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CHEMICAL ENGINEERING AS A BASIC FACTOR IN MODERN INDUSTRY.

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THE past twenty years or so have been remarkable for the rise of important new industries and the rapid multiplication of new manufacturing processes. Most of these developments have been the direct result of the industrial application of new scientific knowledge, particularly in the domains of chemistry and physics. Apart from the spectacular growth of the industries concerned with the manufacture of motor cars, aircraft, wireless apparatus, photographic films and artificial silk, successful processes have been developed for the commercial production of synthetic ammonia, of nitrates from the atmosphere, of numerous organic solvents from simple carbon compounds, of synthetic plastics, of paints, lacquers, dyestuffs, foodstuffs, rubber goods, fine chemicals, drugs, &c. When any new process comes to be tried out under industrial conditions, numerous manufacturing difficulties arise which must be overcome before the process can be operated efficiently and profitably. This calls for a systematic investigation of the different factors concerned, using well-established scientific methods. The development of the science of chemical engineering is the direct outcome of the widespread use of such methods in the investigation of the peculiar problems that arise in many manufacturing industries.

The task confronting a manufacturer has always been, and, presumably, will always be, the conversion of a given raw material into something of greater value to the community. There are two ways in which this can be done: The raw material may be treated mechanically so as to alter its shape or texture, or it may be treated chemically and so become transformed into an entirely different substance. Familiar instances of the former method are provided by the ancient trades of the carpenter, the smith and the weaver, and by the great engineering and manufacturing industries which have grown out of them. In all these processes, the operations involved are essentially mechanical, the material itself remaining chemically unchanged. Manufacturing processes, however, in which the raw material undergoes a chemical transformation or a change of physical state, belong to an entirely different category. The art of the brewer, the charcoal burner, the smelter, the soap maker or the cook depends not so much upon the possession of a certain manual dexterity as upon being intellectually able to make practical use of a fund of empirical knowledge concerning the chemical and physical behaviour of certain materials.

In any chemical process, a given raw material is subjected to a succession of carefully controlled chemical or physical operations, by which it is decomposed and transformed into an entirely different product. These operations depend for their success upon a nice adjustment of the conditions under which they are carried out—for example, the composition and temperature of the reaction mass. Many chemical processes are very sensitive to their chemical and physical environment, so that a slight change in the operating conditions may profoundly modify the character and yield of the product. This characteristic is at once the delight and the despair of the chemist, for, while it provides him with a wider range of products, it also increases greatly the difficulty of obtaining a high yield of the particular product he desires. It is frequently possible with a chemical process to obtain a particular product from any one of a number of widely different raw materials; thus, alcohol can be manufactured by chemical means from potatoes or sawdust, from the waste sulphite liquor of a wood pulp works or from gases such as acetylene and ethylene. With a chemical process, also, it is often possible to obtain from a given raw material a wide range of very different products: by the destructive distillation of wood or coal, it is possible to obtain coke and pitch and various oils, spirits and gases. A chemical process, therefore, may increase the potential wealth of the community in two directions, for it makes available an increasing number of hitherto unrealised raw materials and also provides entirely new products which may greatly extend the scope of existing industries or lead to the formation of new ones.

It is clearly a matter of primary importance to a manufacturing community such as ours that the results of scientific research should be applied to industry in the most effective manner and with as little delay as possible. Modern industry must be armed with science *cap-à-pie* if it is to survive, let alone prosper. Its ideas and its methods must be soundly conceived; they must also be executed with the highest degree of efficiency. In this connection, it must be remembered that the problems of execution are frequently more baffling than those of conception, for they involve more variables and are subject to more rigid restrictions. The difficulties which have to be overcome in the works are totally unlike those which confront a worker in a laboratory. In the laboratory, the reaction is investigated under conditions which eliminate as far as possible all secondary factors. Thus, the chemist works with small quantities of the purest materials he can get in vessels which as far as possible are inert and, preferably, transparent. Every facility is provided for controlling as accurately as possible the temperature, pressure and composition of the system. The success with which the process has been controlled is judged by two criteria: the quality of the product and the actual yield, considered as a percentage of the ideal yield.

When the process is transferred from the laboratory to the works, the operating conditions are profoundly altered; the ideal conditions of the laboratory are no longer attainable. The process is still essentially an affair of molecules or ions and, therefore, is subject to the laws and conditions which are found to obtain in the laboratory. But now it must also satisfy the conditions which are imposed upon it by the engineering and economic requirements of a commercial process. The raw materials are generally impure and may have to be specially treated before they can be used in the reaction. Alternatively, they may become contaminated by the accumulation of impurities derived from the materials of which the plant is made. The presence of quite small traces of impurities may seriously modify the course of the reaction or impair the quality of the product. The scale of operation is such that special storage facilities must be provided for the reaction materials, and, since it is impossible to handle such large quantities, all materials must be transported mechanically by conveyors or pipes. Storage bins and tanks, as well as pipes and other transport equipment, must be made of materials, carefully chosen to avoid undue contamination of the product. The reaction vessels must be made of commercially available materials and must be strong enough to withstand the pressure that may be generated during the reaction. They must also be reasonably resistant to the chemical attack of the contents. It is frequently a matter of the greatest difficulty to find a constructional material which fulfils these requirements and yet is not too expensive.

The rate at which the reaction proceeds, as, indeed, the actual course taken by the reaction, depends upon the conditions of temperature, pressure, and composition that can be maintained at every point of the reaction mass. If heat is to be introduced or removed, the reaction vessel must be designed so that every part of the reaction mass is readily accessible to the heating or cooling surface; this raises the whole question of the transmission of heat to or from such large masses of materials. Where fluids are concerned, this is intimately bound up with the flow of the fluid through the reaction vessel. The design of such a vessel, therefore, calls for a knowledge of the principles of heat transmission and fluid flow. The problem is greatly complicated by the wide variety of fluids which have to be handled and by the general lack of information concerning their properties. When the process is complete, the product has to be separated and finished and stored under suitable conditions, or packed and dispatched to the customer. Thus, the original chemical reaction, when transferred to the works, has to run the gauntlet of the extraordinary conditions imposed upon it by the peculiar requirements of large-scale operation with impure materials in relatively unresistant vessels.

Even if the yield is satisfactory and the product is of the required quality, the process will be a failure if it is not profitable. In designing and arranging the complete plant, therefore, everything must be done to make the cost of production as low as possible, consistent with the required rate of output and quality of the product. In other words, the process must not only be efficient —many an efficient process has had to be scrapped!— it must also, in the last analysis, be financially profitable. The overall efficiency with which a complicated manufacturing process is carried out depends upon the efficiency with which the separate parts of the process are operated. Any attempt that is made to discover the factors upon which the overall efficiency depends must begin by analysing the complete process into the different unit operations of which it is made up. In a mechanical process, these operations—*e.g.*, cutting, rolling, bending, drilling, drawing, weaving, &c.— are relatively simple. Their operation is well understood and the principles underlying the design of the necessary machinery have been thoroughly worked out. The unit operations of which a chemical process is made up are more complex and, from the designer's standpoint, are much more elusive. The design of each individual plant unit depends not only upon the character of the operation that is to be carried out with it, whether, for example, a particular material is to be filtered, evaporated, dried or disintegrated, but it also depends upon the chemical and physical nature of the reaction material, whether it be viscous or mobile, heat-sensitive or -resistant, brittle or tough, soluble or insoluble, volatile or phlegmatic, corrosive or non-corrosive. Owing to the existence of so many variables, the plant units that are designed even for the same unit operation vary widely, both in design and method of operation. Filtration, for example, may be carried out with a filter press, either of the recessed plate or of the plate and frame type, with a streamline filter or a leaf filter or with a continuous rotary filter, to say nothing of box filters, sand filters, centrifugals, and thickeners. The design of plant for other unit operations exhibits just as wide a variety. In the circumstances, it is practically impossible to standardise the design of chemical plant; practically every plant unit of any importance has to be designed from first principles. The difficulty of the task is often accentuated by the almost complete absence of the necessary design data.

We have seen that any industrial process in which a material is subjected to a physical or chemical change properly belongs to the domain of chemical engineering. This includes not only the design and operation of the necessary reaction vessels, but also the choice, arrangement and operation of the auxiliary plant, by means of which the raw materials and products are stored, measured, and transported. When we consider the wide variety of raw materials, intermediates, and products, and the numerous processes to which they may be subjected, the domain of chemical engineering appears to be all-embracing and almost without limit. Beneath this variety of material and multiplicity of processes, however, there is an underlying simplicity. If we ignore the complete chemical processes themselves and concentrate our attention upon the unit operations of which they are made up, we have something which is fundamental to all these "chemical" types of industry. By studying these unit operations intensively from the standpoint of the design and operation of the corresponding unit plants, we obtain an intimate knowledge of the anatomy and articulation of the complete process. These operations provide the industrial counterpart of the chemist's skilful play in the laboratory with test-tubes, beakers, flasks, filters, condensers, &c.

The more important unit operations into which chemical processes can be analysed are: (*a*) Physical operations such as crushing and grinding, dissolving, filtering, and settling, evaporating, drying, distilling, crystallising, &c., and (*b*) chemical operations such as oxidation, combustion, &c.; reduction, hydrogenation; nitration, chlorination, &c.; electrolysis; double decomposition; catalysis; pyrolysis, &c. We may regard these operations as constituting the warp threads, so to speak, of the chemical engineering fabric. When we analyse the design of the plant required to carry out one of these operations, we find that it depends upon a knowledge of the physics of fluid flow, of heat transmission and mass transfer, as well as of the chemistry of heterogeneous equilibria, mass action, surface energy (colloidal behaviour), electro-chemistry, &c. A sound knowledge is also necessary of the mechanical and chemical properties of the available constructional materials, of the engineering methods employed in the construction and erection of the plant and supporting structures, and of the general principles of plant arrangement and control. Further, it is necessary to be familiar with the economic principles that are involved in the financing of industry, in the costing of the production processes, in the sale of the products and in the allocation of the resulting revenue. We may regard all these different requirements as constituting the weft threads of the chemical engineering fabric.

It will be seen, therefore, that, reduced to its simplest terms, chemical engineering is essentially a synthesis of chemistry, engineering, and economics. It seeks to make a scientific study of all the factors, whether chemical, engineering or economic, which play a part in determining the efficiency of any manufacturing process in which a raw material is subjected to a chemical transformation or a physical change of state. By concentrating its attention, in the first instance, upon the efficiency with which the individual unit operations are carried out, it seeks to construct a process which will be efficient at every point and will, therefore, possess the highest possible overall efficiency. This, clearly, is a matter of the utmost importance to the community, particularly when we consider that industry is becoming increasingly dependent upon chemical processes and their products. It will be seen that the application of chemical engineering principles and methods is not confined to those industries which are commonly known as chemical industries. Many of the unit operations with which the chemical engineer is concerned enter at some point into the processes that are employed in such industries as mining, smelting, power generation, petroleum refining, lumbering, food manufacture, brewing, the dairy industry, agriculture, the manufacture of textiles, aircraft, pottery, and rubber goods, and the purification and control of public water supplies.

Chemical engineering is derived, in the first instance, from chemistry and engineering. It seeks to combine the analytical insight of the one with the practical outlook of the other. The problems with which it is peculiarly concerned belong entirely neither to chemistry nor to engineering, but arise from the interaction of the two in the large-scale operation of the chemical process. The engineer's raw materials are coal and water, his constructional materials steel and concrete. To the chemical engineer, anything and everything may be considered to be potentially a raw material; as for constructional materials, metallic and non-metallic, their name already is legion. Similarly, the chemist, working in the laboratory, is concerned primarily with the behaviour of molecules and ions under carefully-defined conditions. The reaction is the thing, and, quite correctly, everything else is subordinated to it. But the chemical engineer has to repeat the experiment in large, opaque vessels of steel or aluminium or stoneware; he must work vicariously; everything has to be paid for, including the disposal of the product, and, when all the costs, both direct and indirect, have been met, the process must show a profit. Many of the problems with which the chemical engineer is confronted are peculiar; some arise from the difficulty of finding suitable constructional materials which will resist sufficiently the chemical action of the reaction mass and at the same time be strong enough to withstand the stresses imposed upon them; others are due to the peculiarly sensitive character of many of the reactions to the conditions under which they are carried out, and to the necessity for controlling these conditions—*e.g.*, temperature, pressure and composition—at every point of the reaction mass.

A great deal of research work is being carried out, at present, with the object of developing new constructional materials. Important results are being obtained with corrosion-resisting and heat-resisting steels, particularly in the construction of special vessels for the high-pressure and temperature reactions used in hydrogenation, oil cracking and ammonia synthesis. Other investigations have for their object a study of the flow of different fluids and of pastes and slurries, with a view to determining their behaviour when flowing through a reaction vessel. This behaviour is closely related to the exchange of heat between such fluids or semi-fluids, and suitably disposed heating or cooling surfaces in their proximity. Equally important research is being directed to the elucidation of the precise mechanism by which such physical changes as evaporation, drying, filtration, and distillation are carried out, so that the design and dimensions of the corresponding plant unit may be related more precisely to its capacity. All this work and much more is necessary to provide the data without which much of the work of the chemical engineer is necessarily a kind of inspired empiricism. Already it is possible to design some types of plant on rational and scientific lines. By this means, the chemical engineer has definitely increased the efficiency with which individual operations can be carried out. Outstanding examples of such improvements in design are provided by the pipe still and the high-vacuum distillation units that are used in the petroleum refining industry; the forced circulation evaporator, in which remarkably high heat transmission coefficients are obtained by forcing the liquor at high velocity over the heating surface; and the new internally-fed rotary filter, in which the tendency of an irregularly-sized slurry to segregate is utilised to improve both the efficiency and rate of filtration. These are typical of a large number of developments that are resulting from an intelligent understanding and application of the scientific principles underlying the different unit operations.

The training of scientific men for industry is a matter of the greatest importance to the community. It is difficult for a man to get a university training in this country that will equip him for the profession of chemical engineering. He can get a training in pure science and learn how various substances behave under ideal conditions. But he must find out for himself how to translate the ideal into the real, when he has exchanged the laboratory for the factory. This is a fundamental mistake. The universities were established in the first instance for the purpose of training students for the professions—law, medicine and the Church. The training they provided was definitely vocational, combining theory with application. The tendency in some universities to-day to look askance at vocational courses is, therefore, entirely without justification. Chemical engineering, as I see it, is not simply a particular form of applied science; it is an attitude towards manufacturing industry which, being based upon a systematic knowledge of the fundamental realities of which industry is the expression, sees it clearly because it sees it whole. Industry in a scientific world needs scientifically-trained men to plan and control its various processes. It needs such men, also, to direct its policy and development with a sensitive finger upon the pulse of scientific progress. To these men will fall the task of directing industry and society through the economic and social changes which, even now, are resulting from the widespread impact of science upon our industrial and social system.

The training of these men is essentially a task for the universities. It must be based upon a systematic treatment of the fundamental sciences and of the way in which they can be applied constructively to the solution of industrial problems. It must be infused with the spirit of research and progress. It must enable the student to cultivate a frank outlook and an unbiassed judgment. It should arouse in him a sense of enterprise and vocation. The present method of training chemical engineers which obtains in the University of London is to supplement an Honours Degree course in chemistry or engineering by a post-graduate course in chemical engineering. This post-graduate course consists of a systematic training in the principles and practice of such subjects as the flow of fluids, the transmission of heat, the mechanical and chemical properties of different materials of construction, the principles of mechanical engineering, the production and distribution of energy in a works, and the design and operation of the different unit types of chemical plant. The theoretical treatment is supplemented by good problems classes and reinforced by practical courses in the machine shop, drawing office, and industrial laboratory. During his training, the student pays frequent visits to selected works to study plant design and operation on the spot, and is encouraged to obtain vacation employment in a works. Thus, he acquires a first-hand knowledge of works organisation and atmosphere. The complete course provides him with a well-founded, systematic training, both in the theory and practice of his profession.

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