Design and control of chemical process systems

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Introduction

Because words are inadequate to define scientific facts, mathematics has become the language of science although words are the more natural means of expression. To many engineers and applied scientists, understanding and expression do not come easily in mathematical terms, and their excessive use can make practical interpretation more difficult. It is often not necessary, and never sufficient, that an engineer should follow the rigorous logic of mathematical derivation; it is always necessary, and often sufficient, that he understands the principles and relationships on which realities are based.

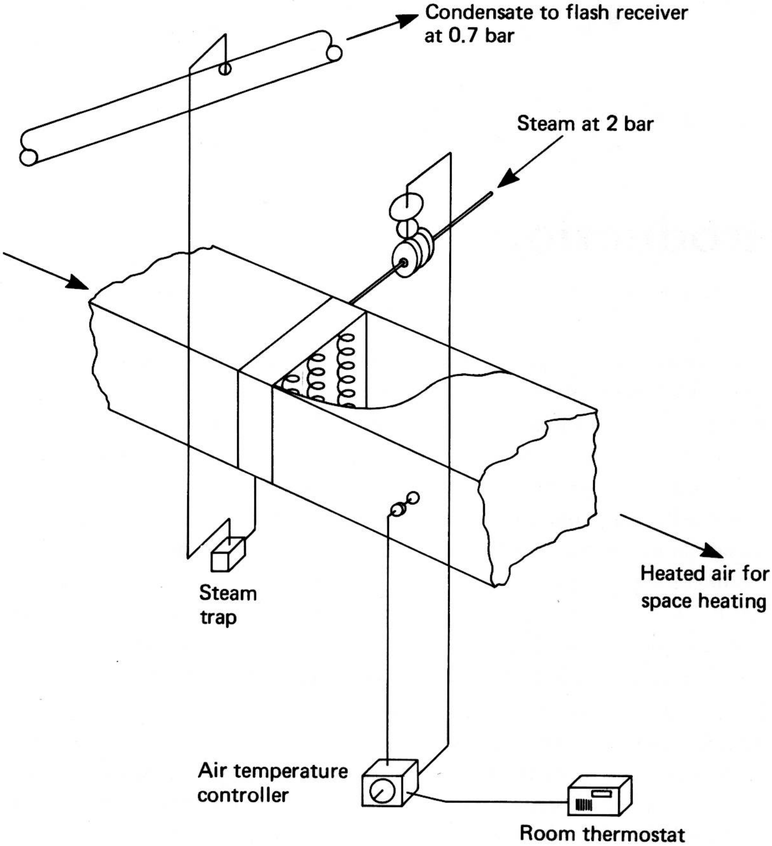
This book is devoted to introducing the concepts and some of the techniques available for the design of process plant systems. For any system to perform its intended functions it must be carefully designed, as a system.

The diagram shows the components of a simple space heating system. Steam heats the air by means of a finned tube heat exchanger and the temperature is controlled automatically by positioning a throttling valve in the steam line, condensed steam being discharged to a collection main above the heater and duct: a simple system and a very common arrangement. The plant manager is at a loss to understand why such a simple system is so much trouble. The control of the air temperature is hopeless, the steam traps cause water hammer and the heat exchanger unit has failed twice in six months with leaking welds. The appropriate plant engineers have investigated each problem, the utilities engineer the steam traps, the mechanical engineer the weld failures, and the instrument engineer the poor performance of the controls, but none of them can find the answer to his particular problems.

There are not three separate problems but one, and the cause is poor system design. There is nothing wrong with the construction of the heater or the steam traps or even the control mechanisms, but there has been inadequate appreciation of the behaviour of these as component parts of a *system*. How *do* they behave?

Before we can begin to answer that question we must define:

1. What is the system required to do?
2. Under what circumstances is it required to do it?



The system is intended to supply air at a steady rate and at such a temperature as will make up for the heat losses from the building. It is required to do this under a wide variety of environmental conditions, outside air temperatures of −5 °C to +15 °C and varying wind velocities. The heater has been designed to transfer the maximum quantity of heat required (at −5 °C, etc.) from condensing steam, through the metal finned tubes, into the air. The steam trap is designed to discharge condensate while preventing the premature escape of steam. The control valve is designed to pass the quantity of steam required to be condensed at any time to achieve the air temperature demanded by the controller. Each of these components has been tested and performs its design functions satisfactorily, so why does the system not perform *its* function satisfactorily?

The quantity of heat transferred from steam to air depends on the surface available for the steam to condense on and the temperature gradient across it from steam side to air side. The steam condenses at a fixed temperature which depends on the steam pressure at the condensing face. The heater will undoubtedly have been overdesigned to provide a margin between its actual maximum heat transfer capability and the maximum duty required: even at maximum duty, therefore, the steam temperature will have to be lower than that for which the heater was designed in order to satisfy the heat transfer requirement. At low duties in spring and autumn the temperature difference across the full heat transfer surface might have to be about one-tenth the maximum. Now steam at approximately 2 bar condenses at 134°C. Under the dictates of the controller the valve progressively closes until the quantity of steam actually condensing equals that passing through the valve from the high pressure side to the lower pressure actually existing at that moment inside the heater. The pressure inside the heater can be calculated as follows:

Air temperature required	20 °C
steam temperature at 2 bar (Gauge)	134 °C
temperature difference steam/air	114 °C
required temp. diff. at one-tenth load	11.4 °C
hence required steam condensing temp.	(20 + 11.4) = 31.4 °C
corresponding pressure	approx. 45 mbar (abs)

This state of affairs will never be achieved in fact because long before the pressure has fallen to vacuum conditions the trap will have ceased to discharge condensed steam. In fact the trap will cease to work as soon as pressure in the heater is insufficient to lift the condensate up into the collection system overhead against the pressure (0.7 bar) in that main:

Height of condensate main above trap	approx. 3 m
Total pressure at trap	approx. 1 bar
condensing temperature at this pressure	120 °C
temperature difference steam/air	100 °C
corresponding to load reduction of $\frac{100}{114}$ =	0.88 of design rate

Condensed steam ceases to be discharged and remains inside the heater. The water is still at the condensing temperature at first and so heat is transferred into the air at first at exactly the same rate. The controller in a vain attempt to reduce this excessive rate causes the valve to close fully, shutting off steam altogether (unless it leaks) and eventually, as the collected condensate cools, the heat transfer rate reduces until the air temperature is lower than that required and the controller begins to open the valve. As the steam enters the heater it raises the pressure above 1 bar and the now cold condensate is discharged suddenly into the collection system by steam pressure. The heater is now empty of water, exposing the whole heat transfer surface once again to steam at high pressure and the heat transfer rate again greatly exceeds requirements.

The explanation for all three problems is now apparent. The controller and valve are quite unable to achieve the appropriate conditions in the heater at anything less than full load, if at all. The steam trap is prevented from discharging smoothly and continuously by the attempts of controller to achieve the impossible and slugs of cold condensate are discharged at intervals into the collection system causing water hammer, giving the impression that the trap is not capable of working correctly. Lastly the alternating and uneven temperature gradients within the heater set up stress conditions which, not surprisingly, lead to early fatigue failure at any welded joints.

The system does not appear to have been designed at all; each component has been designed against a definite specification, but no one has seen to it that these specifications reflect the actual behaviour of the component within the system. How could the system have been designed to work properly?

If the problem had been considered at an early enough stage it might have been possible to arrange for condensate to be discharged into a collection system at low level and at atmospheric pressure. If this were so and assuming that the height of the heater above this main exceeded approximately 10 m, a load reduction of about 10 : 1 would be possible with continuous condensate removal because the head of water which will build up in the line between the trap and the collection main now enables the pressure in the heater to be reduced below atmospheric pressure by the pressure equivalent of this head without restricting flow.

It is unlikely that 10 m elevation could be achieved and the condensate return system may have to be accepted as shown in the diagram. In this event we must make sure that sufficient pressure exists inside the heater at all times to force the condensate out. This can be achieved by replacing the throttling valve in the steam line by one in the condensate line between heater and steam trap. The condensate will now be discharged smoothly and continuously, but a level will be maintained in the heater tubes such that the combined heat transfer from condensing steam and cooling water is in equilibrium with that required to heat the air to the desired temperature. This method of operation, however, will only succeed provided the physical dimensions of the heater battery tubes are correctly designed. If the tubes are of excessive diameter and insufficient height, the quantity of condensed steam 'held up' per unit of heat transfer surface will be large (the heat transfer surface being proportional to diameter, the volume to diameter squared). Condensed steam will lose heat only slowly, and rapid changes of heat transfer rate will not be possible. In addition, while steam pressure will force condensate out at an acceptable rate to increase heat transfer by exposing more surface, the reduction of heat transfer by increase of water level will be dependent on the relationship of condensation rate to volume per unit of heat transfer surface. The tubes should therefore be long (high) and of narrow bore if good control of temperature is to be obtained.

It should be obvious already that the 'system design' cannot be isolated from either the design of the process itself or of the physical components which comprise the plant in which the process takes place. It should also be obvious that design of the system is not the same thing as the design of the process or the design of the plant items and it should not, as unfortunately it often is, be left to chance.

1. What is a 'system'

1.1 Level of resolution

'A word,' said Humpty Dumpty, 'means exactly what I want it to mean.' If he had in mind the word 'system,' his remark is not nearly so idiotic as it at first appears. If we are to consider the design of engineering systems as a discipline, it is essential that we start with a clear concept of what constitutes a 'system'. Perhaps the simplest definition, and one which provides a good starting point, is that a system is more than the sum of its component elements. A motor car comprises an engine, gear box, wheels, body, seats, etc., and the engine comprises pistons, crankshaft, carburettor, petrol pump, etc., but any enthusiastic motorist will agree that the total car is much more than just a collection of these 'bits'. What makes it so is the manner in which all these elements perform *together*, to achieve the overall objective, for each is only relevant as a component part of a system. The engine can be considered as a system, but it can also be considered in a wider context as a component part of the system which is the car.

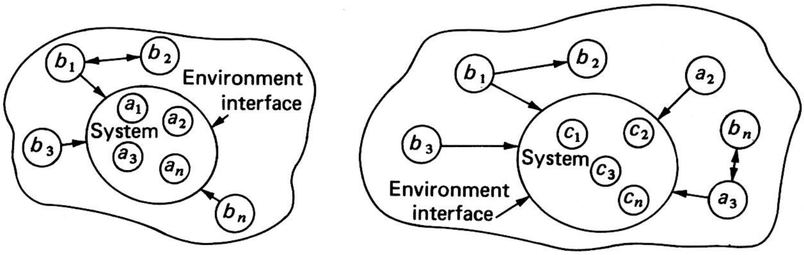
The essential features of any system can be placed in one of two broad categories.

1. The *internal* component elements.
2. The relationships between these elements.

If one of an ensemble of elements is totally unrelated to any of the remainder, it cannot be part of the system since it is not affected by, nor does it have any affect on the system. A suitable definition for a system, then, is an ensemble or collection of two or more *related* elements. Within this definition we can draw the boundaries or limits of a system wherever we wish; for instance, we can consider the car as a system, including the driver, in order to assess how fast it goes, how well it handles, etc., or we may be concerned to assess the performance, torque, fuel consumption, etc., of the engine alone. We are concerned with the performance of the elements of the system under consideration not with their constructional details.

The system we chose to consider receives stimuli from its environment (I) and also influences its environment by producing responses (ϕ) to these stimuli. The car, for instance, pollutes the atmosphere which might be described as an unwanted response—its required response being a change of position.

It has already been noted that an element of the system under consideration may also be described as a system—the engine of the car, for instance. The car itself might be considered an element in a transportation *system.* There is no inconsistency here, for it can be seen from Fig. 1.1 that if the engine is an element a, of the system $a_1, a_2, a_3, \ldots, a_n$ which is the car, we can redefine the terms of reference by including all the other elements $a_2, a_3, \ldots, a_n$ in the environment set, so that $c_1, c_2, c_3, \ldots, c_n$ are elements of the engine (pistons, crankshaft, carburettor, etc.). We have chosen the 'level of resolution'



(a) Car and environment **(b) Engine and environment**

Fig. 1.1.

which we wish to adopt in our study. We could not consider one piston within the engine as a system because it is a single indivisible element from a functional viewpoint and does not satisfy the definition of two or more related elements, but the carburettor could be considered a system in itself.

What then is the utility of the systems approach to engineering design? Engineers have not in the past required such an approach to the design of a car engine or indeed to the design of a car but it is certain that such a project as the moon 'shots' would not have been possible without a rigorous logical approach to the definition and analysis of systems. Established industries, such as the process industries, have developed from rudimentary beginnings methods of operation, construction, and design over many years, and it requires a fundamental change of direction both in management and executive functions to introduce the rigorous approach to design of complex systems which *is* systems engineering. Moreover the success or failure of a project in these industries is not so easily defined as it is with a moon-shot. Nevertheless, there is no doubt that a thorough understanding and application of the basic techniques of systems engineering will produce startling results in these industries and, indeed, is already beginning to do so in the larger and more advanced organizations.

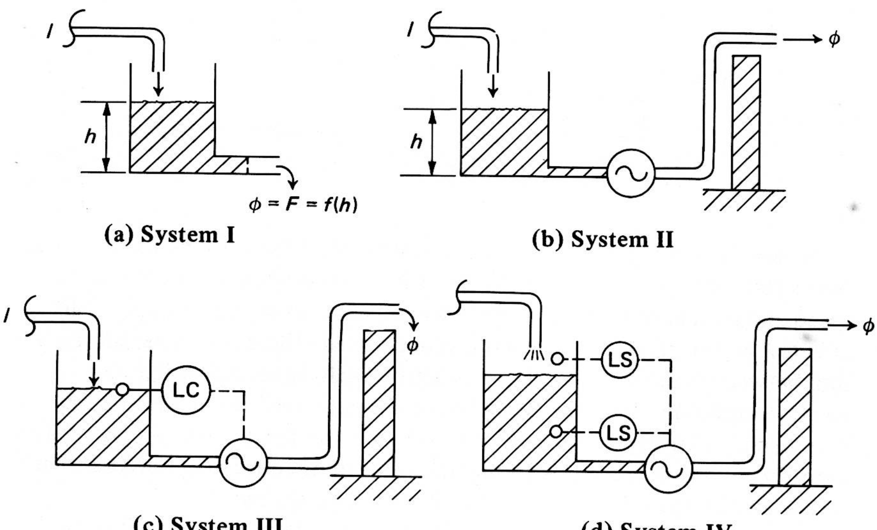
The 'level of resolution' is established by the level of design in which the engineer is engaged; for instance, he may be concerned with the design of a refining column or with the interrelations of complete self-contained process plants forming part of a huge chemical complex. From a systems viewpoint the design of a car engine, for instance, is simple because the interrelations between the elements are to all intents and purposes instantaneous—there is no need to consider the storage of material or energy within the system. The manufacturing process of car engines on a production line, however, *is* a suitable case for applying systems engineering techniques. Even at the lowest levels of resolution within the process industries, design is concerned with the storage or 'hold up' of material and energy and relationships are invariably time dependent. It is this consideration more than any other which dictates the efficacy of systems engineering techniques to any design or analysis problem.

1.2 System states and coupling

The elements of any system are also elements of a larger set or ensemble which we might call the universal set, the remaining elements of which form the environment for the system under consideration. Thus, the remainder of the car is included in the environment of the engine and woe betide the manufacturer who forgets this. The car is part of the environment not the whole of it; the cold outside air which causes the carburettor to ice up is also part of the environment. For the sake of realism we would include in our universal set *all* elements which have any influence on (relationship with) any of the elements of the system under consideration. Since all the elements of the system must by definition be related, any element of the environment influences *all* the elements of the system and we can conveniently consider two sets of elements in adopting the systems approach.

A system which is influenced by its environment is an 'open system' and must exist in equilibrium with its environment. In process systems this implies the laws of conservation of matter and energy, and, except in so far as elements within the system can store either, the rate of gain to the system and the rate of loss from the system of material and energy must be equal. A 'closed system' is one which is entirely isolated from its environment, and such a system must exist in a state of *internal* equilibrium; perhaps the only true closed system is the universe itself. An open system is always part of a larger system which includes the environment of the system under consideration. By establishing the 'level of resolution' we draw in the boundaries of that section of the 'universal set' which we intend to make self-regulating. By doing so we ensure that the system, while performing its intended functions, remains in equilibrium with its environment, for unless it does so it cannot continue to perform its intended functions for any length of time. The behaviour of a system is defined in terms of the 'states' of its internal elements. Each 'system element' will perform some function of storing or transferring either material or energy and its 'state' will be a parameter which reflects this function (some elements may have an energy state and a material state).

The outputs of an open system are a function of some or all of its internal states. Any change in the inputs will affect some of the internal states: if the affect of any change of input is 'coupled' through the interactions of internal states, so that it produces a change in output which tends to restore the equilibrium between system and environment, the system is said to display self regulation. For such a system there will be a unique set of internal states for any given set of inputs. A system which is 'uncoupled' with respect to any input will be driven to some extreme limiting state by the smallest change in that input. Such a system is of no use; it may be modified, however, by the addition of controls to 'couple' the input to the output and make it self-regulating. Four simple systems are shown in Fig. 1.2 in order to illustrate the points made so far. The internal states of system I are h the head in the vessel and F the flowrate of fluid through the fixed restriction. The output is a simple function of F–it is equal to it. The single input influences h which is



(a) System I

(b) System II

(c) System III

(d) System IV

Fig. 1.2.

related to F or ϕ in such a manner that when input I increases, output ϕ responds by increasing also, so restoring equilibrium in respect of material gain and loss. This system, which is 'coupled' in such a manner that it displays 'self-regulation', is stable and has a unique internal state h for each and every value I of the input. It also demonstrates the effect of capacity within a system; a sudden increase in input will result in h *starting* to increase and with it ϕ. It will be some time, however, before h and ϕ attain new 'steady-state' values and restore equilibrium, and meanwhile the system stores both material and energy within the vessel as represented by the increase in h. The rate at which h increases is dependent on the extent of the mismatch between input I

and output ϕ, but, since any increase in h reduces this mismatch, the rate of increase of h becomes less and less and the approach of the system states to their new steady values is as shown in Fig. 1.3.

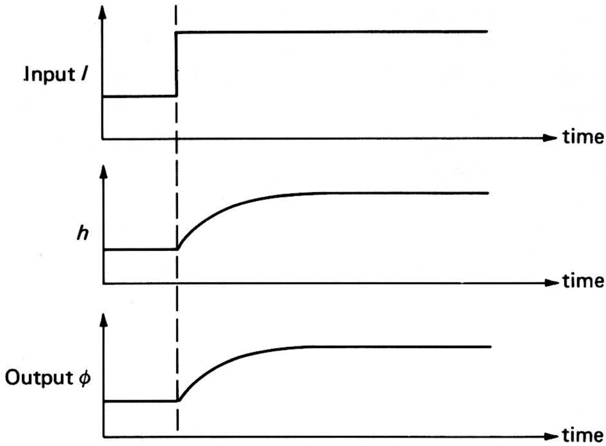


Fig. 1.3.

System II (see Fig. 1.2) is similar to system I but fluid is now pumped out over a wall. The pump is driven by a synchronous electric motor at constant speed and its rate of transfer of fluid ϕ is constant. A change of input still affects h as before, but the output ϕ is uncoupled—there is no internal relationship between h and ϕ. Unless I happens to exactly equal ϕ, h will either increase until limited by the overflow, or decrease until the vessel is empty. The system is 'divergent' and hence unstable, its states tending to diverge from a steady condition when it is stimulated, instead of converging onto another steady condition as does a coupled, self-regulating system.

In system III the addition of a measuring element M and controlling element C establishes a relationship between h and ϕ by varying the pump speed as h varies. The measuring and controlling 'elements' are not system elements since their function is not the storage or transfer of energy or material, but the establishing of a relationship: we shall see later that the controlling and measuring elements must often be considered as system elements when they do store or transfer relatively significant amounts of energy.

In system IV the pump is switched on at high level to pump out the tank and off at low level to allow it to fill up again. When h is between high and low levels the system behaves like system II. The controls added this time, however, cause a steep change of ϕ at discrete values (high and low limits) of h, thus introducing a relationship between h and ϕ. This system does not