APPENDIX

C

PROBLEM SPECIFICATION FOR DISTILLATION

THE DESCRIPTION RULE

As brought out in Chap. 2, the description rule can be used for identifying the number of variables which must be specified in a problem involving a separation process. For single-stage separation processes it may seem simpler to list all variables pertaining to the process and subtract the number of independent equations relating these variables in order to find the number of independent variables which must be specified. As processes and problems become more complex, however, the description rule presents a major saving of time over the method of counting variables and counting equations. This is particularly true for multistage separation processes (Hanson et al., 1962).

Consider the simple plate-distillation column of Fig. C-1 processing a feed of R components. The column is equipped with a series of stages above the stage where feed enters (the rectifying section) and a series of stages below the feed stage (the stripping section). The numbers of stages in each of these sections are denoted as n and m, respectively. We shall consider that these stages are *equilibrium* stages; i.e., the vapor and liquid leaving each stage are in equilibrium with each other.

A reboiler and a condenser are provided. The heat introduced through the reboiler has been denoted as Q_R and the heat removed in the condenser as Q_C. The condenser is a partial condenser.

The pressure in the column is governed by a pressure controller, which adjusts a valve on the overhead product (vapor) line to maintain a predetermined pressure. This fixed pressure is the *set point* of the pressure controller. In order to ensure that operation will occur at steady state, two level controllers have been provided. One of these adjusts the rate of reflux return (or a flow controller governing this rate) so as to hold a constant level (the set point) in the reflux accumulator drum. The other level controller adjusts the bottoms product rate so as to hold a constant level in the reboiler. The feed rate, cooling-water rate, and reboiler steam rate are manually set by means of valves, which are shown.

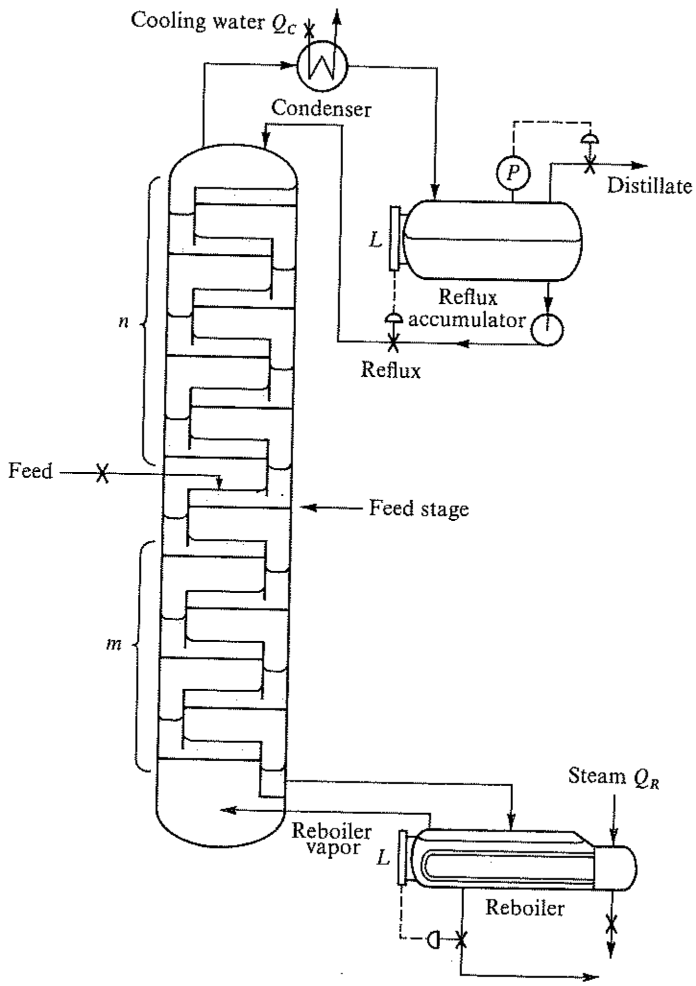

Figure C-1 Typical distillation column with partial condenser.

In order to apply the description rule to distillation we want to identify and count the variables set during *construction* and *operation* of the process: (1) It is apparent that we can arbitrarily set n and m at any values we please during construction of the column. If we pick specific numbers of equilibrium stages for each of these sections of stages, we have set two independent variables. (2) We can operate the column of stages at an arbitrarily chosen pressure by adjusting the set point on the pressure controller. The pressures we can use may be restricted to values between certain limits, but within these limits we are free to make any arbitrary choice, and hence the pressure constitutes another independent variable. (3) We can feed an arbitrarily chosen amount of each of the R components in the feed by altering the feed composition and adjusting the valve on the feed line. This sets R more independent variables. (4) We can arbitrarily set the enthalpy of the feed. This could be done, for example, by adjusting the temperature of the steam in a feed preheater. (5) We can arbitrarily introduce as much heat as we want into the reboiler by adjusting the steam valve or steam temperature. (6)

Again between limits, we can remove an arbitrary amount of heat from the condenser by adjusting the cooling-water flow rate. The set points for the liquid levels in the reboiler and reflux drum are not independent variables. These levels must be kept constant in order for there to be steady-state operation. The particular level in the reflux drum has no effect on the separation process, and the particular level in the reboiler can, at most, affect Q_R, which is already an independent variable.

If the variables set in construction and operation are noted down, the list is:

Amount of each component in the feed	R
Feed enthalpy	1
Pressure	1
Stages above feed entry n	1
Stages below feed entry m	1
Reboiler load Q_R	1
Condenser load Q_C	1
	$R + 6$

These $R + 6$ variables completely describe the process, and if a value is set for each of them, the separation obtained under these values of the variables is completely determined and can be calculated.

While counting the number of independent variables by noting down those set by construction and operation is simple, as a practical matter the particular variables developed in such a list would seldom be set in the description of a given problem. Any or all of them could be replaced with other independent variables to which we are more interested in assigning values. In essentially every problem description, however, certain of the variables just listed will be set, namely, the variables describing the feed and the variable of pressure. If these are excluded from the variables to be further considered for setting or replacement, the remaining variables total four: n, m, Q_C, Q_R, independent of the total number of components. Thus, in describing any distillation problem concerning the column of Fig. C-1, after the feed and pressure have been set, four more independent variables must be set.

The variables which might be used to replace the four listed above could be (1) separation variables, (2) flows at some point or points in the process, and (3) temperatures at one or more points, or in general, any independent variable which characterizes the process. If the column already existed and we wanted to consider the possibility of using it for a new separation, a likely problem might be described by assigning values to the four variables

Stages above feed n
Stages below feed m
Recovery fraction of A in top product $(/_A)_D$
Concentration of A in top product $x_{A,D}$

A second common type of problem is the design of a new column. The separation to be accomplished is specified through two separation variables. A third variable set is usually a flow at some point, often the ratio of reflux to distillate. The fourth variable set is usually the location of the feed. Thus the problem could be described by the four variables

$(/_A)_D$
$(/_B)_D$
Reflux ratio (reflux flow divided by distillate flow)
Feed-stage location

where A and B are two components of the feed.

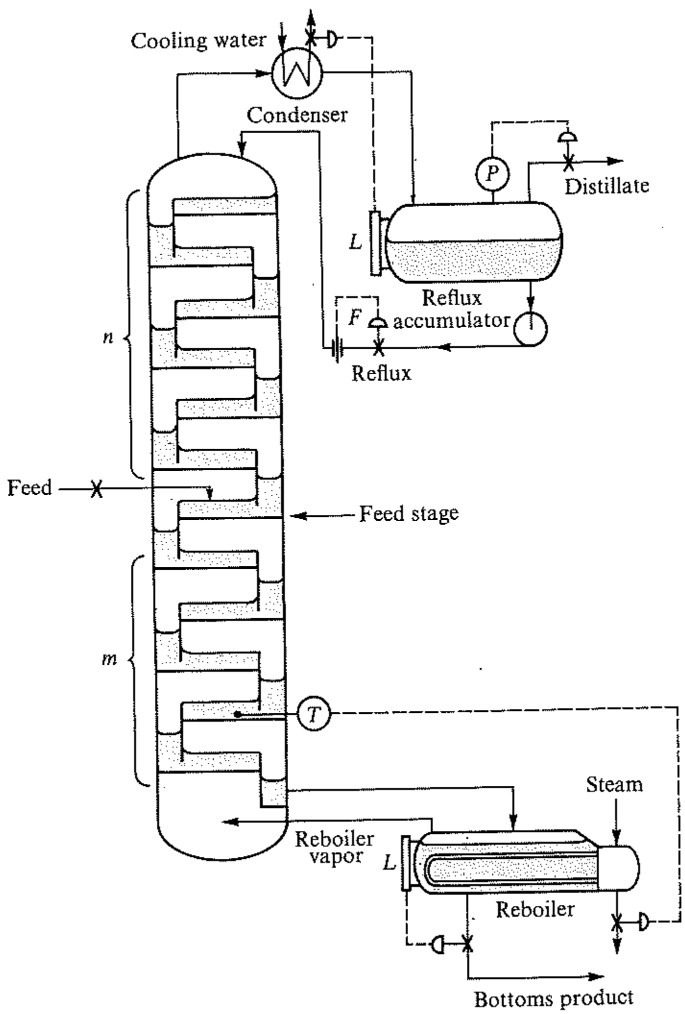

Figure C-2 Alternate control scheme for distillation column of Fig. C-1.

The *number* of independent variables which are set during construction and operation does not depend upon the type of controllers put on the tower. Figure C-2 shows the same tower as in Fig. C-1, but certain changes have been made in the control scheme. The level controller now governs the cooling-water flow rate, the reflux flow may be set by a valve or flow controller, and the reboiler steam rate is controlled by a signal from a thermocouple measuring the temperature of the second stage from the bottom. In this scheme the condenser must be overdesigned. Aside from pressure and feed variables, the following variables have now been set by construction and external means:

Stages above the feed n
Stages below the feed m
Temperature of second stage T_2
Reflux flow rate r

The number of independent variables has not changed. For example, Q_C and Q_R can no longer be independently set by adjusting valves, but T_2 can now be held at a determinable set point (within limits), and r can now be adjusted independently by means of the valve. There are still four additional independent variables. Other control schemes could be shown, all with the same result.

Our approach to the description rule so far has involved the assumption of equilibrium stages; yet if we build five plates in a distillation column we do not necessarily obtain the action of five equilibrium stages. The degree of equilibration of the vapor and liquid stage exit streams will depend upon such factors as the flow patterns on the plate, the intimacy of contact provided between vapor and liquid, etc. However, we are justified in saying that we have provided through construction the action of n *equilibrium* stages above the feed stage and the action of m *equilibrium* stages below the feed stage; n and m are numbers of equivalent equilibrium stages rather than the actual number of plates provided.

TOTAL CONDENSER VS. PARTIAL CONDENSER

If the column of Fig. C-1 is changed by using a total condenser at the top rather than a partial condenser, the column shown in Fig. C-3 results. If the variables defining the feed and the pressure are considered set, the remaining variables are found to be

Equilibrium stages above feed stage n
Equilibrium stages below feed stage m
Reboiler heat duty Q_R
Condenser heat duty Q_C
Reflux flow rate r

Here the remaining variables number five, compared with four for the same column using a partial condenser. In Fig. C-3 it is apparent that the liquid flow leaving the condenser can be split in any desired ratio by adjusting the valve in the reflux line. With a partial condenser, on the other hand, the ratio of distillate to reflux is set by the percent vapor in the total stream leaving the condenser. Thus in a problem description for a distillation column with a total condenser one more variable must be set independently than for a problem where a column has a partial condenser.

A certain amount of consideration reveals that the five variables for a column with a total condenser cannot all be replaced by separation variables or by other variables which influence the separation. This results from the fact that the amount of reflux and the amount of heat removed in the condenser are both controlling only one variable which affects the fractionation, namely, the *internal* liquid flow in the section of the column above the feed; r and Q_C are not independent of each other. One can increase the internal liquid flow either by increasing the reflux flow rate or by increasing the condenser duty while holding the rate of reflux return from the accumulator drum constant. In the latter case the reflux would become cooler and would produce more internal liquid flow when equilibrating with the vapor on the top stage. Hence, if one of these two variables were changed to change the fractionation, the other variable could be changed in reverse direction to return the fractionation to its original condition. This is not true of any other pair of variables we have listed for the case of a total condenser.

Five variables must be set to describe a problem for the column of Fig. C-3 nevertheless. Since all the five listed cannot be replaced with variables which independently affect the fractionation, it is necessary to set at least one variable associated with the condenser load or the reflux. Often this is done by simply specifying the temperature of the reflux, normally with

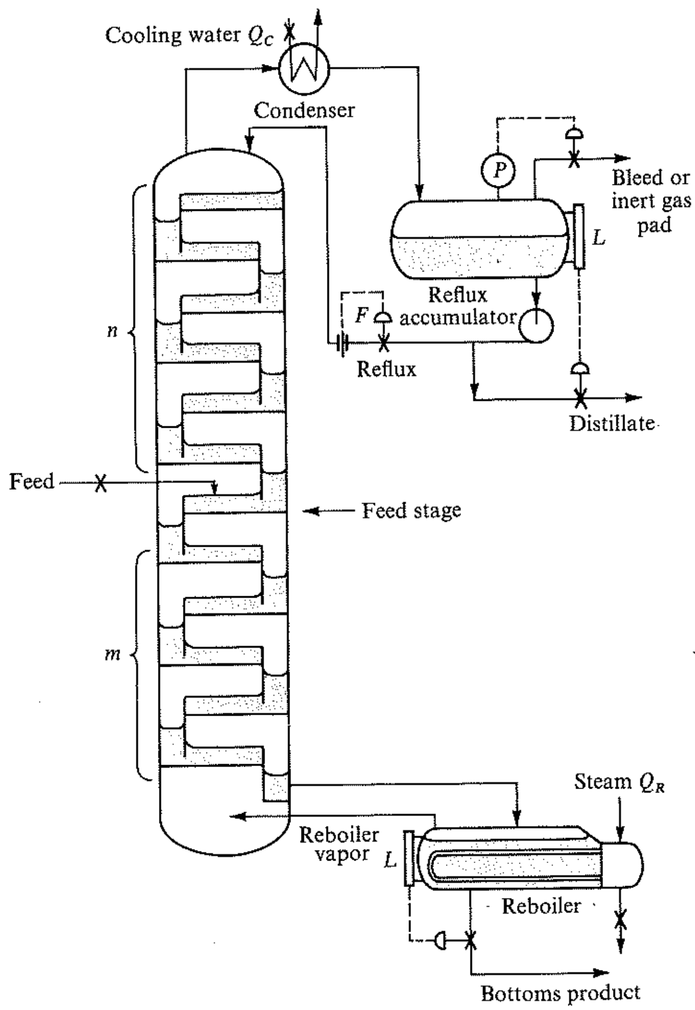

Figure C-3 Distillation column with a total condenser.

the statement that the reflux will be liquid at its saturation temperature or at some other set temperature.

RESTRICTIONS ON SUBSTITUTIONS AND RANGES OF VARIABLES

There are several other restrictions on the process of substituting variables. An obvious one, already mentioned, is that some prospective independent variables can be varied only *within limits.* For instance, in the column of Fig. C-1 with a partial condenser the product streams leave as thermodynamically saturated streams. As a result the overall enthalpy balance with a given feed will limit the extent to which Q_C and Q_R can change with respect to each other. Also the distillate rate cannot exceed the feed rate. The number of stages cannot be less than the minimum for the desired separation, nor can the reflux ratio or boil-up ratio be less than the minimum, etc.

In principle, more than two separation variables can be set in the problem description (Forsyth, 1970), but this is difficult since any separation variables beyond the first two will be bounded within a narrow range. For example, with a four-component feed one can readily set recovery fractions for two of the components, i.e., the keys, but setting a recovery fraction for a third component, e.g., a nonkey, can only be made within the narrow range of possible distributions for that component, given the set recovery fractions for the first two components and all combinations of reflux ratio and number of stages (see Distribution of Nonkey Components in Chap. 9).

If the feed rate is set, we cannot substitute both b and D as additional independent variables. Once F and b are specified, D is immediately fixed by overall mass balance. Any variables *uniquely related by a single equation or subset of equations* cannot be specified independently.

The feed rate or some capacity variable (a rate per unit time) must remain as an independent variable or else the list of independent variables will be reduced by 1. The quality of separation obtained is independent of the capacity if there are equilibrium stages. In the case of the column of Fig. C-1 we could specify the separation completely through the following list of variables, although the capacity would be indeterminate.

Feed composition z_i	$R - 1$
Feed specific enthalpy h_F/F	1
Pressure P	1
Stages above feed stage n	1
Stages below feed stage m	1
Reboiler duty per unit feed Q_R/F	1
Condenser duty per unit feed Q_C/F	1
	$R + 5$

By eliminating all variables having to do with the actual capacity of the column for processing feed (number of moles processed per unit time) we have reduced the number of independent variables by 1 from $R + 6$ to $R + 5$. Note that there are only $R - 1$ feed *composition* variables since Σz_i must equal 1.0.

OTHER APPROACHES AND OTHER SEPARATIONS

The method of counting variables and counting equations has been applied to distillation by Gilliland and Reed (1942) and Kwauk (1956), the results giving the same number of independent variables as the description rule. The method of counting variables and equations is also covered in the first edition of this book, along with examples of applications to several other types of separations.

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