11 Process design: an exercise and simulation examples

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Introduction

One aim of process engineering is the design of process equipment and process flowsheets. The previous chapters in this book have described the scientific and engineering fundamentals of the design of process plant. This chapter allows the reader to develop the skills demonstrated previously, by carrying out a design exercise.

The example chosen is of a plant to manufacture a range of products from milk: cheese, whey protein concentrate, butter and alcohol. The stages of the design follow the stages discussed throughout the book.

It is first necessary to develop the flowsheet, using the ideas of Chapter 1 to follow the flows of all the streams through the system, and to identify areas where heat or cooling is required.

Once the basic flowsheet has been developed, and individual stream flowrates quantified, individual plant items can be designed. The techniques outlined elsewhere in this book can be used to estimate the size of the plant. Specific examples are shown of a tubular pasteurizer (Chapters 3 and 9) and the alcohol producing fermenter (Chapters 8 and 10). Simulations are provided on the enclosed computer disk of the operation both of the whole flowsheet and of these plant items. Computer modelling and computer-aided design is very important in the process industries; the programs given here are very simple, but illustrate the type of problem which can be solved and the use of computers to solve those problems. The simulations also allow an estimate of the cost of the plant and its profitability to be made.

This chapter is divided into two sections. The first outlines an extended design exercise, which is complemented by a spreadsheet program. The second includes details of several simulation exercises, which are also included in the computer disk with this book.

If you work through the design exercise and the accompanying computer-based problems you will learn how to:

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- develop a mass balance within and around a complete process;
- develop energy balances around key operations;
- make a preliminary design of selected operations, including simple heat exchangers (with and without fouling), a spray drier and a fermenter;
- make an overall assessment of the process economics.

11.1 An integrated cheese plant: a design exercise

In this section we outline a more substantial problem, which readers should find a useful exercise in the application of some of the elementary design principles developed in the book. The exercise is based on a published account of an existing plant; in preparing the exercise we have made several simplifying assumptions, both about the process and about some of the basic data, and the reader should not assume that the design here is an accurate representation of the real process. We recommend the reader to attempt to follow through the design stages outlined below, before consulting our 'model' solution, as the point of the exercise is to provide an opportunity for 'learning by doing'.

The solutions to the mass balance and a simplified version of the economic analysis, and solutions to individual designs of a pasteurizer, a spray drier and a fermenter are also provided in a spreadsheet version on the accompanying computer disk. These programs will also provide an opportunity for the reader to explore the consequences of changing selected engineering and economic parameters, such as the feed composition, process efficiencies, product specifications, unit prices and heat transfer coefficients.

Tutors may also find the example, or variations on it, a useful one to adopt for class or group teaching. We have used this example as the basis of an extended preliminary design exercise (over around 10 hours) in our courses using the material in this book.

11.1.1 Process outline

This exercise is based on an extended description of the Golden Cheese Plant of California (see *Chilton's Food Engineering*, March 1986). The reader is strongly urged to read that article in order to gain a full understanding of the process. The process is highly integrated across the various stages of the operation, and it was justifiably recognized in *Food Engineering* as the Plant of the Year in 1985. Our version of the flowsheet incorporates several simplifications to help in the analysis, and we hope that those responsible for the process will be tolerant of our simplifications and any (unintended) misrepresentations.

Equally important, in compiling data and information for the design exercise we have made many assumptions about data and process efficiency, and we must emphasize that these are not meant to represent the actual plant. Wherever possible, we have tried to ensure that our assumptions are reasonable.

A simplified process flowsheet showing only the principal operations and process streams is given in Fig. 11.1. A more detailed flowsheet will be found in the journal article, but it is convenient to give a simplified description of the process based on our flowsheet.

The plant produces four main products from the milk feed: a hard (cheddar) cheese; whey butter; a whey protein concentrate; and concentrated distilled alcohol (ethanol). In addition there are a few additional liquid and gaseous effluent streams. Our calculations do not include the waste treatment of these streams, which is not to deny the considerable importance of this aspect.

We suggest that the process calculations assume a continuous feed based on a daily input of 1500 tonnes of milk to the plant. The milk is held in an intermediate cold store at 4 °C before being fed to the pasteurizer (essentially a heat exchanger operating at around 65–68 °C), and then to a cooler to reduce its temperature at the inlet to the cheese vat to 30 °C. Starter culture and rennin are added in small proportions to the contents of the vat; the cheese-making process results in the solidifying curd, which is salted during the later stages of the process, and an aqueous whey stream, comprising unconsumed proteins, fat, lactose and ash – i.e. mineral salts). The cheese is formed into blocks, sealed, cooled and stored to mature.

The whey stream, meanwhile, is separated into a fat-rich cream and a dilute aqueous stream containing mainly proteins, ash and lactose. The cream is pasteurized as before and used as the feed for butter-making. A stream of aqueous butter whey is a secondary by-product of this operation.

The dilute stream from the separator contains two further potentially valuable components, albeit in low concentration: whey proteins and lactose. In this process the whey proteins are concentrated, using crossflow ultrafiltration, and then spray-dried to produce solid whey protein concentrate. The liquid permeate from the ultrafilters is treated further using reverse osmosis, and some of the ash components are also removed at this stage. Demineralized water is a valuable by-product of this part of the operation, whose main objective is to produce a suitably concentrated lactose solution to serve as the feed to a (batch) fermenter. The anaerobic fermentation produces ethanol in solution, a carbon-dioxide-rich gas stream, and biomass (i.e. spent yeast) for disposal. The ethanol solution is concentrated by distillation to spirit-grade levels; the dilute aqueous bottom product from the distillation process must be treated before final disposal.

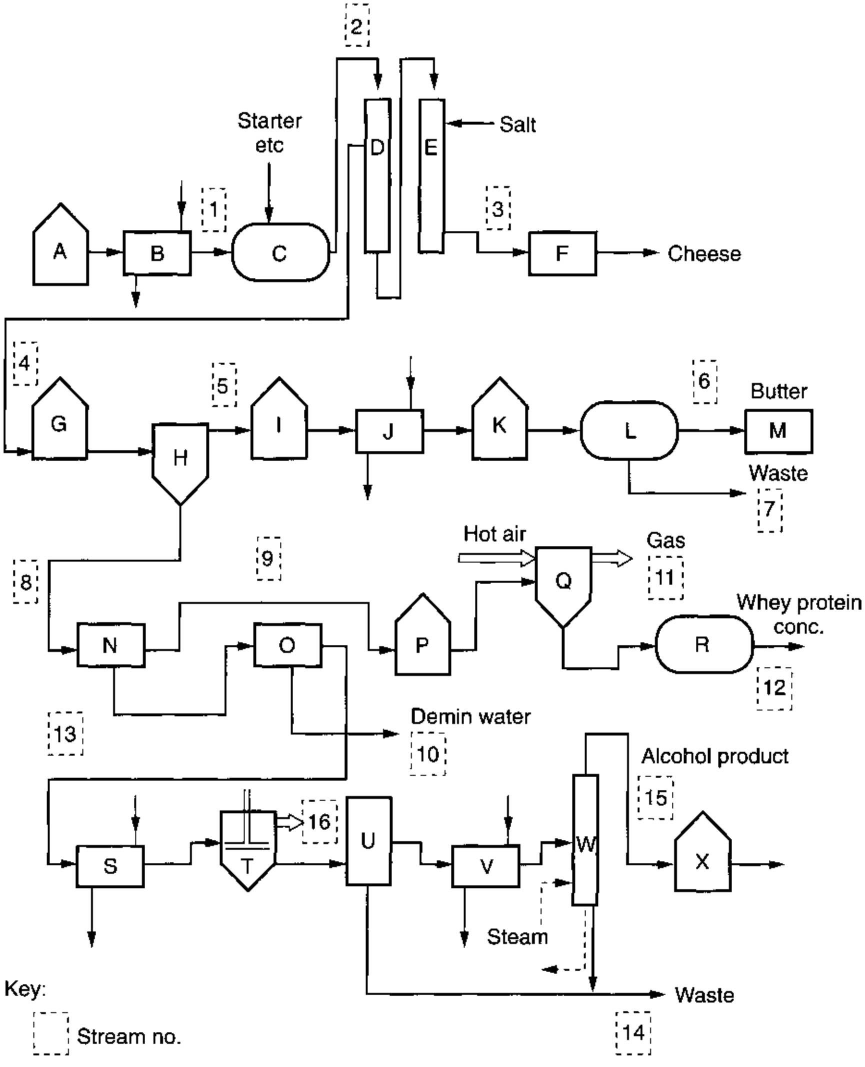

Fig. 11.1 Simplified flowsheet of cheese-making plant: A, milk storage; B, pasteurizer; C, cheese vat; D, cheddar tower; E, block former; F, sealing, cooling and storage; G, whey storage; H, cream separator; I, cream storage; J, pasteurizer; K, cream storage; L, whey butter maker; M, whey butter packaging and storage; N, ultrafiltration plant; O, reverse osmosis plant; P, retentate storage; Q, spray drier; R, whey protein concentrate packaging and storage; S, cooling; T, fermenters; U, broth separator; V, heat exchanger; W, distillation plant; X, azeotropic alcohol storage.

The actual plant has a reported annual intake of 800 million lb (360 million kg) of milk, and produces 80 million lb (36 million kg) of cheese, 5 million lb (2.3 million kg) of whey protein concentrate (containing 50–75% protein), 2.2 million lb of butter and 2.2 million lb of alcohol (1 million kg each).

11.1.2 Suggested design procedure

In reality the first stage in the design process would be the production of a detailed flowsheet showing all the major plant items and the principal flows of materials and services, such as steam and cooling water, and the waste treatment systems. In this case the flowsheet provided may be taken as the basis for the calculations; the reader should first ensure that he or she thoroughly understands the process and the rationale behind the sequence of operations.

Then, the following stages should be attempted.

1. *Material balance over the process.* You should build up a comprehensive mass balance over the whole process in order to define all flows and compositions through the plant. To assist in this process the main streams are indicated on the flowsheet (1, 2 etc.), and the mass balance should encompass all the streams. Section 11.1.3 gives details of input flows and compositions and, where necessary, indicates the suggested assumptions to be made in order to complete the balance over the process units.
2. *Energy balance.* The major energy-requiring operations should be identified and a preliminary estimate should be made of the energy requirements for the plant as a whole.
3. *Detailed unit design.* We have also given additional information on two plant items: the first pasteurizer and the fermenter. This is a sufficient basis for a more detailed process design of these units, including estimation of the equipment size and, in the case of the fermenter, of the power requirements for mixing.
4. *Process economics.* The completed mass and energy balances together with the economic data in the datasheet will allow you to do a preliminary (and very notional) economic appraisal of the plant as you have designed it.

As noted earlier, compiled versions of spreadsheet calculations, which will allow you to check some of your calculations and to carry out some simple sensitivity calculations, are given with this text. In particular, the material balance and economic analyses are contained in the programme CHEESE.XLS. Sample pasteurizer and fermenter designs are contained in PASTEUR.XLS, and CSTR.XLS respectively; an additional program, RECYCLE.XLS, complements the last program by including the possibility of cell recycle to the fermenter. Finally, the programme SPRAYDRY.XLS solves the simultaneous mass and energy balances around a spray drier.

11.1.3 Design data

Suggested values of key parameters needed to complete the material and energy balances are given below. Although the values do not necessarily correspond to the actual values in the Golden Cheese Plant, they are reasonable in the context of this process. You can vary any of the parameters in order to study the sensitivity of the design to the principal assumptions, provided the fundamental constraints (for example, that the components of a mixture must sum to 100%) are not violated.

Suggested design basis: 1500 tonne/day milk

Compositions, yields etc. All compositions are in wt% unless otherwise noted.

1. Milk composition (= feed to cheese vat, stream 1)

Component	Weight (%)
Water	87.2
Fat	3.9
Protein:	(3.3)
Casein	2.7
Whey proteins	0.6
Lactose	4.9
Ash	0.7

2. Starter. Take this to be 1 wt% of milk feed.

3. Rennin. Take this to be 0.01 wt% of milk feed.
(Note: in the calculations count items 2 and 3 as if they were water).

4. The cheese-maker. Assume that the following fractions of these components in the milk feed are retained in the cheese product, stream 3:

Component	$\frac{\text{Component in cheese}}{\text{component in milk}}$
Fat	0.89
Casein	0.94
Whey proteins	0.04

Also, assume that the fat content of the unsalted cheese = 33.1%.

Lactose and ash are incorporated into the aqueous component of the cheese in the same proportions as they occur in the feed milk.

You may compare your results with the following typical approximate compositions:

Cheddar		Sweet whey	
Component	(wt %)	Component	(wt %)
Water	36.8	Total solids	6.5
Protein	24.9	Protein	<1
Fat	33.1	Fat	0.3
C/hydrate	1.3	Lactose	5.8
Ash	3.9	Ash	0.5
		BOD	c. 30000 mg l^{-1}

5. *Salt.* Assume that this is added so as to make 1.5 wt% of the cheese product.

6. *Cream separator.* Assume that the cream (stream 5) is 35 wt% fat and that the bottom product (stream 8, to whey processing) is 0.05% fat.

Assume all other dissolved components in the water phase are distributed between the top and bottom products from the separator in the same proportions as they exist in the feed to the separator.

7. *Whey butter (stream 6).* Assume 95% of fat in the cream is retained in the butter; also assume the butter is 81% fat.

8. *Buttermilk (stream 7).* Neglect any additional wash water added during the butter-making process.

9. *Ultrafilter (unit N).* Assume all the protein is retained in the retentate, stream 9, and that the retentate is 30% protein. Also assume that all the fat is in this stream, and neglect any ash and lactose.

10. *Demineralization and reverse osmosis.* Assume that the units operate so that the feed to the fermenter (stream 13) is <0.5% ash and >4.6% lactose (a reasonable value for this is around 6%). This fixes the amount of water and ash to be removed at this stage.

11. *Spray drier: whey protein concentrate.* Assume that the final product (stream 12) contains 4% moisture.

For comparison with your answer, a typical WPC composition is in the range: 50–85% protein; 1.2–4% fat; 4% + lactose.

12. Feed to fermenter (stream 13)

Lactose	>4.6% (assume 6%)
Protein	<1%
Ash	<0.5%
Yeast extract	$10\,\mathrm{g\,l^{-1}}$
Phosphate	$1\,\mathrm{g\,l^{-1}}$
Mg sulphate	$0.5\,\mathrm{g\,l^{-1}}$
Amm. sulphate	$1\,\mathrm{g\,l^{-1}}$
pH	6–6.4

13. Fermentation. Assume that in this case the fermentation uses the GRAS yeast *Kluyveromyces fragilis*, operating at pH 4 and 38 °C.

	Yield coefficients
$Y_{p/s}$	0.49 kg ethanol/kg lactose consumed
$Y_{x/s}$	0.1 kg cells/kg lactose consumed
$Y_{CO_2/s}$	0.47 kg CO_2/kg lactose consumed

Assume that 98% of the lactose in the feed is consumed in the fermentation. To simplify the calculation assume that all the supplements are utilized.

In sizing the fermenter assume Monod kinetics (Chapter 8) with $\mu_m = 0.3$–$0.4\,\mathrm{h^{-1}}$, with lactose as the limiting substrate and $K_m = 0.1\,\mathrm{kg\,m^{-3}}$.

14. Ethanol product (stream 15). Assume that this product is concentrated to 95% (i.e. the azeotrope).

15. Disposal (stream 14). This will include the spent yeast and the dilute bottom product from the distillation column.

16. Some physical and thermal properties

Milk

Density: $1032\,\mathrm{kg\,m^{-3}}$ at 20 °C
Viscosity: $1.42\,\mathrm{mN\,s\,m^{-2}}$
Mean heat capacity: $3768\,\mathrm{J\,kg^{-1}\,K^{-1}}$
Thermal conductivity: $0.58\,\mathrm{W\,m^{-1}\,K^{-1}}$

Whey: viscosity = 1.16 mN s m^{-2} at 25 °C
Fat: mean heat capacity 2010 J kg^{-1} K^{-1}
Cream: density = 900 kg m^{-3} at 40 °C
Butter: mean heat capacity = 1382 J kg^{-1} K^{-1}
Cheese: mean heat capacity = 2093 J kg^{-1} K^{-1}

17. Some approximate economic data

Installed capital cost (*K*): £100 million
Maintenance (annual cost): 5% *K* p.a.
Discount rate: 10% plus

Unit costs:
Labour: £12000 pa per worker (166 total)
Milk: £0.14/kg
Starter: £0.5/kg
Salt: £20/tonne
Steam: £0.8/tonne*
Electricity: £0.056/kWh*
Power, overall: £60/MWh*
Cooling water: £0.006/tonne*
Waste treatment: £0.2/kg BOD removed
or: £2/m^3 effluent treated

*Note: assume total daily energy and cooling requirements = 60 MWh

Unit prices of products:
Cheese: £1400–1800/tonne
Cream: £1600/tonne
Whey butter: £1400/tonne
WPC: £400–800/tonne
Demin water: £0.4/tonne
Alcohol: £1000/tonne
Spent yeast: £100–300/tonne

11.1.4 Integrated cheese plant: commentary on solution

To help the reader to understand the solution presented in the attached spreadsheet, some notes on the method and assumptions used are presented below. These should, of course, be read in conjunction with the problem statement and the design data above. The programs are written using default values for the major parameters. Most of these can be changed, but we recommend that you save the default version of the programs.

1. Cheese vat (streams 1–4). The unsalted cheese and whey compositions are calculated by assuming that the input comprises milk, starter and rennin (counting the last two as water). The information that 89% of the fat, 94% of the casein and 4% of the whey protein are retained in the cheese allows their masses in the cheese to be calculated directly. The fat is 33.1% of the cheese, so the total weight of cheese can then be calculated. Finally, we assume that the other components (water, lactose and ash) (making up 66.9% of the cheese) are in the same proportion as in the liquid feed to the cheese vat. Thus the quantity and composition of stream 2 can be calculated. The composition of the whey stream (stream 4) now follows directly, from mass balances over the vat on each component.

The composition of the salted cheese (stream 3) differs only from stream 2 by the addition of salt.

2. *Cream separator (calculation of streams 5 and 8).* There are two steps in this calculation.

The first stage is to calculate the flow split across the separator. To illustrate the method, let the total feed be F and its fat content be f. Let the top and bottom output flows be T and B, with fat contents x (= 0.35) and y (= 0.0005) respectively.

Then mass balances give:

$$\begin{aligned} &\text{Overall:} \quad && F = T + B \\ &\text{Fat:} && Ff = Tx + By \end{aligned}$$

Knowing F, f, x and y the two equations can be solved for T and B, and the quantities of fat in each calculated.

The remainder of these streams is the water phase, containing lactose, ash etc. in the same ratios, that is, on a fat-free basis, as in the feed F (see Example 1.2, Chapter 1). Then the aqueous phase components can be computed using a fat-free basis for this part of the calculation.

3. *Whey butter production (calculation of streams 6 and 7).* This involves a similar calculation: knowing that 95% of the fat in stream 5 (the feed) is retained in the butter, and that this is 81% fat, allows one to calculate the fat in the butter, the total butter and, by difference, the sweet whey stream. The composition of the aqueous phases in these two is calculated as in the previous section.

4. *Ultrafiltration and demineralization plant (calculation of streams 9, 10 and 13).* The retentate (9) is calculated directly, knowing that it contains all the protein and that the protein is 30% of the stream. We have assumed that the retentate contains all the fat from stream 8 but no lactose and ash.

Stream 13 contains all the lactose from stream 8; knowing its concentration (here 6%), allows one to calculate the total of stream 13.

We have also assumed that stream 10 from the reverse osmosis plant is pure water plus an ash-rich stream (which for mass balance purposes only are shown as if they were one stream); the ash in this stream must be sufficient to ensure that stream 13 (whose total is already calculated) contains 0.5% ash.

5. *Spray drier (streams 11 and 12).* Stream 9 is the feed. All the protein ends up in the dried concentrate; the total concentrate is readily calculated as it has a moisture content of 4%. The air requirements are not included in the calculation. However, see also section 11.2.6.

6. *Fermenter (streams 14–16).* The composition of the inlet stream (13) assumes a lactose concentration of 6% and an ash content of 0.5%; the other supplements are added in the concentrations specified on the datasheet. The calculation assumes that 98% of the lactose is consumed.

The gas stream may be calculated by assuming that it contains all the carbon dioxide produced (knowing that 0.47kg are produced per kg of lactose used up). The composition of the liquid stream from the fermenter follows by a similar process of calculation, assuming that all the supplements are used up.

The waste streams are calculated by assuming that they together include all the yeast biomass, any residual components (such as lactose) and water. The ethanol concentration in the waste stream has been assumed to be zero in this calculation.

11.2 Computer simulations

11.2.1 Introduction

The computer simulations included on the disk are designed to illustrate selected aspects of the material in this book and, in particular, aspects of process design and control.

No previous knowledge of computer operations is required to run the programs, which run under DOS.

Most simulations presented here are written in Excel. You need this spreadsheet program, or one compatible with it, on your hard disk to run the programs. Instructions on how to load the main program and the simulations are given below. One simulation concerned with process dynamics and control has been written in TurboBASIC and can be called up directly once the computer is switched on and the operating system loaded.

Each simulation is briefly described below.

Spreadsheet simulations. Copies of several spreadsheet simulations are on the disk. Each is described in some detail in the following sections.

To load the programs

- Load the disk in the floppy drive (e.g. drive A)
- Open Excel
- Open the desired program from drive A.

Programs included (entitled NAME.XLS)

- CHEESE: This is a simplified model of the integrated cheese-making plant described in section 11.1. It features the unit-by-unit and overall material balances and an economic evaluation.
- PASTEUR: This is a steady-state design of a continuous shell-in-tube heat exchanger to be used for milk pasteurization, with either steam or hot water as the heating fluid. It corresponds approximately to the pasteurizer (plant item B) in the cheese-making plant.
- CSTR: This simulates the operation of a perfectly mixed continuous anaerobic fermenter with Monod kinetics.
- RECYCLE: This simulates the continuous fermenter with cell recycle. This and the previous program can be used to design the alcohol fermenter in the cheese plant.
- SPRAYDRY: This simulates the steady-state operation of a spray drier, based on simultaneous mass and energy balances. It can be used to carry out a preliminary design of the spray drier used for whey protein concentrate production in the cheese plant.

Process dynamics and control simulation. This simulation is written in TurboBASIC and is compiled to run directly under DOS without the need of any other program. The program is called CONTROL and is a simulation of a feedback temperature control system in a continuous liquid heater tank. It shows the dynamic response of the system to a step change in the feed temperature. Two control laws (P and PI) can be selected and the effect of time delays can be studied.

The program can be loaded directly from the floppy drive (e.g. drive A) by typing **A:CONTROL**.

11.2.2 Integrated cheese production simulation

Program: CHEESE.XLS. This spreadsheet simulates a mass balance and an economic analysis for the main components in the integrated cheese plant described in detail in the design exercise presented in section 11.1. The program is preloaded with default parameters and design assumptions (see sections 11.1.3 and 11.1.4 for details) but you can change many of these, just as with the other spreadsheet programs. Data can be entered only in unprotected cells, which are highlighted on the screen. Process data, such as compositions, process unit parameters etc. can be input into screen 1;

economic data and parameters can be entered via screens 4 and 5. The program can be used to estimate the effect of changes in these parameters on the engineering and economic performance. The feasibility of the project is measured in terms of its net present value and internal rate of return.

11.2.3 Heat exchanger simulation

Program: PASTEUR.XLS. This simulation solves the steady-state design equations for a shell-in-tube heat exchanger. The heat exchanger is to be used for the pasteurization of a milk stream using either steam or hot water as the heating medium. This operation involves heating up the milk to the pasteurization temperature and then maintaining the fluid under adiabatic conditions for the prescribed pasteurization time, usually in a well-insulated section at the heater outlet.

A preliminary design of an appropriate shell-and-tube heat exchanger to heat up the milk to the pasteurization temperature is simulated here. It is required to estimate the heat load and heat transfer area necessary, together with an estimate of the number and length of tubes and the pressure drop on the tube side. Typical fouling resistances can be incorporated in the calculation; by comparing the sizes of the exchanger that result, some estimates of a design fouling resistance and final heat exchanger size can be made.

Default values for all the parameters have been saved into this program, so that the program will produce a filled screen. Data input by the user is allowed in those cells that are highlighted on your screen; the contents of some cells, especially those containing formulae, are protected and should not be changed. If you try to enter new data into these cells a message that the cell is protected will appear. The user can specify the principal operating parameters, such as flowrates, pipe diameter, the fluid velocity in the pipe, all temperatures and the steam and water film heat transfer coefficients.

Design equations. The equations used are based on the heat exchanger design in Chapter 3, namely:

$$Q = Wc_p\Delta T = AU\Delta T_{\mathrm{lm}} \tag{3.25}$$

where W and ΔT are the flowrate and temperature increase of the milk stream. The overall heat transfer coefficient, assuming thin-walled tubes, is given (see section 3.3.3) by

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} + R_{\mathrm{F}} \tag{9.42}$$

where h_1 and h_2 are the process (i.e. milk) and heating-side heat transfer coefficients, and R_F is the fouling resistance. The process or tube-side coefficient is given by the Dittus–Boelter equation:

$$Nu = 0.023\,Re^{0.8}Pr^{0.4} \tag{3.18}$$

The shell-side coefficient depends on the heating fluid; either steam or water can be chosen. In the first case, the user specifies the steam-side temperature. With water as heating fluid, the inlet and outlet temperatures can be specified. The user can also supply values for the shell-side coefficient, for which representative default values are given in the program. The user can also supply values of the fouling resistance R_F.

Data. Assume a milk flowrate of 1500 tonnes day^{-1}, at an inlet temperature of 4 °C. Assume a single-pass exchanger. The manufacturers recommend tube-side operating velocities of ca. 1.5 m s^{-1} inside 2.5 cm external diameter tubes of 1.6 mm wall thickness. Saturated steam at 3 bar is available; this can be used directly or to heat water to 80 °C.

Suggested shell-side heat transfer coefficients are: 4 kW m^{-2} K^{-1} if steam is used, 1.5 kW m^{-2} K^{-1} for water. Estimates of fouling resistance: at $t = 0$, exchanger is clean; final resistance to be between 10^{-4} and 2×10^{-3} m^2 K W^{-1}.

Mean thermophysical properties of milk:

Density, ρ: 1032 kg m^{-3}
Specific heat capacity, c_P: 3.768 kJ kg^{-1} K^{-1}
Thermal conductivity, λ: 0.58 W m^{-1} K^{-1}
Viscosity, μ: 1.42 mN s m^{-2}

Assume a pasteurization temperature of 68 °C.

The simulation assumes a single pass exchanger; choosing a multi-pass exchanger (which is possible in the spreadsheet) will reduce the length of the exchanger. However, for simplicity, we have not incorporated the true effect of multi-pass operation on the overall heat transfer.

Calculation procedure

- Given the flowrate, mean velocity and tube diameter, calculate the number of tubes, *Re*, *Pr*, *Nu* (from equation (3.18)) and thus the tube-side heat transfer coefficient.
- Given the shell-side coefficient and fouling resistance, calculate the overall heat transfer coefficient U from equation (9.42).
- Given the milk flowrate and temperature rise, calculate the heat duty, log mean temperature difference ΔT_{lm} and, from equation (3.26), heat transfer area tube area, and thus tube length.
- Finally, given the tube-side conditions, calculate the friction factor and tube-side pressure drop from equations (2.70) and (2.74).

This last step is NOT included in the spreadsheet.

11.2.4 Steady-state simulation of a bioreactor

Program: CSTR.XLS. This spreadsheet simulates the performance of a continuous well-mixed fermenter with Monod kinetics and constant yield coefficient, and provides the basis for the design of a continuous fermenter similar to the one used in the alcohol production stage of the cheese production plant.

The simulation assumes Monod growth kinetics (see Chapter 8) with the following constant parameters:

$$\mu_m = 0.4\,\mathrm{h}^{-1}$$
$$K_m = 0.1\,\mathrm{kg\,m}^{-3}$$
$$Y_{xs} = 0.1\ \mathrm{kg\,cells\ (kg\,substrate)}^{-1}$$

The yield coefficient Y is defined in Chapter 1. These parameters are fixed.

Assuming Monod kinetics (equation (8.13)), the equations for the outlet substrate and cell concentrations for a continuous steady well-mixed reactor (section 8.3.4) with sterile feed are

$$c = \frac{K_m D}{\mu_m - D}$$

and

$$x = Y_{xs}\left(c_i - c\right)$$

The user can explore the consequences on c and x of changing the inlet substrate concentration c_i, feed flowrate and fermenter volume (i.e. dilution rate, $D = Q/V$). It is also interesting to study how the productivity $\mathcal{P}$ (i.e. production rate of cells per unit volume of fermenter) varies with dilution rate (i.e. residence time). The productivity is given by

$$\mathcal{P} = Dx$$

Based on the simulation here you are recommended to undertake a specific exercise to design a continuous fermenter to convert the lactose stream to ethanol in the continuous cheese-making plant. For this, assume a liquid feed (stream 13 in the flowsheet) of 1150 m^3/day, with a lactose (i.e. substrate concentration) of 6 wt%. You may also assume a yield coefficient Y_{ps} = 0.5 kg ethanol/kg lactose consumed; also assume that the ethanol production is growth-related (that is, the rate of ethanol production is directly proportional to the rate of cell production). The maximum productivity for ethanol production thus corresponds to the point of maximum cell productivity. The design process involves:

- the choice of optimum dilution rate D (which should be chosen to maximize productivity);

- estimation of the fermenter volume, for the specified flowrate;
- assuming a standard configuration, calculation of the fermenter dimensions;
- calculation of the input and output concentrations, flowrates and ethanol productivity.

Having sized the fermenter you can then estimate the mixing power requirements. Assuming a standard fermenter configuration, you should calculate the power requirements for selected Reynolds numbers using the power number/Reynolds number curve (Fig. 10.11). For each condition you can calculate the stirrer-tip speed and the characteristic mixing time in the fermenter. On the basis of this information, recommend a suitable set of conditions. Assume that the broth properties are the same as water.

Note that only the cell growth part of this exercise is included in the spreadsheet.

11.2.5 Steady-state simulation of bioreactor with cell recycle

Program: RECYCLE.XLS. This spreadsheet, like CSTR.XLS, simulates the performance of a well-mixed fermenter, assuming Monod growth kinetics. Unlike the previous spreadsheet, however, this program includes the possibility of cell recycle. A flowsheet, on which the nomenclature is also defined, is given in Fig. 11.2.

The simulation assumes Monod growth kinetics (see Chapter 8) with the following default values (all of which can be changed):

$$\mu_m = 0.5\,\mathrm{h}^{-1}$$
$$K_m = 0.5\,\mathrm{kg\,m}^{-3}$$
$$Y_{xs} = 0.4\ \mathrm{kg\,cells\,(kg\,substrate)}^{-1}$$

The yield coefficient Y_{xs} is defined in Chapter 1.

Process model. The reader should derive the steady-state equations for the system. The following assumptions have been made in the model simulated here:

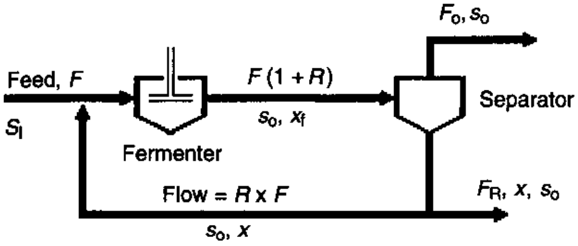

Fig. 11.2 Fermenter with cell recycle.

- steady-state behaviour;
- no reaction outside the fermenter;
- no cells in separator overflow, F_o;
- cell concentration x identical in the recycle stream and in the product stream F_R ($F_R = F - F_o$).

Note that the cell concentration leaving the fermenter, x_F, and the concentration in the recycle (or product) stream, x, are related by

$$x_F(1+R)\,F = x\left[(1+R)F - F_o\right]$$

Calculation procedure. The program is preloaded with the default parameters listed in the table below. All these parameters may subsequently be changed.

Parameter	Default value
Feed flowrate, F	$1000\,m^3\,h^{-1}$
Substrate concentration, c_i	$30\,kg\,m^{-3}$
Overflow, F_o	$0.95F = 950\,m^3\,h^{-1}$
Recycle ratio, R (Recycle = $R \times F$)	0.5 (recycle flow = $500\,m^3\,h^{-1}$)
Volume, V	$1000\,m^3$
Specific growth rate, μ_m	$0.5\,h^{-1}$
Growth yield, Y_{xs}	0.4 kg cells/kg substrate consumed
K_m	$0.5\,kg\,m^{-3}$

It is suggested that readers study the effect of varying the key recycle parameters on the fermenter performance and, in particular, compare its performance (cell concentration, substrate utilization and productivity, shift in washout conditions) with the fermenter without recycle. The simulation reduces to Example 11.8 by setting R and $F_o = 0$.

Finally, the system design for the lactose conversion stage in the cheese-making plant can also be developed here, for comparison with the design in the previous simulation. This program also allows easy changes in the growth kinetic parameters, and you may like to explore the sensitivity of the design to the chosen parameters whose default values are slightly different across these examples.

11.2.6 Mass and energy balance over a spray drier

Program: SPRAYDRY.XLS. This spreadsheet is based on the mass and energy balances developed in Example 1.11 to represent the input/output performance of a spray drier to provide a dried milk product. The default values are close to those used in Example 1.11. The simulation calculates the input air flow, output flows of gas and solid and their compositions when the following parameters are defined:

- input flowrate, solids content and temperature of liquid milk;
- inlet air temperature and humidity;
- outlet solids temperature and moisture content;
- outlet air temperature.

You can readily examine the range of feasible operation and the variation in the input air flowrate with changes in the design conditions.

When you have familiarized yourself with the program, you should then attempt to establish the likely operating conditions for the spray drier in the whey-processing line of the cheese-making plant (i.e. stream 9, the retentate stream from the ultrafiltration plant). The whey protein concentrate will normally be at least 70 wt% solids. You should assume that the thermal properties of the dilute whey stream are the same as those built into the program as default values.

You should also calculate the energy input (i.e. as hot air) into the process in order to study how this varies with the design conditions. This calculation must be performed manually.

11.2.7 Simulation of the dynamics and feedback control of a simple process

Program: CONTROL.EXE. This simulation is compiled and, therefore, can be run directly from the operating system. Simply type the command **CONTROL**, making sure that the current drive corresponds to that where the CONTROL.EXE file is located: for example, if your disk is loaded in drive A type **A:CONTROL**.

The simulation is based on a dynamic model of a stirred continuous heat exchanger with feedback temperature control.

The process model is a set of ordinary differential equations representing the mass and energy balance around the heater:

Mass balance:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = F - F_\mathrm{i}$$

Energy balance:

$$\frac{\mathrm{d}\left(V\rho c_p T\right)}{\mathrm{d}t} = F_\mathrm{i} T_\mathrm{i} - FT + Q$$

where V is the heater liquid volume, F is the volumetric flowrate, T is the temperature, ρ is the liquid density, c_p is the liquid specific heat capacity (both are assumed independent of temperature); the subscript i denotes feed conditions. The steady-state model parameters give an open-loop time constant of 10 min. Q is the rate of heat input, controlled by a feedback temperature controller, and is a function of the deviation between the outlet temperature and the temperature set point (T_{sp}):

$$Q = Q_o + f\left(T - T_{sp}\right)$$

Q_o is the steady-state heat input, while the function $f(\cdot)$ depends on the type of controller used. The simulation allows the selection of either a proportional (P) or a proportional + integral (P + I) control law:

Controller	Control law = $f(T - T_{sp})$
P	$K_c(T - T_{sp})$
P + I	$K_c\{(T - T_{sp}) + (1/\tau_I) \int (T - T_{sp})dt\}$

where K_c is the proportional gain and τ_I is the reset or integral action time.

The program also enables the user to incorporate a pure time delay in the system response, to illustrate the effect of transmission lags, for example.

After typing in the command **CONTROL**, the user is asked to select either a P or a P + I controller. Next, the parameters for the P or P + I law will be requested. Finally, the user can incorporate a time delay in the system.

The program will then run, illustrating the dynamic response of the system to a step change in the inlet temperature.

Initially, study the dynamic 'open loop' response of the outlet temperature, without control action (that is, select proportional control and set gain = 0 and time delay = 0).

Then compare responses for different values of the controller parameters. Work using P control first and, later, use P + I. Initially, consider the system without time delay. Large values of the proportional gain or small values of the reset time will be seen to correspond to a 'stronger' control action. It will be seen that incorporation of the integral term eliminates offset but, with decreasing reset time, at the expense of an increasingly oscillatory response.

The best set of control parameters would be those that lead to an acceptable level of offset, give a quick return to the set-point temperature, and do not show undue oscillation in the response. By varying the parameters you can select and compare the best set of parameters for both P and P + I control, with and without a system time delay. You will also find that the control loop can become unstable at certain values of the control parameters, and that this problem is made worse by increasing the time delay.

If the program crashes because of an inappropriate input, simply load it again and retry.

To return to the operating system, key simultaneously CTRL-BREAK.

Conclusions

The core of this final chapter is the extended design exercise, which should help put in context much of the material that was treated more formally in earlier chapters. If you have worked through the exercise you should have a good grasp of the methods, and also the difficulties and limitations, of setting up material, energy and economic balances. In addition, the spreadsheet solution which we have provided should have given you the opportunity to assess the sensitivity of the results to the conditions or principal assumptions. We hope, too, that the exercise provides a good model for the important process of checking the consistency and plausibility of descriptions of technologies and processes.

The more detailed examples contained on the disk and outlined in the text should also have provided an opportunity to put into practice some of the material contained in this book.