \frac{QUl}{C_p \rho \theta v}.$$

$$\text{IV.}\quad \frac{\text{Chemical heat developed}}{\text{Heat removed by conduction}} = \frac{QUl^2}{\lambda \theta}.$$

Where ν_j is the stoichiometric coefficient of substance j, for the chemical equation

$$\nu_1 A_1 + \nu_2 A_2 + \cdots \rightarrow \nu_3 A_3 + \nu_4 A_4 + \cdots\cdots$$

U is the true chemical reaction velocity $\frac{\text{Moles}}{\text{Cm.}^3\ \text{Sec.}}$

l = linear dimension of system.

C_j = molar concentration of substance j.

D_j = Diffusion coefficient of j, $\frac{\text{Cm.}^2}{\text{Sec.}}$

Q = Heat of reaction per mole, $\frac{\text{Cal.}}{\text{Mol.}}$

C_p = Specific heat of reaction mixture at constant pressure.

ρ = density of reaction mixture.

v = flow velocity of reaction mixture.

θ = temperature above an arbitrary zero.

K = Thermal conductivity of reaction mixture.

If any of these numbers be identical in the two systems, large and small, then a chemical process must be proceeding identically in both but with different total performances. Damkohler has considered the simplified case of a cylindrical reaction vessel, and derived from the groups I, III and IV, relative dimensions for the small- and large-scale sizes with a ratio of output n. The chemical process assumed is a continuous one, with a turbulent flow through the system, the rate of chemical reaction being the controlling factor.

		Small	Large
I.	Homogeneous reaction—		
	Length in direction of flow	L	$Ln^{\frac{2-m}{2+m}}$
	Diameter	D	$Dn^{\frac{m}{2+m}}$
	Fluid velocity	v	$vn^{\frac{2-m}{2+m}}$
II.	Heterogeneous reaction—		
	Length in direction of flow	L	$Ln^{\frac{2}{2+2m}}$
	Diameter	D	$Dn^{\frac{m}{2+2m}}$
	Fluid velocity	v	$vn^{\frac{2}{2+2m}}$

It is found that $m \sim 0{\cdot}8$, for turbulent flow, and $m \sim 0$, for laminar flow. Thus when $n = 10$, that is for a tenfold increase in production, the cylindrical reaction vessel must be 3·3 times longer and its diameter only 1·7 times more. The reaction vessel is thus geometrically distorted.

R. Edgeworth-Johnstone has more recently taken the subject up a little further [*Trans. Inst. Chem. Eng.* (England), 1939, p. 129] by introducing simpler dimensionless factors derived from the rate of reaction formula and the Arrhenius equation relating to reaction velocity with temperature. For homogeneous chemical reactions of any order n, two dimensionless factors can be used ($\chi_n \cdot a_2 \cdot\cdot a_3 \ldots a_n \cdot t$) and E/RT, where χ_n is the constant in the Arrhenius equation $K_n = \chi_n \cdot e^{E/RT}$, a_n is the stoichiometric concentration, and the other symbols have the usual significance. For heterogeneous chemical reactions, the extent of interfacial areas must also be taken into consideration. On the basis of the above similarity principles Edgeworth-Johnstone has shown that if two reaction vessels have volumes V and n^3.V, *i.e.*, are related by scale factor n, then for a chemical reaction taking place at the same temperature and with the same initial concentrations, the volume rates of flow should be Qn^3 for the homogeneous reaction, Qn^2 for a heterogeneous system filled with geometrically similar catalyst grains, but Qn^3 for a heterogeneous system filled with catalyst grains of identical size in both systems.

The theoretical considerations outlined above regarding the application of similarity theory in chemical plant design constitute an important development of considerable significance in Chemical Engineering. Their practical utility is at present somewhat limited, but to a large extent they serve to visualise and to understand the nature of the difficulties in the designing of large-scale equipments on the basis of pilot plant work.

CENTENARIES

Lukin, Lionel (1742–1834)

LIONEL LUKIN, British inventor of life-boats, was born at Dumow 18 May, 1742. He became a member of the Coachmakers' Company in 1767 and continued in that business till 1824. He was a personal favourite of George IV and of Windham, the Secretary of State for War. He was also full of fertile mechanical gifts.

The first life-boat was conceived by Lukin in 1785. His pamphlet on this invention was published in 1790. Despite the patronage of the king, public apathy in regard to shipwreck stood in the way of Lukin getting his due recognition during his life-time.

Lukin secured buoyancy by means of a projecting gunevale of cork and air-chambers inside. He secured stability by a false iron keel. Lukin also invented a raft for rescuing persons from under ice, a rain gauge and an adjustable reclining bed for patients.

Lukin died at Hythe, Kent, in his ninety-first year, 13 February, 1834.

Seaward, Samuel (1800–1842)

SAMUEL SEAWARD, a British Engineer, was, with his brother John, the joint-owner of the Canal Iron Works which specialised in marine engines. The brothers supplied machinery to all parts of the world. They were pioneers in the construction of engines which provided speed without loss of comfort. The double-slide valve both for the steam and the exhaust, which they invented, resulted in a great saving in the consumption of fuel. This led to the adoption of their engines by the vessels of the East India Company and of several navigation agencies. They also advocated the use of auxiliary steam power for the voyage to India.

Samuel Seward died in London 11 May, 1842.

Lofting, John (1659-1742)

JOHN LOFTING, a Dutch inventor, was born in 1659. He set up practice in London in 1688 as a merchant and manufacturer of fire-