Model Development and Simulating of a Spinning Cone Evaporator

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Abstract

The idea of milk pre-concentration at the farm has attracted worldwide interest for many years. A new pilot-scale evaporator (called spinning cone evaporator), which can be operated on the farm and has a compact and efficient design, has been developed at Massey University. However, there is a shortage of knowledge on the design, operation and control of this new evaporator. The main goal of this thesis is to develop a dynamic mathematical model in order to better utilize this evaporator and make further developments.

This thesis consists of three parts. Firstly, a first-principles model of a pilot scale spinning cone evaporator is developed using the sub-system modelling techniques of the evaporator from the Laws of Thermodynamics and the general mass and energy balances. The model is dynamic and includes the evaporator, the compressor, the condenser and the product transport sections. The system model describes the dynamic relationships between the input variables (cooling water flowrate, M_c, speed of compressor, N_{comp}, feed flowrate, M_f, feed temperature, T_f and mass composition of feed dry matter, w_f) and the output variables (outlet temperature of cooling water, T_{co}, evaporating temperature, T_e, mass composition of product dry matter, w_p and product flowrate, M_p),

Secondly, the evaporator model was implemented using the software package Matlab along with its dynamic simulation environment Simulink. The differential equations for the evaporator model are embedded in a block diagram representation of the evaporator system. The evaporator Simulink model is divided into three levels, the blocks at the top represent the overall model and global constants used in it. The second level contains the individual sub-systems and the bottom level elements within each sub-system. Results of the model verification are satisfactory.

Finally, the model validation is presented for both steady state and dynamic comparisons. The product flowrate (except in the case of feed temperature changes) and evaporation temperature can be predicted at a given time, and the outlet temperature of cooling water and product dry matter composition can also be predicted at a steady state. It can be seen that the results predicted using this spinning cone evaporator model, which accounts for the varying concentrate flowrate and evaporation temperature with time, are in good agreement with experimental data. This model provides a valuable tool to predict performance in a spinning cone evaporator and to modify the design parameters.

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Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

1.1 Introduction

Evaporation technology is an intensively used process in the dairy industry because it is well suited for concentrating food solutions (Kessler, 1981). The process usually consists of two stages with an evaporator concentrating the milk to a critical dry matter content and then a spray dryer removing the remaining water. Various types of evaporators have been used as part of the powder production process to make whole milk, powder, skim milk, lactose, whey protein concentrates, in fact a very wide range products. Nowadays, the dominant evaporators used in New Zealand are the falling film evaporators.

Although the falling film evaporators are tending to become larger and despite the efforts to improve the efficiency of the process, the evaporation process is still costly. The cost of the bulk material to be stored and transported, however, is still considerably reduced. The conventional evaporation system in the dairy industry is operated as follows: on the farm, the fresh whole milk is first collected in the buffer tank, then is chilled in a heat exchanger and then passed to the storage tank. Finally the whole milk is transported by the tanker to the dairy factory for further processing. The system is shown in Figure 1.1.

With increases in the cost of transporting milk between farms and dairy factories, the concept of the on-farm evaporation system is looking more attractive. When milk can be concentrated on farm and the pre-concentrated milk transported to a factory there will be many benefits; including reduced transportation cost, factory processing cost and effluent, overall energy requirements and refrigeration cost on the farm. If a suitable design is used, taking into account the whole energy consumption on the farm, an evaporation system would be an effective method of on-farm concentration (Jebson et al., 1993).

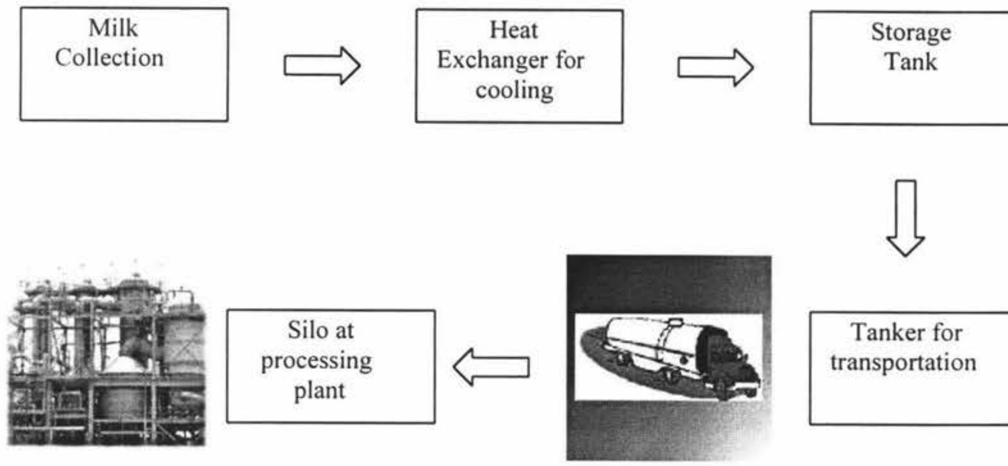

Figure 1.1: The convenient evaporation system in the dairy industry

The process system at the heart of this thesis is a pilot-scale, thin-film evaporator with the rotating heat transfer surface resident in the Institute of Technology and Engineering, Massey University, called the spinning cone evaporator. This plant is a scaled version of the type of process that will be used in the dairy farms and was designed to research the on-farm evaporation system.

The spinning cone evaporator is a compact, on-farm method for pre-concentrating milk. There have been very few studies on this new evaporator, but to better understand this evaporator, a comprehensive study of the model (including a simulation) is needed. This paper presents an application of process modelling to simulate dynamic behaviour of a concentration process in a spinning cone evaporator.

1.2 Objectives of this thesis

The production of milk powders is a major part of the New Zealand dairy industry. The spinning cone evaporator is a newly developed, compact, on-farm method for pre-concentrating milk. It will be used as an important part of an on-farm evaporation system to remove most of the water in the raw milk (Chen, 1997). However, there is a shortage of knowledge on the design, operation and control of this new evaporator. To better utilize this evaporator and make further developments, a comprehensive study of the model and simulation of this evaporator is well motivated. The work, discussed, in this thesis was initiated with the aim of improving this situation.

The objectives of this work can be split into three parts.

1.2.1 Develop Model

A first principle model of a pilot scale spinning cone evaporator will be developed from the Laws of Thermodynamics and the general mass and energy balances. The model is dynamic and includes the evaporator, compressor, condenser and product transportation sections. Considerable attention will be focused on the derivation of the model.

1.2.2 Implement Model

The evaporator model was implemented using the software package MATLAB, along with its dynamic simulation environment SIMULINK. The differential equations for the evaporator model are embedded in a block diagram representation of the evaporator system.

1.2.3 Validate Model

The model validation is to determine whether the model is an adequate representation of the physical process. Some of the model parameters are likely to need adjusting from the theoretical or experimental values in order to improve the model.

A pilot-scale spinning cone evaporator was used for the experimental approach. The research work carried out in this project was intended to satisfy the requirements for the development and control of the spinning cone evaporation system.

1.3 Overview of thesis

The six subsequent chapters in this thesis are:

Chapter 2 reviews the liquid film flow and heat transfer enhancement by surface rotation, spinning cone evaporator, modelling and simulation techniques. It focuses mainly on the evaporation system and application dynamic models, modelling and simulating methodologies applied in related fields.

Chapter 3 presents a detailed explanation of the analytical model that has been formulated for the proposed spinning cone evaporator. The sub-system modelling techniques of the evaporator are used to create the dynamic model that includes the evaporation sub-system, compressor sub-system, condenser sub-system and product sub-system. Each sub-system is analysed and their equations are derived from the first law of thermodynamics and the general mass and energy balances. The main attention is focused on the factors affecting heat transfer and discharge flow in the spinning cone evaporator. The system model has been developed to describe the dynamic relationships between the input variables and the output variables, and to provide a method of better understanding the principle and operation of the spinning cone evaporator.

Chapter 4 explains the model implementation that is to implement a simulation of the system model described in Chapter 3 and to verify the model comparing its simulated output to the spinning cone evaporator, with data calculated from the mathematical equations.

Chapter 5 presents the experimental system and experiment methods for this project. The objective of the experiments to be undertaken is to collect data for validating the model of the spinning cone evaporator.

Chapter 6 explains the model validation for both steady state and dynamic comparisons. It gives the predicted results of the system model and experimental results of actual system. A comprehensive discussion of above results is presented.

Chapter 7 gives the conclusions of this research work and recommendations for any future work.

1.4 General background

Milk is one of the most precious natural materials and has been a basic component of human food for a long time. It is one of the oldest foods and at the same time the most important one. However, in many cases the milk cannot be consumed in its raw form. It needs to be prepared in order to be consumed and digested by humans. During treatment, the chemical and physical modifications can reach such levels that the raw material is distinctly different to the finished product. The non-desirable parts are to be removed or an enrichment or reduction of the nutritional content takes place.

Raw milk formation takes place in the milk gland of the cow. Milk production (called milking) is the discharge of milk from the udder either manually or mechanically.

Milking must be done in such a way that the udder remains healthy, and milk is not damaged. Then the milk is thermized or/and chilled, and can be stored for several days on the farm.

The raw milk is collected on the farm, and then is transported to the dairy factory to process the milk, including heat treatment as a precondition for milk processing. It is a basic process in each dairy plant. The type and intensity of the treatment are selected accordingly.

Processing milk into a wide variety of products requires a highly developed technology (Spreer, 1998). Evaporation is, and no doubt will remain, a major technique used for the removal of water in the dairy industry, although there are other concentration techniques (membrane technology and freeze concentration etc.) being developed. In New Zealand, evaporation is the only process used for the concentration of milk (Chen, 1997).

1.4.1 Evaporation technology

Evaporation is a special case requiring heat transfer to boil liquid. This particular heat transfer application is so common and important that it is treated as a separate unit operation. Historically, the first form of evaporation was the use of a direct fire pot or pan. Later the development of the steam heated pots; the enclosed vacuum pans and multiple effect evaporation expanded the use of this operation and added many economies to the process. Today, evaporation is one of the basic unit operations in use throughout industry (Bhatia, 1983). It is, and will continue to be an important technique used for the removal of water and sometimes other liquids in industry.

There are a variety of evaporation methods and a wide range of industrial applications, however the predominant applications of evaporators are the food industry. Evaporation is extensively used in the food industry for the following reasons (Russell, 1997 and Chen, 1997):

1. Pre-concentration of liquor to further processing, for example before spray drying, freeze and crystallization, etc.
2. To reduce transporting or storage volumes of liquid foods, hence prior to reduce packaging, transportation and distribution costs.
3. To reduce 'water activity' in certain foods by increasing the concentration of soluble solids in order to aid preservation.

4. For the utilization and reduction of effluent.

The number of the food processes that use the evaporators are extensive and include the milk powder, fruit juice, wine, salt and sugar processing. In New Zealand, evaporators are common within the dairy industry. These are used to pre-concentrate the milk before spray drying it to produce the milk powder.

Evaporation as a unit operation in industrial processes needs is done to separate materials (volatile liquid). Successful evaporation needs two things (Nisenfeld, 1985):

1. The necessary heat must be supplied to the liquid.
2. The vapour produced must not be allowed to accumulate above the surface of the liquid; it must be removed immediately.

1.4.1.1 Heat transfer principles in a single effect evaporator

An evaporation stage is referred to as an effect. The principles of evaporator heat transfer are most simply explained for a single effect. A simple single effect evaporator is illustrated in Figure 1.2. A flow of cold dilute solution and heating steam are fed to an effect. The effect brings these two flows into contact via a heating surface transferring heat from the hot steam to the cold liquid. If heat losses are ignored then all the energy given up by the steam is transferred to the liquid solution as sensible heat and latent heat of vaporization. The saturated vapour produced as the liquid boils is separated from the liquid phase and drawn out of the effect. Generally the concentrated liquid is the desired product of the evaporation process.

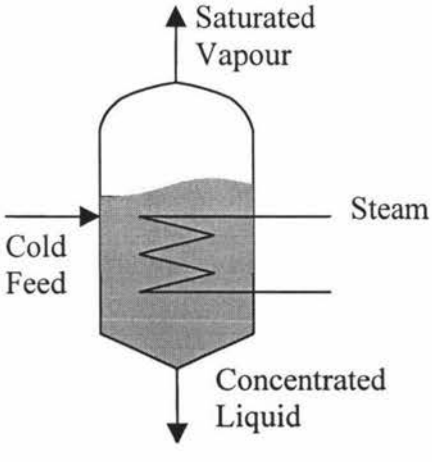

Figure 1.2: Schematic of a single effect evaporator

To analyse heat transfer in this single effect use is made of the basic heat transfer equation (Jebson, 1988).

$$q = U \cdot A \cdot \Delta T \tag{1.1}$$

Where: q is the overall rate of heat transfer, W

U is the overall heat transfer coefficient, W/m^2K

A is the total heat transfer area, m^2

ΔT is the temperature difference between the steam and the boiling liquid, K

A good understanding of this equation is important for the design, selection and operation of evaporators. Each of the four terms in this heat transfer equation 1.1 will now be considered separately.

q, the overall rate of heat transfer, is calculated from an energy balance on the evaporator as follows (heat loss to surroundings is ignored):

$$\begin{aligned} q &= VH_V + LH_L - FH_F \\ &= S\lambda_S \end{aligned} \tag{1.2}$$

Where: V is the mass flowrate of vapour streams, kg/s

L is the mass flowrate of Liquid streams, kg/s

F is the mass flowrate of feed streams, kg/s

S is the steam usage, kg/s

H_V is the vapour enthalpy, kJ/kg

H_L is the liquid enthalpy, kJ/kg

H_F is the feed enthalpy, kJ/kg

λ_S is the latent heat of evaporation/condensation of steam, kJ/kg

A, the total heat transfer area, is usually based on the area where the resistance to heat transfer is greatest. For an evaporator this is almost always the inside of the tubes available for the heat transfer, so A is the internal tube surface. It is calculated as follows:

$$A = N\pi Dl \tag{1.3}$$

Where: N is the number of tubes

D is the tube diameter (usually internal), m l is the tube length, m

ΔT, the temperature difference for heat transfer, is calculated simply as follows:

$$\Delta T = T_s - T_l \quad 1.4$$

Where: T_s is the temperature of condensing steam, K

T_l is the temperature of boiling liquid, K

U, the overall heat transfer coefficient, is easily the most complex term in equation 1.1. In general, the overall heat transfer coefficient depends on the properties of the solution, the heating medium, and the surface geometry and type, including smoothness, cleanliness, composition, and thickness of metal.

Consider the plane wall in Figure 1.3 (Geankoplis, 1993) with a fluid at temperature T_s on the inside surface and a cold fluid at T_l on the outside surface. U is calculated as follows:

$$\frac{1}{U} = \frac{1}{h_i} + \frac{\delta_w}{k_w} + \frac{1}{h_o} \quad 1.5$$

Where: h_i is the heat transfer coefficient inside tubes, W/m^2K

h_o is the heat transfer coefficient outside tubes, W/m^2K

k_w is the thermal conductivity of tube wall, W/mK

δ_w is the thickness of tube wall, m

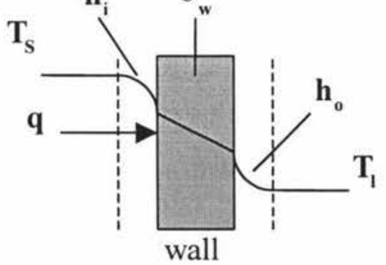

Figure 1.3: Heat transfer through a plane wall

Equation 1.5 is most simply regarded as the summing of three thermal resistances or three resistances to heat transfer from the condensing steam to the evaporating liquid inside the wall.

1.4.1.2 Type of evaporation

Ever since the beginning of the industrial use of evaporation a large number of evaporators of different design have been developed (Kessler, 1981). We will discuss here the most important types of evaporators that are of interest to the dairy industry. Basically an evaporation system involves a number of necessary elements which are together designed and constructed for a specific application. The essential components of a continuous industrial evaporation system consist of (Chen, 1997):

1. A heat exchanger to supply sensible heat and latent heat of evaporation to the liquid, this is usually via saturated steam.
2. A separator in which the vapour is separated from the concentrated liquid phase.
3. A condenser to condense the vapour and remove the condensate from the system.
4. A vacuum device to withdraw non-condensable gases and maintain a constant evaporating temperature.

These elements are usually of stainless steel construction that are easily cleaned and non-corroding.

There is not any single type of evaporator that could be satisfactory for all applications and different kinds of feed. In general, the different designs for the heat exchangers result in different types of evaporators. The main types of evaporators and their applications are briefly described below (Billet, 1989):

The natural circulation evaporator was the first type of evaporator to receive wide acceptability for the industrial concentration of liquids, known as the standard evaporator. The vertical tube bundle with a central downtake is located inside a steam chest enclosed by a cylindrical shell. The circulation of liquid (natural convection) past the heating surface is induced by boiling, which improves the heat transfer.

The forced circulation evaporator was developed from the standard evaporator. It has a vertical heated tube bundle located in an external heater separated from the downtake, which made it possible to pump the liquid upwards through the tube bundle. The fast liquid velocities improve the heat transfer and reduce the degree of fouling.

The agitated thin film evaporator employs a heating surface consisting of a large diameter tube in which the liquid product is spread over the inside wall by a series of rotating blades. These blades produce a thin film of liquid that is heated by steam surrounding the vessel. The action of the blades also suppresses the formation of fouling on the heating surfaces.

The falling film evaporator has vertical heating tubes and the liquid is carefully distributed to the top of the evaporation tubes. Then the liquid forms a thin film and flows down on the inner surfaces of the tubes. As the liquid moves down it boils off and the separation of the vapour and the concentrate takes place at the bottom of the tubes. This evaporator works successfully with a small temperature difference and has a low residence time.

The flash evaporator is a low-pressure chamber without heaters, in which a hot liquid is fed and the flash evaporation of the liquid occurs. This type of evaporator is the most suitable for solutions that are prone to salting or scaling and are very corrosive. It has been successfully used for producing potable water from seawater (Chen, 1997).

The centrifugal evaporator, also known as Centritherm evaporator (Figure 1.4), consists of a stack of hollow, rotating conical elements. The steam is fed into each cone and the liquid product is sprayed over the cones as they rotate. The centrifugal force spreads the liquid thinly over the heating surfaces to provide rapid heat transfer. The concentrate accumulates around the outer edge of the cones and is displaced upwards. Since a spinning cone evaporator is one kind of centrifugal evaporator, a more detailed outline of the uses, operation and characteristics of spinning cone evaporator is presented in following sections.

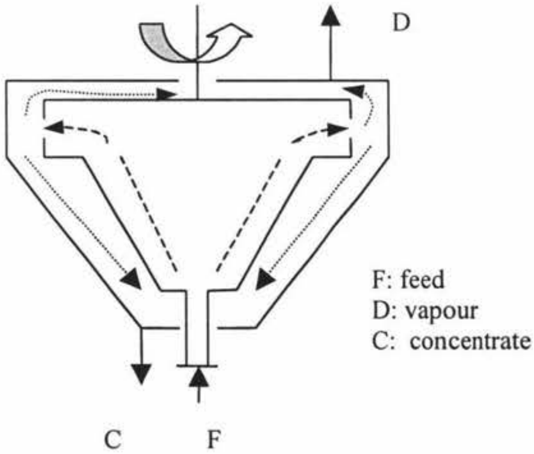

Figure 1.4: Centrifugal evaporator (Billet, 1989)

1.4.1.3 Vapour recompression

For an evaporation system, there are more efficient methods of using steam to heat the effects for reducing steam consumption, namely vapour recompression methods. In vapour recompression a part or the whole of the vapour from an evaporator is compressed with a resulting increase in temperature and is then used to heat the same evaporator again. In other words, the vapour recompression involves compressing the vapour generated in an effect to increase its temperature before returning it to the same effect as the heating steam. There are two methods of performing vapour recompression. Compression can be carried out either mechanically or thermally (Davidson et al., 1996).

Thermal vapour recompression (TVR). Here, the vapour is compressed by a steam-jet ejector to increase the temperature and pressure of the steam supply. This method can only compress part of the vapour from the effect so the remainder of the vapour is passed on to the next effects. The thermal compressor is relatively simple and inexpensive, without moving parts and therefore has a long useful life. A thermo compressor consists of a spray nozzle or propelling nozzle, a suction chamber with fittings for sucking in the vapour, a mixing chamber and a compression chamber.

Mechanical vapour recompression (MVR). The vapour is compressed by a mechanical compressor driven by electric motor, fuel engine or steam turbine. The exhaust vapour from an effect is fed to the compressor and then returned to the system. Only a small amount of make-up steam is required. Evaporators using mechanical recompression have the lowest operating costs but have the highest capital and maintenance costs. Mechanical compression can be effected by axial flow, by rotary piston or by single stage or multiple stage radial flow compressors.

Basic analysis of a fan compressor

In general, fan compressors are used at relatively low pressures, often at high flowrates. The fan operates on the centrifugal principle. Because of the change in density during compressible flow, the integral form of the Bernoulli equation is inadequate. The Bernoulli equation, however, can be written differentially and used to relate the shaft work to differential change in pressure head. In compressors the mechanical, kinetic, and potential energies do not change appreciably, and the velocity and static-head terms can be dropped. Also, the compressor is assumed to be frictionless. With these simplifications, the Bernoulli equation becomes (McCabe et al., 1993)

$$dP_{comp} = \frac{dP}{\rho} \qquad 1.6$$

Where: P_{comp} is work by ideal compressor, J/kg

P is pressure, kPa

ρ is density, kg/m^3

Integration between the suction pressure P_e and the discharge pressure P_{comp} gives the work of compression of an ideal frictionless gas:

$$P_{comp} = \int_{P_e}^{P_{comp}} \frac{dP}{\rho} \qquad 1.7$$

Where: P_{comp} is the discharge pressure

P_e is the suction pressure

Power required for the compression of gas. To use Eq.1.7, the integral must be evaluated, which requires information on the path followed by the fluid in the machine from suction to discharge. For the isentropic (adiabatic) compression of an ideal gas, the relation between P and ρ is given by Eq.1.8:

$$\frac{P}{\rho^{\gamma}} = \frac{P_e}{\rho_e^{\gamma}} \qquad 1.8$$

Where: $\gamma = C_p/C_v$

ρ_e is the inlet density

Substituting ρ from Eq.1.8 into Eq.1.7 and integrating gives (Eck, 1973):

$$P_{comp} = \frac{p_e \gamma}{(\gamma - 1)\rho_e}\left[\left(\frac{p_{comp}}{p_e}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad 1.9$$

Temperature relation. When the pressure on a compressible fluid is increased adiabatically, the temperature of the fluid also increases. For the isentropic (adiabatic and frictionless) pressure change of an ideal gas, the temperature relation is,

$$\frac{T_{comp}}{T_e} = \left(\frac{p_{comp}}{p_e}\right)^{1-\frac{1}{\gamma}} \qquad 1.10$$

Where: T_{comp} is outlet absolute temperature

T_e is inlet absolute temperature

Substituting Eq.1.10 into Eq.1.9, this equation becomes

$$P_{comp} = \frac{p_e\gamma}{(\gamma-1)\rho_e}\left[\left(\frac{T_{comp}}{T_e}\right)-1\right] \qquad 1.11$$

Equation 1.11 shows the importance of the temperature ratio T_{comp}/T_e. It will be used to derive the outlet temperature of a compressor in the chapter 3 of this thesis.

1.4.1.4 Condensing and vacuum generator

The vapours produced in an evaporator are re-used where possible, either to heat other effects or for preheating the feed. Surplus vapours must be condensed and the heat removed from the system. Condensers operate at the end of the evaporation process to maintain the heat balance in the system, control the temperature of the effects and to provide a vacuum for evaporator operation. Most condensers are water-cooled surface condensers or mixing condensers (Russell, 1997).

Most evaporation systems in the food industry are operated under vacuum to lower the boiling temperature and so protect the food products from heat damage. This further improves the energy consumption of the systems.

The vacuum in the system is created by the condensing vapour in the condenser or/and the vacuum pump. Air may flow into the plant via leakage and non-condensable gases may enter. These gases may accumulate and interfere with the performance of the process if not removed.

Although the underlying principle of evaporation is simple, the detailed liquid flow patterns and the evaporation mechanisms on the heating surfaces are not very well understood. Complications in the evaporation process also arise as a result of the variety of products processed that have different properties. The behaviour of the liquid during evaporation must be considered in designing, selecting and operating evaporators. In other words, many parameters that depend on the characteristic properties of the evaporating liquid, govern the choice of equipment and the operating conditions (Chen, 1997).

1.4.2 On-farm evaporation system

On-farm evaporation systems have attracted worldwide interest for many years. When milk can be pre-concentrated at a farm the pre-concentrated milk, clearly, should be cheaper to transport to the processing plants than normal milk. Similarly, all other volume dependent handling and processing costs should be favourably affected by concentration. For example, pumps, milk storage capacities and refrigerated loads would be reduced proportionately, as well as cheese vat capacities or evaporator loads in milk powder plants. The dairy factory effluent would also be reduced.

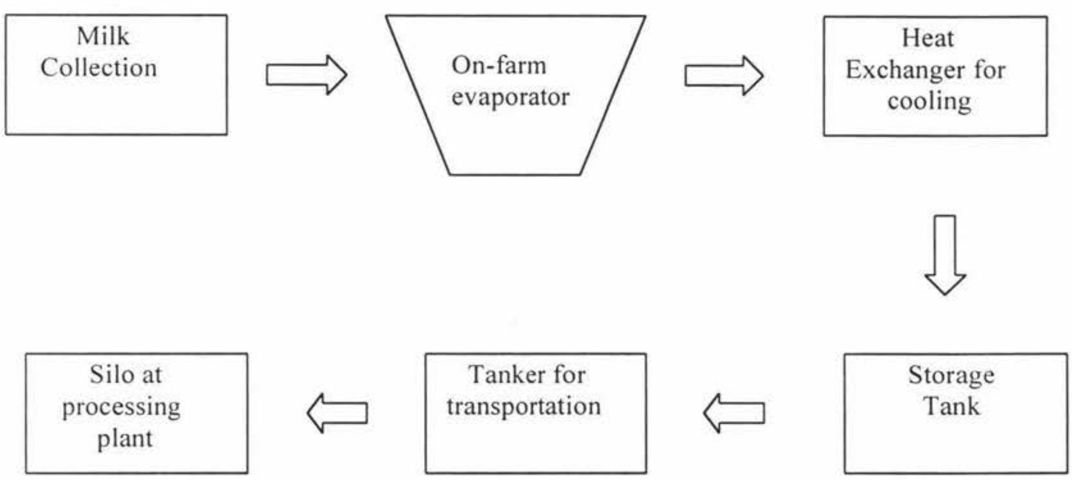

Figure 1.5: On-farm evaporation system

The on-farm evaporation system is shown in Figure 1.5. This system is operated as follows:

- The fresh whole milk is first collected in the buffer tank and then pumped into the on-farm evaporator.
- The concentrated milk from the evaporator is chilled in a plate heat exchanger and then passed to the storage tank. The storage temperature is about 5 °C and the maximum storage time is about three days.

- Finally the concentrated milk is transported by tanker to the dairy factory for further processing and may be stored in the dairy factory for a while (maximum two days) before processing (Chen, 1997).

The trials of the on-farm concentration have been undertaken for application of membrane technology and evaporation technology (Xu and Jebson, 1994). But membrane technology requires very pure water, which is not readily available on many farms (for cleaning). Therefore, evaporation technology is the only practicable alternative for on farm pre-concentration of milk.

The ideal evaporator to be used in the on-farm evaporation system should be highly efficient and compact, and cause minimal damage to milk. Research on both chemical and microbiological qualities of the pre-concentrated milk were completed (Xu, 1996). The results showed that pre-concentrated milk had an acceptable quality to be used in the dairy industry. A spinning cone evaporator, a highly efficient and compact evaporator, is being developed for the on-farm evaporation system in the Institute of Technology and Engineering at Massey University.

1.4.3 Spinning Cone Evaporator

In plain language, the spinning cone evaporator is a compact, cost-effective, newly developed, on-farm method for concentration of the sensitive materials, i.e. milk. A spinning cone evaporator provides an alternative of small to medium capacities in food, chemical, and pharmaceutical industries. The spinning cone evaporator utilizes the centrifugal force generated in a rotating system called 'spinning cone' to enhance the heat transfer performance and reduce the fouling on the evaporator heat transfer surfaces. This reduces the heat contact time in the evaporation process to a minimum, so that it is possible to evaporate quite sensitive materials at relatively high temperatures.

As shown in Figure 1.6 the spinning cone evaporator has an externally heated rotating rotor in the form of truncated cones. The general processes occurring in the spinning cone evaporator can be briefly described as follows:

- The steam for heating is fed into the steam jacket and condenses on the outer surfaces of the rotating cones.
- The preheated liquid to be concentrated is fed into the inner surfaces of the spinning cone. Under the centrifugal field, the liquid is immediately spread on the inner

surfaces in a film, which moves very fast in a radial direction, consequently the liquid film becomes extremely thin. Its heat transfer resistance is small, therefore, vapour is released rapidly.

- Vapour passes out via the vapour outlet to a condenser.
- The condensate from the steam is flung off by the action of the centrifugal force from the outer surfaces of the cone as soon as the condensate is formed, which results in a greater area being exposed for steam to be condensed. Further, the fast moving liquid film also reduces the formation of deposit on the heating surface because the formation of deposit on the heating surface is caused not only by the temperature but also by the movement of liquid on the heating surface. Therefore, the measured overall heat transfer coefficients on the spinning cone surfaces could be as high as 10 kW/m^2K(Chen et al., 1993) compared to 2-3 kW/m^2K for a falling film evaporator (Chen, 1992). Unvaporized liquid is removed using a pump and the centrifugal force of the rotating cone.

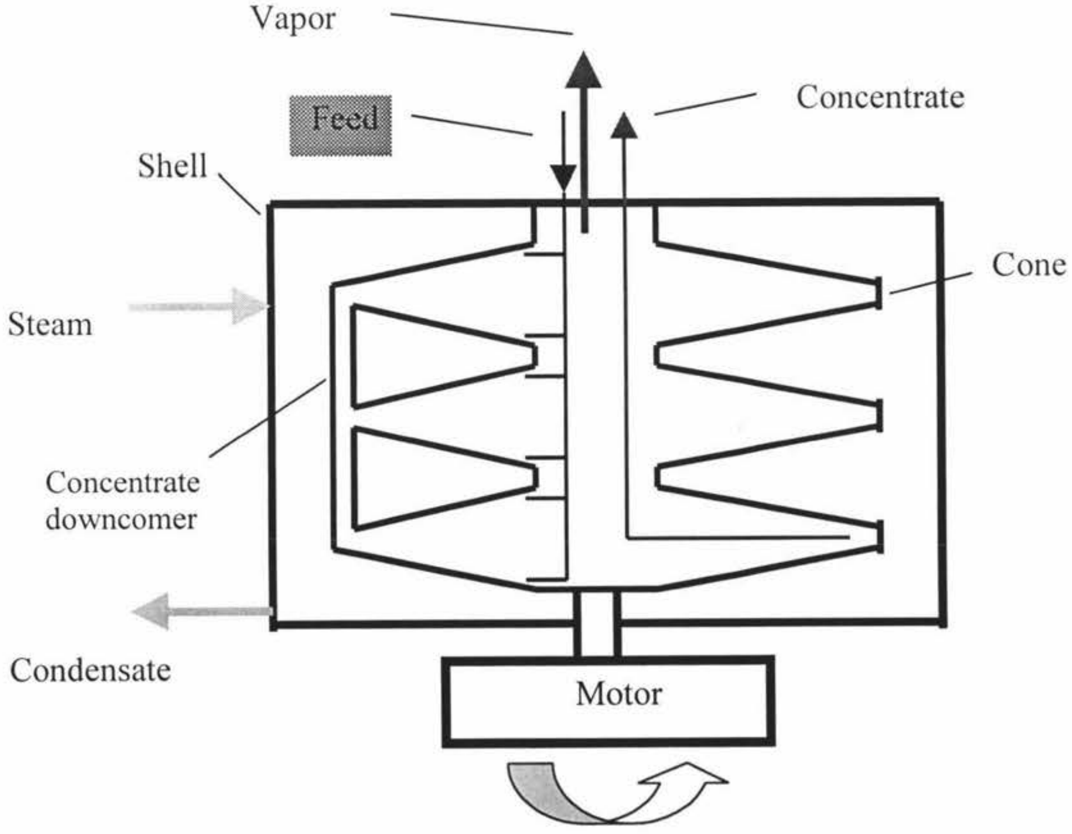

Figure 1.6: Structural diagram of a spinning cone evaporator

This type of evaporator is especially suitable for heat sensitive biological materials. As the liquid film passes over the heating surfaces rapidly, the liquid residence time in the actual evaporation zone may be only a fraction of a second (Billet, 1989).

This type of evaporator can also be used to concentrate viscous solutions, because the liquid can be distributed and moved along the heating surfaces with the assistance of the centrifugal force generated. The viscosity of the final product produced in this evaporation system could be up to 20 Pa.s (Chen, 1997).

A comparison between a falling film evaporator and a spinning cone evaporator has been taken by Billet (1989). Table 1.1 presents the data from this comparison. The spinning cone evaporator offers the following features (Chen, 1997) compared with the falling film evaporators that are used so popularly in the dairy industry or other evaporators:

Table 1.1: A comparison between falling film and spinning cone evaporators

Magnitude	Falling film	Spinning cone
Heat transfer coefficient (W/m2K)	730	2900
Temperature difference (°C)	40	10

1. The spinning cone evaporator has shorter residence times, which is important for heat sensitive products such as enzymes, antibiotics, herbal medicines, protein solutions, fermented liquids. When evaporating or concentrating these heat-sensitive liquids, it is required that the process liquid receives a specific quality of heat at a minimum temperature for an extremely short time period. The spinning cone evaporator satisfies all three of these important criteria.
2. It has a higher overall heat transfer coefficient. Rotation of the heating surface does not only improve the heat transfer on the liquid side by effectively distributing and quickly passing the liquid to be evaporated on the surface, but also benefits the steam condensation on the other side. As soon as the steam condenses on the outer surface of the cone, the condensate forms droplets, which are flung from the rotating surface by centrifugal force. Therefore, no condensate film, which would offer resistance to heat transfer, is formed. The dropwise condensation is considered to be

a major mechanism of condensation, which gives rise to very high heat transfer coefficients. Further, as presented above, the fast moving liquid film also reduces the formation of deposits on the heating surface because the formation of deposit on the heating surface is caused not only by the temperature but also by the movement of liquid on the heating surface.

3. It operates with high concentrated liquids. It was reported that the milk concentrate produced in the spinning cone evaporator (Evapo unit) can be up to 85% dry matter (Anon, 1990).
4. It is also highly suitable to concentrate high viscosity products. In a conventional falling film evaporator, the liquid film flow is assisted by vapour velocity, but at high liquid viscosity this is less effective (Jebson and Iyer, 1991). Hence, the final concentration of the products is limited. In the spinning cone evaporator, however, because the centrifugal force generated in the rotating system could be more than one hundred times greater than the force of gravity, the liquid transport can be enhanced using mechanical assistance, which means considerably higher velocity and hence larger heat transfer coefficients and the possibility of obtaining a higher final concentration.
5. It meets the requirement for cleaning production plants, since the amount of volatile decomposition products, which can enter the atmosphere or the effluent through the vacuum system, is reduced due to extremely short residence times.

Thus spinning cone evaporators will be accepted rapidly and allow a fair amount of scope in providing small to medium capacities in the chemical, pharmaceutical and the dairy industries. They permit applications in which conventional evaporators would fail entirely or, at the most, involve a compromise leading to reduced yield and quality. From the aspect of modern process engineering, they represent an irresistible development and can be considered more as welcome companions than as competitors to the other types with short residence times. In view of the increasing severity of legislation on the environment, they also meet the requirements for 'clean' production plants. This may be a convincing argument in swaying decisions on equipment selection in favour of these evaporators (Billet, 1989).

A schematic diagram for a spinning cone evaporation system is shown in Figure 1.7. It consists of a spinning cone evaporator, a fan compressor and a surface condenser, the feed section and the product transportation section.

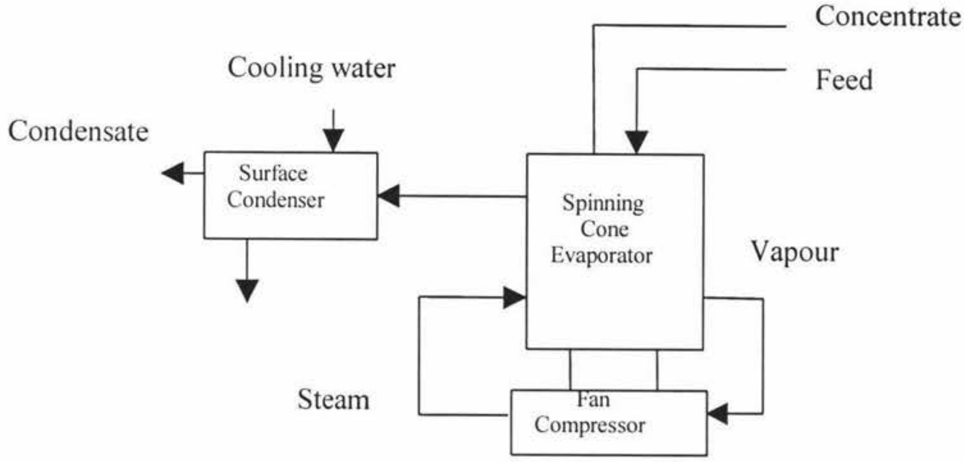

Figure 1.7: Schematic diagram for a spinning cone evaporator system

Figure 1.8 shows the flow chart of the spinning cone evaporator system at Institute of Engineering and Technology of Massey University. The general processes occurring in the evaporator can be briefly described as follows. The liquid to be concentrated is fed into the inner surface of the rotating cone. Under the centrifugal field, the liquid is immediately spread on the inner surface as a film, which moves very fast in a radial direction. Since the film is very thin, its heat transfer resistance is small, consequently vapour is released very rapidly. Vapour passes out via the vapour outlet to a condenser, where the vapour is condensed.

The steam for heating is fed into the steam jacket and condenses on the outer surface of the rotating cone. The condensate from the steam is impelled off by the action of the centrifugal force from the outer surface of the rotating cone as soon as the condensate is formed, which results in more areas being exposed for steam to be condensed.

Vacuum is provided by a vacuum unit. When the water is pumped by the circulation pump through the ejectors, a vacuum is created. The vacuum is adjusted manually during operation, and released at the end of the operation.

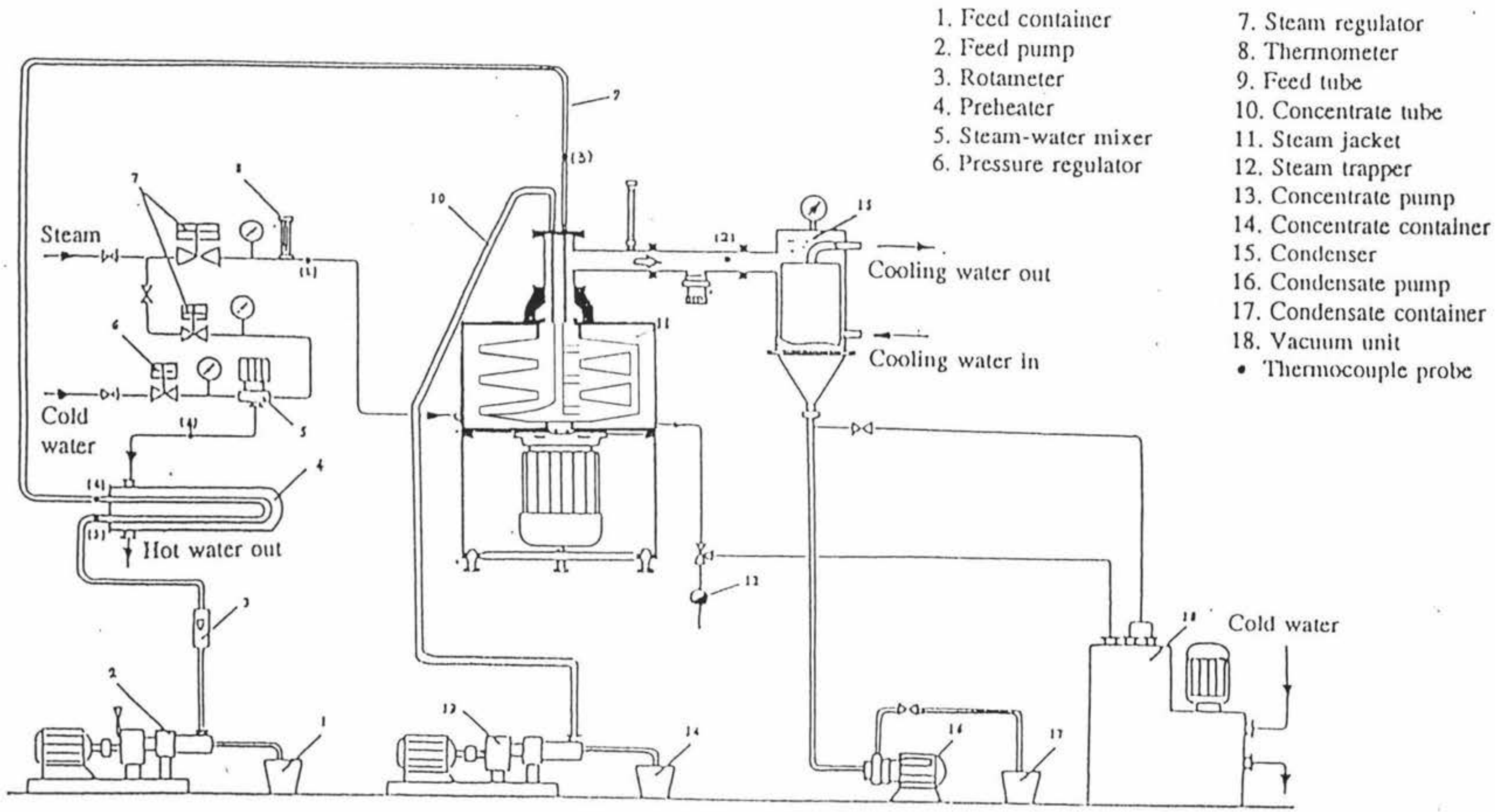

Figure 1.8: Flow chart of the spinning cone evaporator system

(Adapted from Hong, 1997)

1.4.4 Analytical, dynamic modelling

Process modelling and computer simulation have proved to be extremely successful engineering tools for the design and optimisation of physical, chemical, and biological processes. The use of simulation has expanded rapidly during the past three decades because of the availability of high-speed computers and computer workstations (Ramirez, 1997). In developing this new evaporator and its control system, a process simulation should be used to test and refine the performance of the evaporation system. This is an important step in remedying any problems before the system is implemented on the real system. Additionally, a process simulation allows the settings of different variables to be optimised.

A good mathematical model should be general (apply to a wide variety of situations), realistic (based on correct assumptions), precise (its estimates should be finite numbers), accurate (its estimates should be correct) and there should be no trend in the deviations of the model from the experimental data. A good model should be robust and fruitful.

The first step in building a mathematical model is the definition of the system. Factors affecting the system should be identified, and the data should show the effects of the individual factors. The system may be simplified by neglecting the effects of the marginal inputs. A single equation or a set of mathematical equations will usually be derived after using many fundamental principles and techniques. Comparison of the mathematical model, i.e., solution of the equations, with the experimental data is the final stage of modelling. The model is validated if it agrees with the data. If such an agreement should not be obtained, all the steps of modelling, starting with the definition of the system, are repeated until a satisfactory representation is obtained (Fig. 1.9).

The first task in the process would be the development of an analytically-derived dynamic model of the system. The ultimate application of the dynamic model largely determines the method of analysis of the system and the complexity of the final model. Models for the purpose of design or analysis of the process mechanisms often require distributed models containing partial derivative information. On the other hand models for design of the evaporator and its control system do not require as much complexity and lumped-parameter analyses usually suffice.

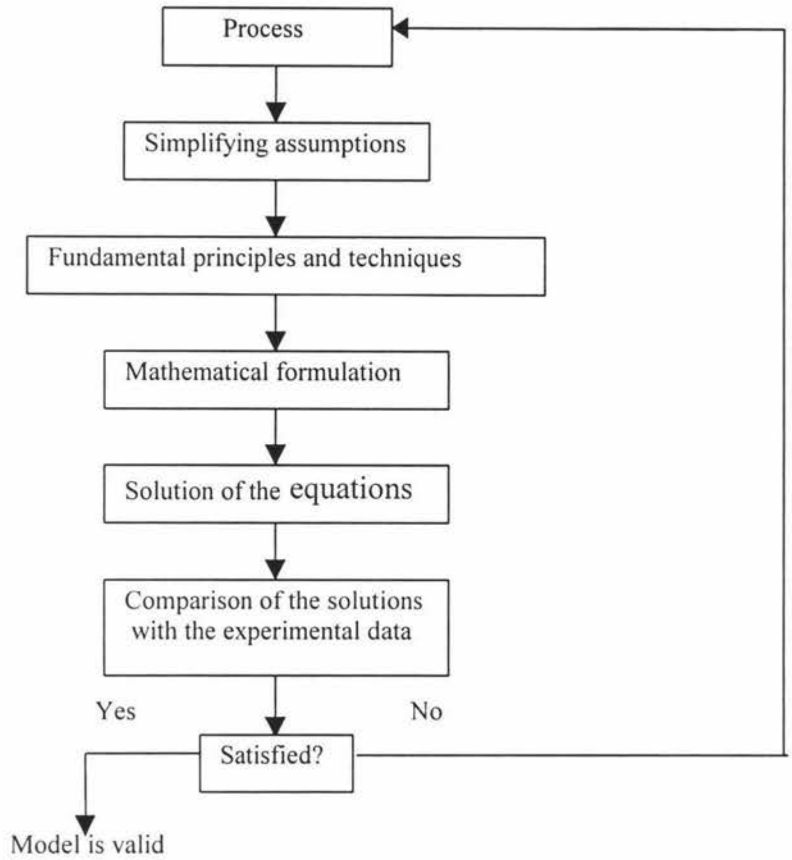

Figure 1.9: Schematic description of modelling (Ozilgen, 1998)

The mathematical simulation of complex operations is one type of tool which can be used to improve resolutely the type of process performance of the existing complex operation, to increase with change in construction size and the quantity of products, to decrease the specific material requirement and to perfect the energy balance. It has become exact and effective in last decade, on the one hand by utilising new scientific results of process engineering related to the internal mechanism of the processes and on the other hand by using computers (Benedek, 1980).

Simulation and modelling generally use technical devices. The modelling consists of creating a "quasi-object" suitable for studying the behaviour of a system, from which the output of the system to a given input may be established. This type of research is termed simulation. Simulation is used to obtain by simple means and with low cost that information which could otherwise only be available by measurement on the original system.

Other reasons to use a process simulation include:

1. Process optimisation. Through investigation of the process simulation one could find the optimal settings that should be applied on the actual plant.
2. Testing operating scenarios. Various operating scenarios could be run without danger of disrupting the actual process. This could benefit the process engineer who wishes to determine the effects of applying different operating strategies, using different raw materials or making physical alterations to the plant.
3. Operator training. Simulation models could provide off-line training to operators and an understanding of how the characteristics and responses of the process can be gained.
4. Process monitoring tool. Generally a model represents a perfect system. Any deviations the plant makes from the model may indicate areas where the process needs attention, for example it may indicate when the vacuum has been changed.