Fouling of a Plate Heat Exchanger by Cheese Whey Solutions

By

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Under the Supervision of

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Declaration

I hereby certify that this material, which I submit for assessment on the programme of study leading to the award of Degree of Master of Science is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work

Signed Brian Corcoran ID No 93701047

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Abstract

Title: Fouling of a Plate Heat Exchanger by Cheese Whey Solutions
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A plate heat exchanger rig was developed at Dublin City University to study fouling of plate heat exchangers using cheese whey solutions The rig consisted of an Alfa-Laval plate heat exchanger, 316 stainless steel pipework, pressure and temperature measurement and was temperature controlled with all information logged via an Anville data acquisition system

Cheese whey solutions of various concentration were passed through the plate heat exchanger for periods of up to four hours The effect of flowrate, temperature, whey concentration and cleaning on fouling resistance were investigated Increasing the processing temperature was found to increase the rate of fouling Maximum deposition on the plates of the heat exchanger was found to occur at low whey flowrates Increasing whey concentration was found to increase the rate of fouling An induction period was noted and asymptotic fouling found to occur at low flowrates and high temperatures Cleaning of the plates of the heat exchanger was found to significantly affect the rate of fouling

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6) To my brothers Alan and Derek Thanks Derek for the kick start to get finished and the help along the way Enjoy the adventure you are about to start You were right Alan about this job!

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Nomenclature

Symbol	Physical Quantity	SI Units
A	area	m^2
C_p	specific heat capacity	$J\ kg^{-1}K^{-1}$
D_e	hydraulic diameter	m
d	distance between plates	m
f	friction factor	
G	mass velocity of fluid	$kg\ m^{-2}\ sec^{-1}$
h	local heat transfer coefficient	$W\ m^{-2}\ K^{-1}$
k	thermal conductivity	$W\ m^{-1}\ K^{-1}$
L	length	m
m_f	mass of deposit per unit area	$kg\ m^{-2}$
M	flowrate of fluid	$m^3\ sec^{-1}$
q	heat flux	$W\ m^{-2}$
R	resistance to heat transfer	$m^2\ K\ W^{-1}$
Rf	fouling resistance	$m^2\ K\ W^{-1}$
$Rf(max)$	asymptotic fouling resistance	$m^2\ K\ W^{-1}$
s	distance between corrugations	m
ΔT_{mean}	corrected LMTD	K
ΔT_{LMTD}	log mean temperature difference	K
T	absolute temperature	K
t	time	Seconds
U	overall heat transfer coefficient	$W\ m^{-2}K^{-1}$
v	velocity	$m\ s^{-1}$
μ_{av}	average fluid viscosity	$kg\ m^{-1}sec^{-1}$
μ_w	fluid viscosity at wall	$kg\ m^{-1}sec^{-1}$
W	width of plate	m
x	thickness of deposit	m
x_f	thickness of fouling deposit	m

Greek Symbols

β	removal rate constant	sec^{-1}
ρ	density	$kg\ m^{-3}$
ϕ_d	rate of deposition	$m^2\ sec^{-1}$
ϕ_r	rate of removal	$m^2\ sec^{-1}$
k	thermal conductivity	$W\ m^{-1}K^{-1}$
τ	shear stress	$N\ m^{-2}$

Subscripts

av	average
c	cold
c_i	cold fluid inlet
c_o	cold fluid outlet
h	hot

h_i	hot fluid inlet
h_o	hot fluid outlet
i	inner wall
m	mean value
o	outer wall
w	wall
f	fluid

Constants

a	constant	
b	constant	
c	constant	
K_1	constant	$kg^{-1}m^{-2}$
K_2	constant	$m^2 N\,^1 sec\,^1$

Dimensionless

Nu	Nusselt Number	$\frac{hD_e}{k}$
Pr	Prandtl Number	$\frac{\mu C_p}{k}$
Re	Reynolds Number	$\frac{\rho v D_e}{\mu}$

Chapter 1

Introduction

Fouling of heat transfer equipment appears to be a topic that defies generalisation However if progress is to be made in understanding this important subject, it is essential that research be directed towards the formulation of a general theory An adequate theoretical foundation is required if satisfactory design methods for heat exchangers subject to fouling are to be formulated

Fouling may be defined as the formation on heat transfer surfaces of unwanted deposits which impede the transfer of heat and increase the resistance to fluid flow The growth of these deposits cause the thermal and hydrodynamic performance of the heat transfer equipment to decline with time (Edwards *et al* , 1974)

Since 1960 considerable progress has been made in understanding the fouling process, however this has not resulted in significant improvements in the ability of the designer to predict fouling resistances The incentive for increased attention to fouling of heat exchangers is certainly economic In an era of inexpensive energy and materials, a crude method of estimating a fouling resistance was satisfactory even though considerable excess surface area was often specified in the design of heat exchangers Overestimation of these resistances and the resulting over-capacity of heat exchangers often led to a reduction of flowrates per channel to the extent that fouling was often enhanced (Cooper, 1974)

Fouling of heat transfer equipment has been frequently observed in the dairy industry and remains one of the major unsolved problems (Taborek *et al* , 1972) This is especially true in the case of food products such as milk which contains thermosensitive compounds In milk processing, cleaning procedures must remove the fouled material and return the soiled surface to its original condition of cleanliness and hygiene (Sandu & Lund, 1985) Milk is always preheated whatever its transformation process but other derivatives are also of industrial interest e g cream, whey, milky desserts etc This is why the ability of such products to foul heat exchangers has been studied in detail

Plate heat exchangers are widely used in the food and bioprocess industries due to their compactness and high thermal performance They are generally used in the processing and heat treatment of milk products and derivatives with temperatures ranging from 70°C for pasteurisation to 140°C during ultra high temperature sterilisation processes However they can be prone to fouling due to the narrow gap between each channel By comparison with other industries where annual cleaning of heat transfer equipment is sufficient, it is commonplace in the dairy industry to clean daily (Delplace & Leuliet, 1994) Deposit formation may be so severe as to block exchanger channels making cleaning in place (CIP) virtually impossible Repeated cleaning due to fouling results in the large consumption of cleaning agents, increased costs and ecological problems

This thesis examines the fouling of a plate heat exchanger using various types of whey powder The deposits generally found in processing this material include protein aggregates and inverse solubility salts Whey is a highly foulant fluid of industrial interest and is often chosen as a model fluid to study fouling in the dairy industry

Improvements in the design of plate heat exchangers will require a better understanding of the fouling process to counteract the rapidly increasing costs of energy, raw materials and cleaning processes associated with this problem

In the next chapter, the hydraulic and heat transfer characteristics of plate heat exchangers are discussed This is followed by a general review of heat exchanger fouling, with particular emphasis on the mechanism of whey fouling and on the impact of fouling on the performance of the plate heat exchanger

Chapter 2

The Plate Heat Exchanger

2.1 Introduction to Plate Heat Exchangers

The original idea of a plate heat exchanger (PHE) was patented over a century ago and the first commercially successful design introduced in 1923 by the Aluminium Plant and Vessel Company i e **APV** Initially, cast gun metal plates were enclosed in a frame similar to a filter press, with the current design evolving in the 1950's using pressed plates in thin gauge stainless steel (Alfa Laval Thermal Handbook, 1968)

Owing to its construction, the PHE is well suited to heating and cooling in a wide variety of applications found in the dairy, food pharmaceutical and power industries (Clark, 1974) Its compact design, high efficiency and high heat transfer coefficients make it ideal where other heat exchangers have definite limits The principal advantages of the plate heat exchanger in heat transfer include the fact that they have high heat transfer coefficients (often 3-8 times those of shell and tube or spiral units), they are fully accessible for inspection, cleaning and maintenance, and they offer uniform heat treatment during sterilisation treatments A major short-coming of the PHE is that both fluids have an identical channel geometry (Edwards *et al*, 1974) Most applications involve unequal flowrates and varying channel lengths for each stream Other disadvantages include the fact that gasket material may not always be compatible with process fluids, and the fact that plate heat exchangers are limited to low pressures (20 bar) and low temperatures (300 °C)

The plate heat exchanger consists of a series of corrugated plates sealed with gaskets which direct the fluids into alternate channels The plates are hung from a support bar and clamped between a fixed and moveable head plate (Alfa Laval Thermal Handbook 1968) The following is a description of the various components used in the construction of a plate heat exchanger

2 1.1. The Frame

The frame forms a rigid structure to hold the plates in alignment and maintain the correct gasket compression It consists of a head and end plate, top and bottom carrying bar, tie bar and nuts and end support columns Depending on the flow configuration, fluid connections may be made to the head or end plates (Carlson, 1992)

2 1 2 The Plates

Plate material must be ductile for pressing and is typically formed from 0 5 - 0 9mm thick material Corrugations are pressed into the plate for two basic reasons, firstly to promote turbulence in the fluids and secondly to support the plates against differential pressure Many types of corrugation are available (Clark, 1974) and these include *Washboard* with perpendicular corrugations where turbulence is promoted due to continuously changing flow direction and velocity Support is achieved by pressing dimples into the plates which prevents the plates from collapsing under pressure *Chevron or Herringbone* corrugations are the most widely used with the pattern pointing in opposite directions which produces a swirling motion in the fluid Support here is achieved at the very large number of contact points, enabling thin material to withstand high differential pressures These corrugations increase the heat transfer area by up to 25% with velocities in the turbulent region ranging from 0 1 - 1 m/sec

Plates are available in a wide variety of materials for various applications (Sorell, 1994) These include Stainless Steel, Titanium, Incoloy and Palladium to name but a few Gaskets are available in a wide range of elastomers including Nitrile and Butyl rubber, EDPM, Viton etc Gaskets provide a double seal preventing intermixing of the fluid streams and also determine fluid paths within the exchanger Most applications of plate heat exchangers involve liquid/liquid duties with operating temperatures below 150°C, although some versions can operate at temperatures up to 275°C (Cooper, 1974)

2.2. Heat and momentum transfer in Plate heat exchangers

Several works have been published on the theory of heat transfer in heat exchangers giving a comprehensive analysis of the physical processes involved (Raju & Chand, 1980, Cooper, 1974, Marriott, 1971) The concept of the heat transfer coefficient is widely used in the determination of heat transfer between the wall of a plate heat exchanger and the fluid forced to flow over it The rate of heat transfer between the fluid and the wall of the heat exchanger may be expressed as,

$$q = h\left(T_w - T_f\right) \tag{2 1}$$

In a plate heat exchanger, the thermal resistances in the path of heat flow from the hot to the cold fluid include,

1) Skin resistances associated with the boundary layers
2) The thermal resistances of wall material itself
3) Scale and fouling resistances from deposits in the walls

Neglecting fouling, the total thermal resistance of a plate heat exchanger may be expressed as,

$$R = \frac{1}{h_i} + \frac{x}{k} + \frac{1}{h_o} \qquad (2\ 2)$$

The total thermal resistance may also be expressed as an overall heat transfer coefficient based on either the inner (U_i) or outer (U_o) side of a heat exchanger,

$$U = \frac{1}{R} \qquad (2\ 3)$$

When the wall thickness is small and its thermal conductivity is high the wall resistance may be neglected and the overall heat transfer coefficient expressed as,

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o}} \qquad (2\ 4)$$

In applications where the heat transfer surface is fouled with an accumulated deposit introducing additional resistances, this effect may be introduced into the equation in the form of a fouling resistance (R_f),

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o} + R_f} \qquad (2\ 5)$$

2.2 1 Boundary Layer Theory

Heat transfer within a plate heat exchanger is affected by a variety of factors including flow regime (characterised as laminar, transition or turbulent), fluid properties (density, viscosity, thermal conductivity) and flow passage geometry (flat, cylindrical, tubular) Significant changes in the velocity profile occur as a fluid flows across the plates of a plate heat exchanger Viscous forces tend to retard the flow in regions near the plate walls Fluid elements in contact with the plates assume zero velocity whereas in a region sufficiently far away from the surface the free stream velocity remains essentially unaffected In the thermal boundary layer region the temperature gradients are very steep and so heat transfer between the plates and the fluid is governed by the characteristics of the temperature profile within the thermal boundary layer The *relative thickness* of the thermal and velocity boundary layers affects the heat transfer between the process fluid and the wall of the heat exchanger Characteristics of this boundary layer flow are governed by the fluids Reynolds Number (Rogers & Mayhew, 1980)

2.2 2 The Reynolds, Nusselt and Prandtl number

Defined as the ratio of inertia forces to viscous forces, the Reynolds number defines the character of the flow It is defined by the equation,

$$Re = \frac{\rho v D_e}{\mu} \qquad (2\ 6)$$

For each flow geometry the change from laminar to turbulent flow usually occurs at a certain *critical Re* For plate heat exchangers, critical Reynolds numbers as low as 40 may be found (Jackson & Troupe, 1964) As a general rule all types of plate exchanger will operate in fully turbulent conditions at *Re* above 1000 and laminar flow below *Re* of 10 For a plate heat exchanger with 10-12 chevron plates the transition region lies between Reynolds numbers of 10 - 150 The equivalent diameter, D_e, is defined as four times the cross-sectional area of the channel, divided by the wetted perimeter of the channel, or,

$$D_e = \left[\left(\frac{4Wd}{2W+2d}\right)\right] \qquad (2\ 7)$$

In this equation, D_e equals approximately $2d$, since d is negligible in comparison with W (Raju & Chand, 1980)

The Nusselt number is defined by,

$$Nu = \frac{hD_e}{k} \qquad (2\ 8)$$

The Prandlt number is a dimensionless group involving three fluid properties and is

$$Pr = \frac{\mu Cp}{k} \qquad (2\ 9)$$

Heat transfer data for plate heat exchangers is generally reported using correlations of the form,

$$Nu = C(Re)^a(Pr)^b \qquad (2\ 10)$$

where the numeric values of the constants and exponents are determined by the best fit to experimental data The constants and exponents are valid only for a particular plate design (Prifti & Troupe, 1960)

A widely used correlation for estimating film coefficients for turbulent flow in plate heat exchangers is (Buonopane *et al* , 1963),

$$h = 0.2536\left(\frac{k}{D_e}\right)(Re)^{0.65}(Pr)^{0.4} \tag{2.11}$$

Attempts have been made to derive relationships which include plate geometry. Prifti and Troupe (1960) report the following correlation for turbulent flow,

$$h = (0.383 - 0.0505^{l/s})\left(\frac{k}{D_e}\right)(\mathrm{Re})^{0.65}(\mathrm{Pr})^{0.4} \tag{2.12}$$

where l is the straight length of channel before a directional change, and s is the spacing normal to local flow direction. For plates with single lateral corrugations, l/s will be in the range 1.5 to 10, but for many types, such as cross corrugated herringbone patterns and double corrugated, l/s is impossible to determine. For laminar flow (Re<40), Jackson and Troupe (1964) proposed the equation,

$$h = 0.742 C_p G(Re)^{-0.62}(Pr)^{-0.667}\left(\frac{\mu_{av}}{\mu_w}\right)^{0.14} \tag{2.13}$$

Flow is normally laminar in plate heat exchanger handling highly viscous and polymeric materials. Under laminar flow conditions heat transfer coefficients benefit from the narrow gap between the plates of the exchanger and the resulting high shear rates are of particular significance when handling non-Newtonian fluids with pseudoplastic properties found in the food industry.

2 3 Pressure Drop Correlations

The overall pressure drop in plate heat exchangers can be estimated by the equation recommended by Cooper (1974)

$$\Delta P = \left(2fG^{2}L\right)/\left(D_{e}\rho\right) \tag{2 14}$$

Where the friction factor f is given in the turbulent flow regime by $2\ 5 / Re^{0\ 3}$ Friction factors calculated from average velocities and reported by Usher *(1970)* were found to be 10-60 times higher for turbulent flow in plate heat exchangers than those for flow inside a circular tube at the same Reynolds number Superficial velocities for water-like liquids in turbulent flow range from 0 3 - 1 m/sec but actual velocities may be four times higher due to plate corrugations All heat transfer and pressure drop relationships are based on the superficial velocities of the flow per channel (Marriott, 1971) Since plate heat exchangers normally have identical channel geometry for both fluids, similar film coefficients will be achieved for similar pressure drop and pass arrangements when the fluids have similar physical properties (Edwards *et al* , 1974)

2 4 The Log Mean Temperature Difference Method (LMTD)

In the thermal analysis of plate heat exchangers, the total heat transfer rate Q through the heat exchanger is the quantity of primary interest It is convenient to establish a mean temperature difference between the hot and cold fluids such that the total heat transfer rate Q may be determined from the following rate equation,

$$Q = UA\left(\Delta T\right)_{mean} \tag{2 15}$$

An explicit expression for the mean temperature difference may be established by considering an energy balance over a differential length along the heat exchanger and integrating over the entire path of flow (Rogers & Mayhew, 1980) The result for pure countercurrent flow of hot and cold fluids is,

$$(\Delta T)_{mean} = LMTD = \frac{\left(T_{h_i} - T_{c_o}\right) - \left(T_{h_o} - T_{c_i}\right)}{Ln\left(\left(T_{h_i} - T_{c_o}\right) / \left(T_{h_o} - T_{c_i}\right)\right)} \qquad (2\ 16)$$

The above expression involves two important assumptions One is that the fluid specific heats do not vary with temperature and secondly that the convective heat transfer coefficients are constant throughout the exchanger The second assumption is usually the most serious due to the entrance effects, viscosity and convective changes

The LMTD defined above is strictly applicable for single pass, non-cross flow heat exchangers For other arrangements the resulting expressions are so complex they are not practical In such situations it is customary to introduce a *correction factor, F,* for these arrangements (Rogers & Mayhew, 1980)

$$\Delta T_{mean} = F\left(\Delta T_{LMTD}\right) \qquad (2\ 17)$$

F is equal to unity for an ideal counter flow exchanger and less than unity for all other arrangements (Kandlikar & Shah, 1989) When flow ratios between fluids fall between 0 66 to 1 5, it is usually possible to have equal number of passes on both sides of the exchanger In this case the correction factor is high When flow ratios vary widely e g multipass arrangements, the passes will be unequal and the correction factor will be low Values for correction factors F for various pass systems at NTU up to 11 are offered by Marriott (1971) For all but the most extreme cases, correction factors are in excess of

0 95 (Cooper, 1974, Buonapone & Troupe, 1969, Kandlikar & Shah, 1989) Buonpane, Troupe and Morgan (1963) found fluids in single pass heat exchangers required correction factors of 0 95 to be applied to the LMTD However while exchangers are most efficient when having an equal number of passes, alternative pass arrangements enable widely different flow rates to be handled at the expense of a substantial LMTD correction factor to allow for the partial co-current conditions that exist

2 5 Fouling of Plate Heat Exchangers

As stated earlier, the fouling of plate surfaces introduces an additional thermal resistance to the above equation, resulting in the following expression for the overall heat transfer coefficient,

$$U=\frac{1}{\frac{1}{h_i}+\frac{1}{h_o}+R_f} \qquad (2\ 18)$$

Fouling is reduced in plate heat exchangers due to highly turbulent flow (which keeps solids in suspension), smooth plate surfaces and the absence of low velocity regions (dead spots) where fluids can stagnate (Bird & Fryer, 1991) Corrosion-resistant plate material also reduces fouling tendencies because deposits of corrosion products to which fouling can adhere are absent (Marriott, 1971) High turbulence also enhances cleaning in place and should the extent of fouling require manual cleaning the exchanger is easily opened, cleaned and returned to service

The importance of accurate prediction of fouling resistances in plate heat exchangers cannot be over-stressed Fouling resistances for tubular exchangers quoted by the Tubular Exchangers Manufacturers Association (TEMA) are usually conservative and if applied to plate units result in considerable overdesign Many of the high fouling resistances quoted have been obtained from poorly operated plant It is therefore essential in the design of plate exchangers that much lower resistances are used, typically 10 - 20% lower than for tubular units Failure to reduce these resistances at the design stage leads to excess surface area which can often accelerate fouling and decrease the operating period The size of a plate heat exchanger could be doubled merely by using typical tubular resistances under the same service conditions (Cooper, 1974)

As stated previously plate heat exchangers are widely used in the dairy industry but they may be prone to fouling due to their generally small hydraulic diameter and small gap between the channels These channels may be easily blocked once any initial fouling layer is formed Fouling from milk based fluids has been thoroughly studied (Sandu & Lund, 1985, Hallstrom & Lund, 1981, Lalande *et al*, 1989) but little progress has been made towards reducing fouling in commercial plants The resulting cleaning programs are expensive and time consuming and plant operating time considerably reduced (Bird & Fryer, 1991) The following chapter examines the area of fouling in the dairy industry in greater detail

Chapter 3

Fouling mechanisms and categories

Fouling refers to the deposition of unwanted material on a heat transfer surface, usually resulting in an increase in resistance to heat transfer and a subsequent loss of thermal capacity of the heat transfer equipment Fouling has had a long history affecting the efficiency and operation of many industrial processes The first reference in the literature appears to be by Leindenfrost (1756) who reported that after the complete evaporation of a droplet of water a deposit was left on the heated surface This resulted from the precipitation of material dissolved in water Since 1960 considerable progress has been made in understanding the fouling process However this has not resulted in significant improvement in the ability of the designer to predict fouling resistance in heat exchangers While flow and heat transmission are well understood, fouling remains one of the major heat transfer problems yet to be completely solved (Taborek *et al*, 1972) This is especially true in the case of food products such as milk and its derivatives which contain thermosensitive compounds

3.1. Fouling resistance

As stated previously, the effect of fouling in terms of fouling resistance (frequently referred to as a fouling factor) on heat transfer equipment may be expressed in the fundamental equation for the overall heat transfer coefficient as,

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_o} + R_f} \qquad (3\ 1)$$

R_f is the resistance to heat transfer with appropriate units of m^2k/W Sandu and Lund (1985) underlined the necessity to treat fouling and cleaning of heat exchangers as two connected processes He defined the dynamics of fouling/cleaning as the increase/decrease in thickness of the fouled layer on the heat transfer surface as a function of the position and the time for a given set of design and process parameters These give the time-dependence of the fouling resistance and pressure drop in a heat exchanger subject to fouling Therefore the most widely used methods for monitoring fouling are based either on,

a) The measurement of the fouling resistance deduced from the overall heat transfer coefficient (Lund & Bixby, 1975)

b) The measurement of the mean thickness of the deposit deduced from the overall pressure drop (Lalande & Corrieu, 1981, Hiddink & Lalande, 1986)

3.2 Classification and fouling categories

According to Epstine (1979) classification of the various forms of fouling which have been identified in the food industry fall into the categories outlined below

3 2 1 Precipitation fouling This involves the crystallisation of dissolved material in the flowing fluid and occurs whenever the fluid reaches its supersaturation point This may involve normal or inverse solubility salts Liquids containing inverse solubility salts which come in contact with a heated surface at such a temperature as to cause supersaturation will form crystal nuclei and deposition will occur Fouling by normal solubility salts is not as common as that of inverse solubility but it does occur Deposits high in silica (geothermal brines) will precipitate and deposit on cold surfaces Precipitation fouling is common with desalination systems, boilers, cooling water systems and food processing units The deposit is usually hard and adherent Reviews of precipitation fouling are offered by Epstein (1979), Troup and Richards (1978) and Bridgewater (1979)

3 2 2 ***Particulate fouling.*** This occurs in a variety of processes and is the accumulation of deposits from a fluid containing suspended solids Gravitational settling is of minor importance except in the case of non-vertical systems Of far greater importance is the presence of fine particles in the liquid streams Consideration of the fluid mechanics involved in particulate fouling assumes that when a particle arrives within the vicinity of the wall several surface forces arise and profoundly influence whether it remains or not These include Van der Waals forces, electrical interaction forces and viscous forces Excellent reviews of particulate fouling are offered by Gudnumdssen (1981)

3 2 3 ***Chemical reaction fouling*** This occurs when a reaction takes place at a heat transfer surface and solid products of reaction are deposited on the surface Taylor and Wallace (1968) provides the major source of reliable information on fouling in petrol streams Broad generalisations state that fouling rates increase markedly with an increase in dissolved oxygen or air and that the presense of sulphur, nitrogen and metal compounds in even trace mounts within hydro-carbon streams significantly increases the fouling rates A review is offered by Froment (1981) Food product streams are outstanding examples of this form of fouling and a thorough review of fouling of streams encountered in the food processing industry is given by Lund and Sandu (1981)

3 2 4 Corrosion fouling. Here the heat transfer surface reacts to produce corrosion products which foul the surface and promote the attachment of other foulants Lister (1981) and Somerscales (1981) distinguish between two different types of corrosion fouling Corrosion products may be formed at locations remote from the heat transfer surface and transported to and deposited on it, or corrosion may take place in-situ due to corrosion products that form and remain at the heat transfer surface Literature on corrosion of aqueous systems is voluminous but the effect of corrosion in promoting fouling as opposed to loss of metal has rarely been quantified

3 2 5 Bio-fouling. This is the development on the heat transfer surface of an organic film, consisting of the micro-organisms and their products or from macro-organisms such as barnacles Conditions within a heat exchanger are often suitable for the promotion of this category Temperature has a marked effect on deposition The initial deposit of bio-film on a surface is promoted by low fluid velocity This bio-film adds to the thermal resistance and pressure drop as well as entrapping suspended solids To date some 2000 species of organism have been recorded as a fouling nuisance A review is offered by Charackis and Bott (1981)

3.3 Milk and milk based products

Fouling from milk based products over a temperature range of 65-115 °C is generally considered as chemical reaction fouling with an autocatylic rate (Lalande & Corrieu, 1981) The determination of general laws to explain this behaviour posed some difficulties for Lund and Bixby (1975) who fitted several possible equations to experimental results and they chose to express the dynamics as,

$$R_f = R_{f_o} e^{\beta t} \qquad (3\ 2)$$

On the basis of experiments lasting up to 6 hours, Lanlande and Corrieu (1981) and Roignant and Daufin, (1986) established that the rate of growth of milk deposits was proportional to time to the power 2,

$$m_f = at^2 \qquad (3\ 3)$$

This implies, in terms of a heterogeneous reaction, that the deposition flux is governed by an autocatylic reaction of the order 0 5 Concerning the parameters influencing the deposition flux, all authors established the key role played by the product bulk temperature and the exchanger temperature gradient In the temperature range 120-140°C (UHT sterilisation) the mechanism of fouling seems more complex since a linear as well as anincreasing rate is observed (Lalande & Corrieu, 1984)

3.4. Modelling of the fouling process

The earliest mathematical model of fouling, that of McCabe and Robinson for scaling of evaporators, was published in 1924 A quarter of a century later not a single new fouling model was available In fact it was not until another ten years that a second model appeared in literature, that of Kern and Seaton (1959) Data at this time suggested that fouling-time curves usually assume asymptotic form and that fouling can be expressed by a transient equation of the form,

$$R_f = R_f^{\max}(1 - e^{-\beta t}) \qquad (3\ 4)$$

In order to explain this, Kern and Seaton proposed the following material balance equation, Rate of accumulation = Rate of deposition - Rate of removal

$$\frac{dx_f}{dt} = \phi_d - \phi_r \tag{3 5}$$

Assuming ϕ_d is a constant and ϕ_r is a first order in x_f, (i e $\phi_r = \beta x_f$) this equation may be solved to give,

$$x_f = \frac{\phi_d}{\beta}(1 - e^{-\beta t}) \tag{3 6}$$

Therefore,

$$R_f = \frac{x_f}{k} = \frac{\phi_d}{\beta k}(1 - e^{-\beta t}) \tag{3 7}$$

In order to explain the experimentally observed velocity dependence of $R_f^{\max}$ and β, Kern and Seaton proposed,

$$\phi_d = K_1 cM \tag{3 8}$$

$$\beta = K_2 \tau \tag{3 9}$$

Therefore

$$R_f^{max} = \frac{K_1 cM}{kK_2 \tau} \tag{3 10}$$

Implementation of the above model is only possible on the basis of experimental data which would include the variation of all the pertinent variables and would enable the establishment of a functional relationship among the various fouling parameters (Taborek *et al*, 1972) The persistent observation by Kern and Seaton that industrial heat exchangers often fouled asymptotically led them to introduce the above mentioned idea that the net fouling rate was given by the difference between the rate of deposition and removal Processes controlling the build up of fouling may be divided into two distinct groups, the deposition rate factors and the removal rate factors

3 4.1. Deposition rate factors

Depending on the fouling mechanism the deposition rates may be controlled in a number of ways

a) *Reaction rate controlled deposition* This frequently limiting mechanism is applicable to many situations in which the fouling layer results from a chemical reaction of components in the product stream

b) *Nucleation site controlled deposition* This only applies to the initial stages of the fouling process on a fresh surface and accounts for an induction period

c) *Diffusion controlled deposition* Diffusion often becomes the limiting mechanism in low velocity streams The mass transfer by this mechanism always increases with velocity However above a certain velocity it serves only in transporting fouling material to the surface where another mechanism may determine the deposition rate

d) *Other mechanisms* These include gravity-controlled settling, electrophoresis and thermophoresis

For chemical reaction fouling, the fouling material itself is transported to the heat transfer surface With in-situ corrosion fouling ionic species form the fouling deposit (Characklis & Bott 1981) Reviews of the attachment/formation reaction are given by Lyster (1970) and Sandu and Lund (1985) It is clear from these reviews that this process is very complicated involving both physical and chemical processes making if difficult to incorporate it into the fouling model From the available knowledge the attachment/formation process depends on the presence or absence of a fouling deposit on the exchanger surface ie a clean surface will react differently to a fouled surface (Baier, 1981) If mass transfer coefficients depends on velocity, where mass transport is slower than attachment/formation reactions, the rate of fouling will be sensitive to fluid velocity If attachment/formation reactions are slower than transport processes, the rate of fouling will be sensitive to variables other than velocity e g surface temperature From investigations of natural water and certain biological fluids, deposits form immediately on a clean surface These deposits do not represent significant fouling in terms of resistance, however they have significant effects on the ability of subsequent species to deposit Initial formation of deposits must be investigated for two reasons,

1) Available evidence (Characklis & Bott, 1981) indicate that the later stages in the development of fouling deposits depends on the nature of initial events

2) Information on initial fouling characteristics of different materials will draw attention to any materials or treatments which would decrease the rate of fouling growth

3.4 2 Removal rate factors

The net rate of deposit removal depends on the fluid shear tending to remove the deposit and adhesive forces tending to keep the deposit in place

a) *Fluid shear* This is simply the friction component of the flowing fluid against the fouling deposit and is a function of the Reynolds number, the deposit roughness and the flow configuration It should be noted that as a deposit builds up the cross sectional area must decrease causing an increased shear at constant flowrate

b) *Deposit adhesion* This is usually defined as the adhesive strength of the deposit per unit area at the plane of weakest adhesion Speculation includes that adhesion will increase with uniformity of deposit structure Adhesion may decrease with deposit thickness due to an increase in the number of planes of weakness within the deposit

Adhesion is a function of the heat exchanger surface characteristics only if the surface-interface bond of the deposit is weaker than its internal adhesive strength This accounts for the fact that specially prepared smooth heat exchanger surfaces retards fouling in some cases only but not in all

So how does a particle ever get deposited if it becomes subject to a re-entrainment mechanism as it approaches the deposition surface? In turbulent flow a convincing resolution was presented by Cleaver and Yates (1973) who argued that the fluid shear alone is not sufficient to dislodge particles from a flat surface They state that re-entrainment occurs as a result of random and distributed turbulent bursts which originate at the fouling surface These bursts act like miniature tornados lifting deposited material from the surface The bursts are accompanied by gentler fluid sweep-back to the surface Deposition occurs via these back sweeps and re-entrainment via the turbulent bursts Several models for the deposition process exist m terms of the local mass flux to the fouling surface All show either linear or falling rate characteristics but without a re-entrainment term none show asymptotic behaviour The deposition term depends on a transport and attachment process The removal process is not as well understood as the deposition process with the need to develop experimental techniques which may lead to a better understanding of this aspect The type of processes that act on the fouling deposit and result in its removal include dissolution, erosion, turbulence, etc , and more than one may act on the deposit during the fouling period Dissolution is related to the solubility of the deposited material (Lyster, 1981) Re-entrainment by the flowing fluid involves mechanical forces and mutual interaction between the elements of the deposit

3 5. The Induction Period

Milk is a highly foulant fluid when processed in plate heat exchangers but other products derived from milk (cheese, whey, cream, milky deserts) also have the ability to foul heat exchangers One of the most intensively investigated fluids directly related to milk has been whey (Delsing & Hiddink, 1983, Hege, 1984, Daufin *et al*, 1987, Hiddink, 1985) During studies on the heat treatment of some dairy products, Roignant and Daufin (1986) concluded that whey is a highly foulant fluid of industrial interest and liable to be chosen as a model fluid for the study of the non-casein fraction of milk Numerous observers have identified an induction period related to fouling of heat exchangers when these units are used to process whey products During the induction period only negligible deposition was found and only negligible fouling was observed At a certain point in the fouling time curve, deposition sites become so numerous that they combine into a blanket and the fouling rate increases rapidly either in linear form or at an asymptotic rate At this point the induction period is deemed to have concluded This induction period is of vital importance as once fouling enters a linear increase, equipment becomes rapidly inoperable

It is of vital importance to know which deposits form the first layer on the heat transfer surface during the induction period Baier (1981) experimented with milk at a bulk temperature of 50°C and found only protein deposits Similar results were presented by Delsing and Hiddink (1983) at temperatures ranging from 50-70°C Tissier and Lalande (1986) presented evidence that minerals may form most of a thin layer immediately adjacent to the heat transfer wall Heavy protein deposits appeared to grow from protruding sections of the mineral layers He stated that the time required for the formation of the mineral deposit may correspond to the induction period Danfin *et al*, (1987) experimented at bulk temperatures between 25-88°C and again found mainly proteins with some minerals These results suggested that both proteins and minerals were involved in the early stages of fouling and in the induction period Bird and Fryer (1991) carried out work on whey protein concentrate and determined that protein was the first species to be adsorbed This was confirmed by Belmar-Beiny and Fryer (1992) using electron microscope analysis which identified protein as the first species to be absorbed The lack of depositable material up to 73°C indicated a lag phase in which some conformational changes on the absorbed protein must occur before increased fouling occurs This lag phase was deduced to correspond to the induction period

The length of the induction period appears to increase with increasing velocity (Belmar-Beiny & Fryer, 1992) However it is strongly dependent on surface cleanliness At the end of the induction period the rate of fouling may be correlated with the volume of fluid that is hot enough to react The induction layer acted as a surface on which subsequent layers of deposit occurred in low shear areas or around flow obstructions After the surface is covered by a layer of deposit it is easier for fouling to occur so the fouling rate increases Proteins already attached to the wall can react with proteins in the fluid at the solid-liquid interface, denatured and aggregated proteins in the bulk fluid react more readily at the wall with native protein because their free sulphydryl groups are exposed The rate limiting step becomes the generation of material which is able to absorb (Lalande *et al* , 1989)

There is evidence to show that deposition of a fouling layer during the induction period may increase the heat transfer coefficient in certain cases (Crittenden & Alderman, 1988) If the initial fouling layer deposited during the induction period is rougher than the heat transfer surface, it will increase the local film heat transfer coefficient due to increased turbulence The formation of the fouling layer will decrease the cross sectional area and hence increase the velocity of the fluid also increasing the local film coefficients The magnitude of the roughness effect depends on the ratio of the roughness height to the hydraulic diameter (Perkins & McEgliot, 1973) A low or negative fouling resistance is observed in the initial stages of fouling depending on the Reynolds number and particle size

3.6 The role of β-Lactoglobulin in whey fouling

Work carried out by Lyster (1965), Burton (1968) and Lalande and Corrieu (1984) confirmed the composition of milk deposits on plate heat exchangers Two types of deposit were distinguishable depending on the temperature of the heat transfer equipment surface (Lalande *et al*, 1989)

1) **Below 100°C** A soft white voluminous spongy soil containing 50 - 60% protein, 30 - 35% mineral and 4 - 8% fat was the nature of the deposit formed This deposit, named 'Type A' by Burton (1968), looks spongy and has low density, which causes a major problem in heat exchangers by blocking channels and increasing the pressure drop Tissier and Lalande (1986) using a scanning electron microscope showed that the spongy structure of 'Type A' deposits is due to a network composed mainly of the protein phase Precipitated minerals appeared to be included in the network as aggregates In the dairy industry, plate heat exchangers containing the most troublesome deposits operate around this temperature

2) **Exceeding 100°C.** Deposits were found to be grey in colour with a brittle-like structure containing 70% minerals, 15 - 20% protein and 4 - 8% fat This deposit, named 'Type B' by Burton, was found to be different in appearance and composition It had a high density and corresponded to the well known 'milkstone' found in the dairy industry

Fouling below 100°C was found to result from a complex mixture of reactions at the heat exchanger surface and in the bulk fluid and was closely related to the thermal stability of the native milk protein β-lactoglobulin. Half the protein deposit formed below 100°C was in fact β-lactogloublin This forms only 10% of the whole milk protein β-lactoglobulin deposits due to its thermal instability on heating above 74°C Above this temperature it becomes thermally unstable, partially unfolding or denaturing, exposing reactive sulphydrls It then polymerises with other β-lactoglobulin molecules or other proteins such as α-lactoalbumin (Arnebrandt & Burton, 1987)

In whey (Lyster, 1970, Hillier & Lyster, 1979, Levieux, 1980) the kinetics of the irreversible denaturation of β-lactoglobulin follow a second order rate equation and show a sharp change in activation energy at about 80°C Below this temperature the activation energy is about 300 kJ $mole^{-1}$ but above 80°C it is about 40 kJ $mole^{-1}$ During the heat treatment of milk in a pilot scale plate heat exchanger Skudder and Thomas (1981) showed that a decrease in the concentration of free -SH groups in milk markedly reduces the amount of protein deposited on the heated surface This was achieved by the addition of potassium iodate which is believed to act by the rapid oxidation of the -SH groups as soon as they become free under the influence of heat As soon as protein is removed from whey solutions the fouling dynamics follow a linear relationship in agreement with the classical behaviour of inverse solubility of salts (Epstine, 1979) Lund and Bixby (1975) found two separate regions of 'Type A and B' i e the deposits tended to be homogeneous with 'type A' affecting heat transfer more significantly Some benefit was to be gained from prefouling with 'Type B' before placing the plate exchanger into service Over 3 hour trials the U-value decreased by 30% from clean However when prefouled with 'Type B' no decrease in U-value occurred but the initial value of U was half that for clean heat transfer

3 7. Whey fouling

Early work on modelling of whey fouling concentrated on surface reactions where the rate of deposition was modelled as a function of the surface temperature and not the bulk fluid temperature (Lalande & Corrieu, 1984) The thermal stability of β-lactoglobulin is closely related to fouling therefore reducing the sulphydrl groups reduces the rate of fouling However the bulk reaction temperature is also important in milk protein fouling and Belmar-Beiny et al , (1993) have shown recently that fouling is proportional to the volume of fluid hot enough to produce denatured and aggregated protein At temperatures above 80°C β-lactoglobulin denatures in approximately 2-4 seconds However it appears that aggregation will follow only if it is aided by other species present in the solution such as NaCl and calcium ions (Belmar-Beiny & Fryer, 1992) Calcium does not appear to be involved in the first layer of deposit but is involved in the build up of subsequent deposits It has been observed by several authors (Delsing & Hiddink 1983, Daufin *et al*, 1987) that the amount of fouling from decalcified whey is less than from standard solutions A recent model constructed by DeJong and Bowman (1992) considered both surface and bulk reactions With both the heat transfer surface and the bulk fluid hot enough for protein denaturation then both regions would subsequently contribute to the deposit formation

Another model developed by Schrefier and Fryer (1994) was designed to simplify the fluid mechanics of fouling The model demonstrated the effect of bulk fluid temperature on fouling If the temperature in the bulk fluid is low there will be few aggregates in the bulk flow and there will be a high driving force away from the exchanger wall and so the rate of fouling will decrease If the temperature in the bulk fluid is high, there will be many aggregates and a low driving force away from the wall and fouling will increase This mass transfer may suggest why the bulk temperature effects are so important (Belmar-Beiny & Fryer, 1992a) A number of reactions appear to be taking place, those which govern the initial interaction between protein and surface and those by which thick deposits build up affecting heat transfer It may therefore be said that during fouling a reaction is taking place in the fluid and at the exchanger surface but the rate controlling step changes during the course of the process The process is controlled by a reaction between the surface and the protein and during the induction period a layer of material builds up on the heat transfer surface As more material builds up, it becomes easier for further deposition to occur as the nature of the interface changes from metal to protein These results contradict those of Lund and Sandu (1981) who describe the induction period as the time required for the spaces in a rough surfaceto be filled in It seems reasonable to postulate that the rate of fouling in the post induction period is controlled by the bulk denaturation aggregation rate

Lund and Bixby (1975) concluded that factors affecting the rate of whey fouling in plate heat exchangers include flowrate, surface temperature i e wall temperature, the type of surface interface and the product bulk fluid temperature Deplace and Leuliet (1994) noted that with increasing pressure drop the average velocity also increased resulting in an increased film coefficient with the ability to counteract the decrease in overall heat transfer due to fouling Also just before a linear decrease in heat transfer coefficient, its value appeared to be slightly higher than during the induction period This was attributed to the deposit formation around the contact points giving an increase in turbulence (Belmar-Beiny & Fryer, 1994)

Even though data on fouling is available it is not suited to a general predictive model The qualitative information suggests that the overall process consists of a number of related processes,

1) processes within the bulk fluid,
2) transport of the deposit to the heat transfer surface,
3) attachment and formation reactions at the fluid interface,
4) removal of the deposit from the fouled surface,
5) transport from the deposit-fluid interface

The possibility of breaking down the overall fouling process into a number of sub-processes suggests that research directed towards an understanding of each of these groups may provide better models for both designers and operators of plate heat exchangers

Chapter 4

Materials and Methods

4 1 Heat exchanger rig design

To study the fouling process a rig was designed at Dublin City University consisting of a plate heat exchanger, instrumentation, control equipment and associated equipment This equipment was mounted on a custom built frame which housed the plate heat exchanger, pumps, ancillary pipework, instrumentation and data acquisition hardware The frame was manufactured with ease of access and exchanger dismantling in mind

4.2.1. Heat exchanger

The heat exchanger rig was developed around an Alfa Laval P30 plate heat exchanger (Fig 4 1) This exchanger is a simply designed pilot scale exchanger with relatively few thermal plates resulting in low pressure loss and high economy The product and heating fluids flow through alternate plates in a counter-current direction (Schematic A) The technical specification for the plate heat exchanger was as follows,

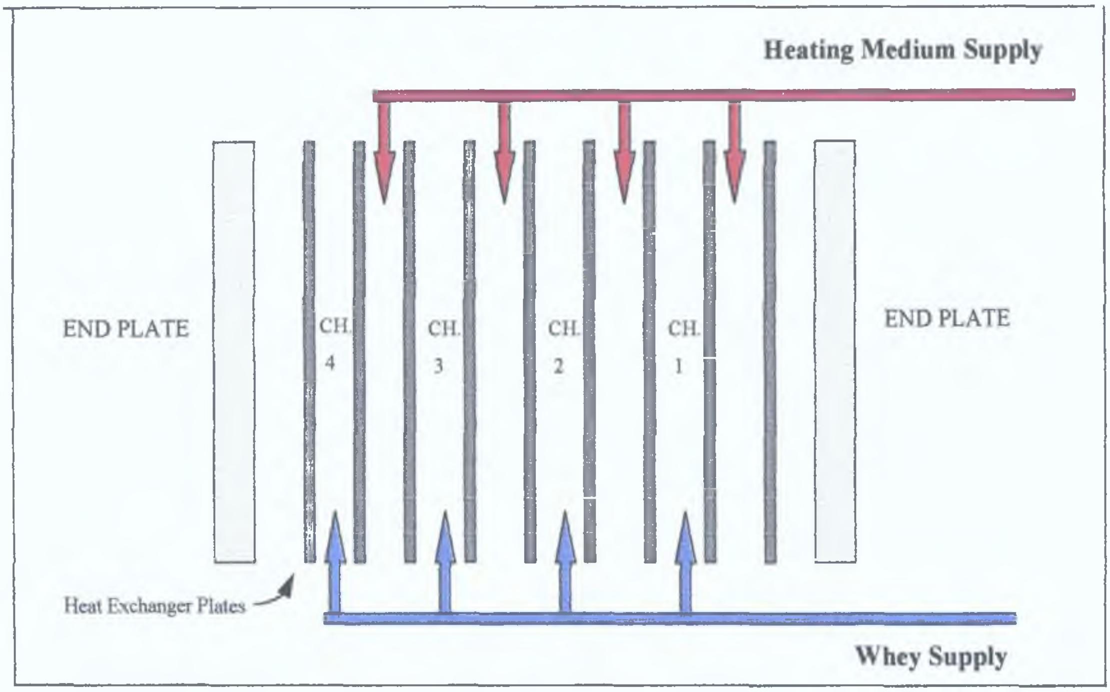
Frame material	Aluminium
Plate material	316 stainless steel
Gasket material	Nitrile 120°C
Max working pressure	4 bar
Surface area of plates	0 406m^2
Number of plates	9

Due to a special gasket it is impossible for the product and heating fluid to mix, allowing leakage to be easily observed and remedied

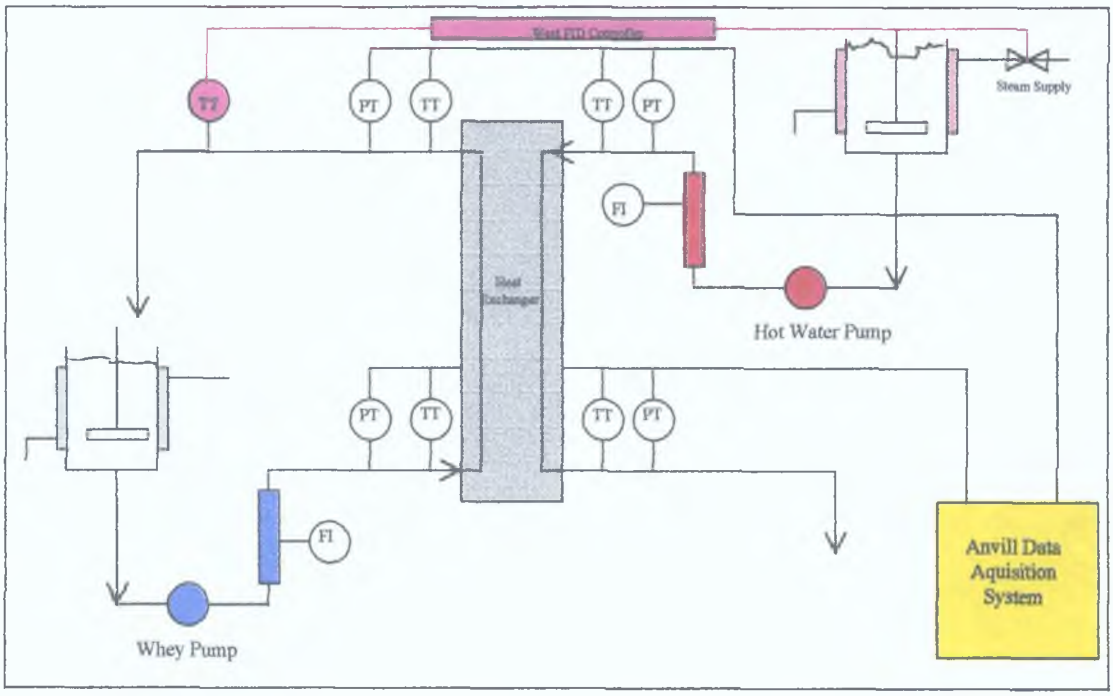
Fig. 4.1 Plate Heat Exchanger used during this project.

4.2.2 Product feed and return pipework

The whey product feed was pumped from a feed tank to the heat exchanger via a Berdsford PV51 centrifugal chemical pump supplied by Frazer Ross Ltd. (Schematic B). The pump was selected to meet the system needs in terms of chemical cleaning, temperature, pressure drop and handling of food-based products. The pump flowrate was regulated using a 25mm 'Vee Reg' valve purchased form BSS Ltd., and a platon



Schematic A. Flow pattern through the Plate Heat Exchanger



Schematic B. Piping and Instrumentation on the Plate Heat Exchanger

PG/1 flowmeter with a range of 4-40 l/min supplied by Manotherm Ltd. (Fig. 4.2). Before entering the exchanger, the temperature and pressure of the product was measured and continually logged to the data acquisition system. On exit from the exchanger the outlet temperature and pressure of the product was logged and the product returned via a flexible 25mm hose to the feed tank.

Fig 4.2. Plate Heat Exchanger rig during construction.

4.2 3. Heating feed and return pipework

To accurately control the heating conditions within the exchanger a stand-alone West 6100 PID temperature controller supplied by Manotherm Ltd , was used to control a hot water heating circuit The hot water was circulated using a Beresford PV51 pump As with the product circuit the flowrate was controlled via a Platon PG/1 flowmeter and both the temperature and pressure of the feed and return lines logged to the data acquisition system (Schematic B)

4 2.4. Data acquisition system and software

To record and analyse the temperature and pressure signals from the heat exchanger an Anville Series 410 data acquisition system was installed (Fig 4 3) Signal conditioning was automatically provided and an internal microprocessor converts all inputs to correct engineering units i e Bar or °C Technical specifications for the system are as follows,

1) No of channels	8 analogue and 8 digital
2) Inputs Temperature	PT100 (-100°C to +200°C)
Pressure	Transducer (4 to 20 mA)
3) Signal conditioning	Automatic
4) Engineering units	mV, V, °C, %, mA

The Series 410 software package was purpose-written and ran under Windows 3 1 It provided easy mouse-operated control of the system and an excellent display of all relevant data on the PC screen (Fig 4 4) Incoming data was filed on hard disk and also displayed on screen as a graphical display This display included last read data and trend graphics of the 8 analogue inputs, individually or simultaneously The fact that two different types of sensor may be handled simultaneously made this system ideal for analysing heat exchanger systems Further data analysis and modelling was carried out using Microsoft Excel and Sigma plot (Jandel Scientific) Both the data acquisition system and the software were purchased from Manotherm Ltd

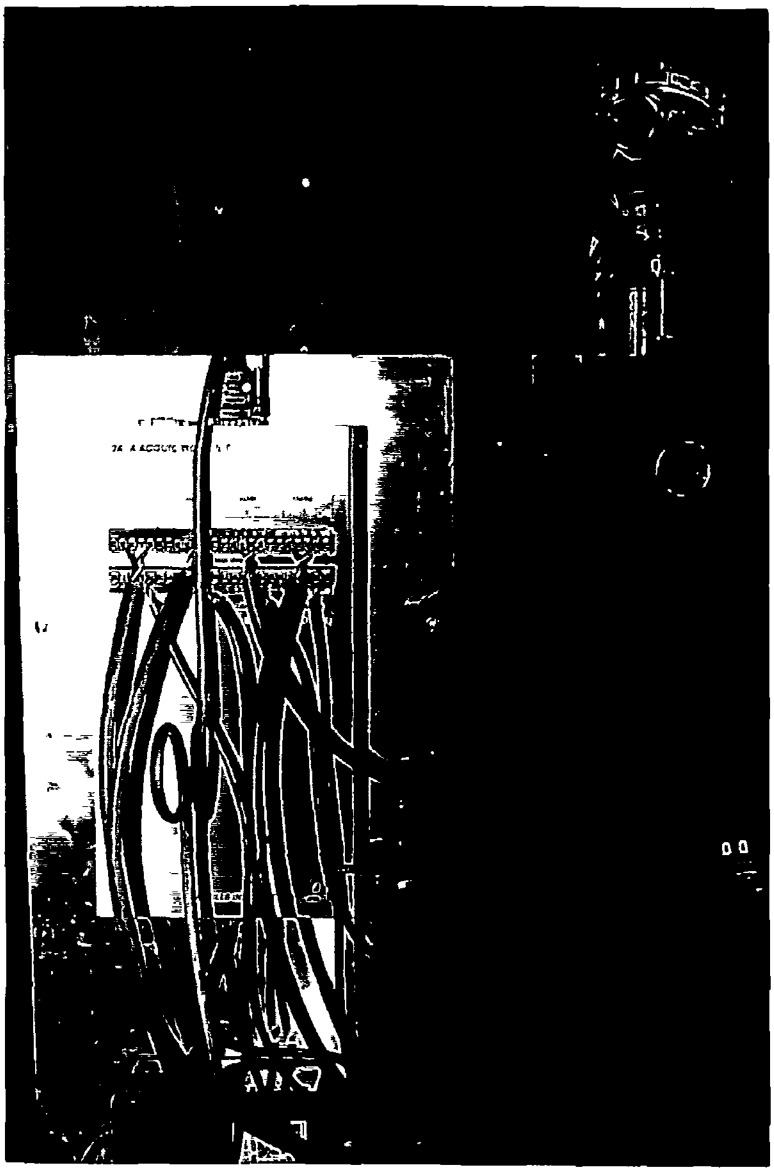


Fig 4.3 Anville Data Aquisition System

4.2 5 Pressure transducers

The pressure of each heat exchanger line was measured using Trans instruments Series 2000 pressure transducers These units were self supporting directly on the pipework with G 1/4 pressure connections Mounting was omni-directional to a maximum torque of 15 8 Nm The technical specification of the probes is as follows,

1) Range..2.5 bar.

2) Output...4 to 20 mA.

3) Supply...12 to 36 volts DC.

4) Pressure limit...Twice the normal range

5) Temperature range.................................-40 to +100°C.

4.2.6. Temperature probes

To measure the temperature in each pipe of the heat exchanger, Platinum Resistance thermometers were used which again were self supporting on the pipework. The probes were fitted with PT100 sensors to BS1904, with errors minimised by using 4 wire compensation. The overall probe length was 100mm with the stem manufactured from 316 stainless steel. Technical specifications are as follows,

1) Useful range...-50 to +300°C.

2) Sensor...100 ohms at 0°C.

3) Material...Aluminium head.

4) Cable resistance...No significant error.

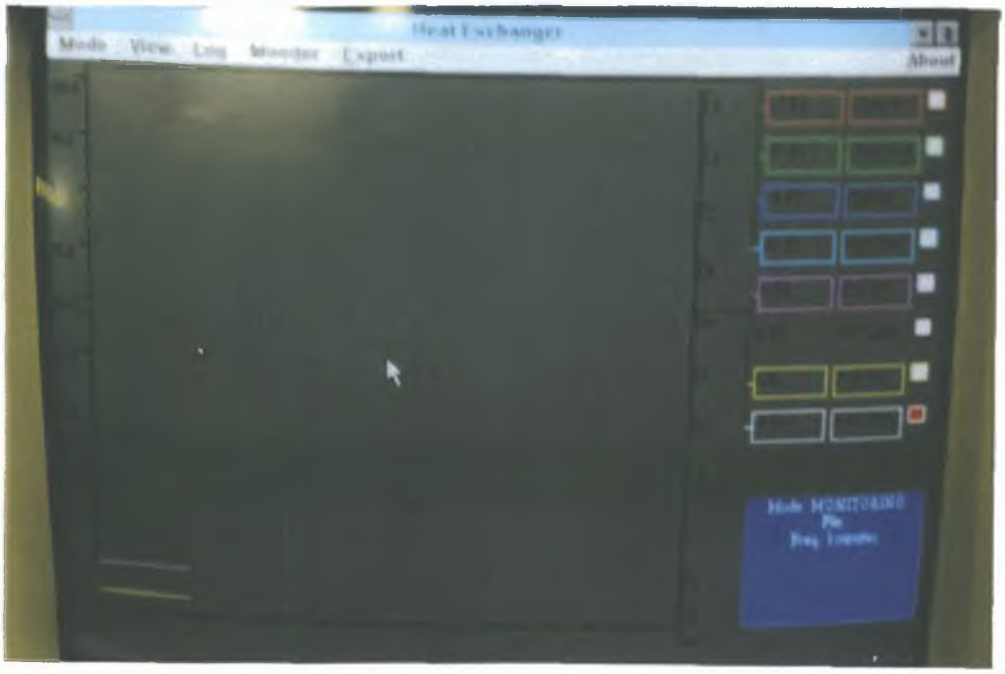


Fig 4.4. Anville Graphics Display

4.3 Preliminary tests

To test the rig design a number of preliminary trials were carried out with distilled water (Fig. 4.5). These trials assisted in the initial set-up of the system, calibration of the probes and the general identification of operating parameters. Both system tanks were filled with distilled water. The PID controller set point was set to 92°C i.e. the outlet temperature of the whey from the heat exchanger. The cold water flowrate on the product feed tank was set to 5 l/min which resulted in a bulk tank temperature of 85°C, well above the protein denature temperature of 72°C associated with the whey powders used.

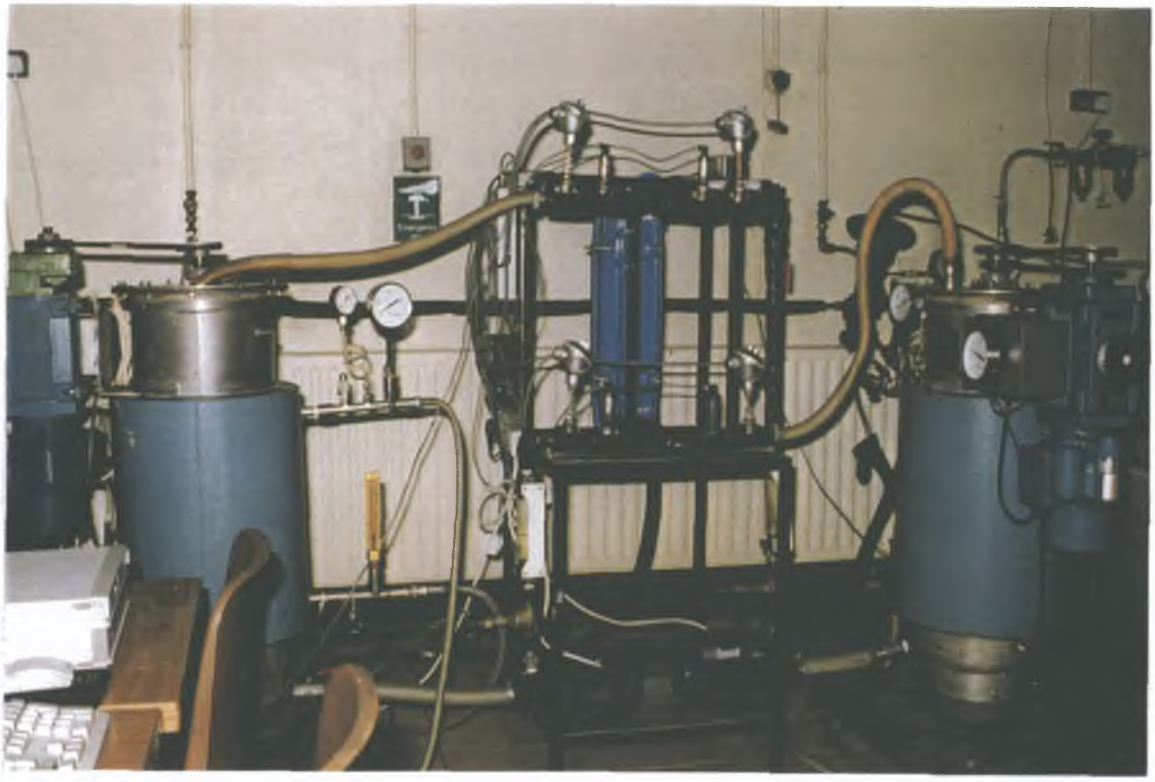


Fig 4.5. Final Rig Design

Runs lasting one hour were carried out to determine the clean overall heat transfer coefficient at different flowrates. This data was later used (Fig 5.5) to determine the fouling resistances. These tests generated excellent data for clean conditions and proved invaluable for general familiarisation with the rig and software package use throughout the experimental runs The following sections will detail the experimental methods used to analyse the fouling experiments

4.4 Experimental method

Roignant and Daufin (1986) concluded that in the study of dairy products whey was a highly foulant fluid of industrial interest and was suitable as a model fluid for the study of fouling in the dairy industry The following is a list of the technical specification of the product used during the experiments reported here

Product . Avonmore Avonlac 115 whey powder

Chemical analysis	Units	Analysis	Limits	Mtd of Analysis
Moisture	%	4 0	4 0 - 4 5	IDF 26 1964
Fat	%	1 0	1 2 - 1 5	ADMI 1971
Ash	%	8 0	8 5 - 9	IDF 1979
Protein	%	12	12 - 14	AOAC 16 1980

4.4.1. Typical experimental run

The product and heating tanks were filled with 50 litres of distilled water Both pumps were started and the flowrates duly adjusted The PID controller was set to 92°C and the cooling water flowrate of the whey feed tank adjusted to give a bulk tank temperature of 85°C The system was then allowed to stabilise while the whey powder was weighed to give a certain concentration This was added to the product tank and thoroughly mixed Anti-foam was also added to prevent foaming due to high protein concentrations

At this point the process was analysed via the Anville data acquisition system The temperature and pressure of each line of the heat exchanger was monitored and recorded on the P C by switching from stand-by to record mode The eight channel readings were displayed on the P C screen as a graph of pressure and temperature versus time and the data updated every 60 seconds Initial experimental runs lasting 5-6 hours resulted in asymptotic fouling in many cases after approximately 2 hours Therefore runs were limited to 3 hours for the remaining experimental procedures

After each run the experiment was stopped by switching the Anville system to stand-by mode, thereby preventing further analysis Both pumps were switched off and the 'hold-up' volumes in the exchanger allowed to drain back to the tanks The steam and cooling water supplies were turned off and the PID controller disconnected The data acquisition file for each run was copied to floppy disk, backed up and exported to Microsoft Excel for further analysis

The heat exchanger was now dismantled and the plates carefully removed The plates were initially visually inspected and fouling patterns noted Each plate was carefully weighed and results of the deposits per plate and per channel were recorded Once the deposits were measured the rig and exchanger were ready for cleaning The rig was cleaned according to dairy industry methods Initially the plates were manually cleaned using hot water The deposit was of type A and was easily removed The plates were then reassembled onto the rig and a cleaning cycle initiated The following cleaning procedure was used after each run,

1) Flush the system with water at 50-55°C to remove initial deposits and debris due to dismantling Drain the system completely
2) Clean with 1% NaOH (sodium hydroxide) for 20mins at a temperature of 65-70°C Drain system completely
3) Flush with water at 50-55°C for 5 mins Drain system completely
4) Clean with 0 5% HNO_3 or H_3PO_4 (nitric or phosphoric acid) for 15 mins Drain system completely

5) Flush with water at 50-55°C until outlet gives neutral pH

The data recorded from various experiments was exported to Microsoft Excel for detailed analysis (See Appendix B)

Chapter 5

Results and Discussion

As with most research work this project was not without its share of problems The initial and final rig designs differed considerably as changes were made to eliminate various problems as they were encountered The initial rig was designed around existing equipment including uninsulated tanks, manual temperature control and inadequate mixing The result of this was inconsistent and unreproducble data A brief summary of preliminary work is given below

5.1 Feed tanks supplying the heat exchanger rig

The use of two 200 litres tanks generated problems with mixing and temperature control due to their shape To keep the cost of raw materials and the quantity of distilled water low, a product sample of 50 litres was used per run This barely covered the bottom of the 200 litre vessel and resulted in poor mixing, poor temperature control and coagulation of the whey proteins The combined effect of these was highly inconsistent data The use of two specially modified 50 litre vessels eliminated these problems These tanks were well insulated, highly agitated and slender in shape The outlet ports were modified from half inch to one and half inch diameter to ensure adequate supply to the feed pumps

5 1 1 Temperature Control

During early trials the temperature control on the rig was carried out manually using a steam pressure reducing valve However the temperature profiles generated were highly unstable and steady state conditions were impossible to achieve This manual system was replaced with a West 6100 stand alone PID temperature controller, a modulating steam diaphragm valve and an I/P converter The effect of these modifications was complete temperature control over a wide range of temperatures

5 1.2 Mixing of the Whey Product Feed Tank

The importance of adequate mixing of the product cannot be overemphasised A number of problems arose from the initial rig design When no mixing was used other than recirculating the product back to the feed tanks, the denatured whey protein settled at the bottom of the feed tank The settled protein then acted like a filter cake removing particles and only allowing liquid to pass through The result was very little fouling on the exchanger plates Any disturbance of this protein cake via mixing resulted in an immediate rise in system temperature and rapid deposition within the heat exchanger These effects were eliminated by use of adequate agitation

5.1.3 Cleaning of the rig

Initial cleaning methods proved inadequate These consisted of manually cleaning the plates with high pressure water after which the plates appeared to be clean However after 3-4 runs a deposit appeared on the plates which was impossible to remove by manual cleaning alone Plates with this type of deposit, when returned to the exchanger, fouled rapidly giving strength to the theory that surface composition has a dramatic effect on the fouling rate The cleaning method adopted was that used in dairy cleaning of plate heat exchangers This removed all deposits but added considerably to the time required for cleaning and was very labour-intensive

5.1 4 Insulation of the Heat Exchanger rig

To improve the accuracy of the results and to reduce the heat loss from the system, all exposed pipework, valves and fittings were insulated Both feed tanks were also well-insulated These modifications resulted in excellent temperature control around any set-point

5.2 Temperature control of the Heat Exchanger

A typical starting point for monitoring fouling of plate heat exchangers is to log the change in temperature of each inlet and outlet port of the unit over a period of time. Figure 5.1 represents a plot of the four heat exchanger temperatures against time for a typical run of duration 5 hours. During this run the whey outlet temperature was held constant with a set point of 90°C. This was achieved via the West PID controller which controlled the hot water temperature supplied to the heat exchanger.

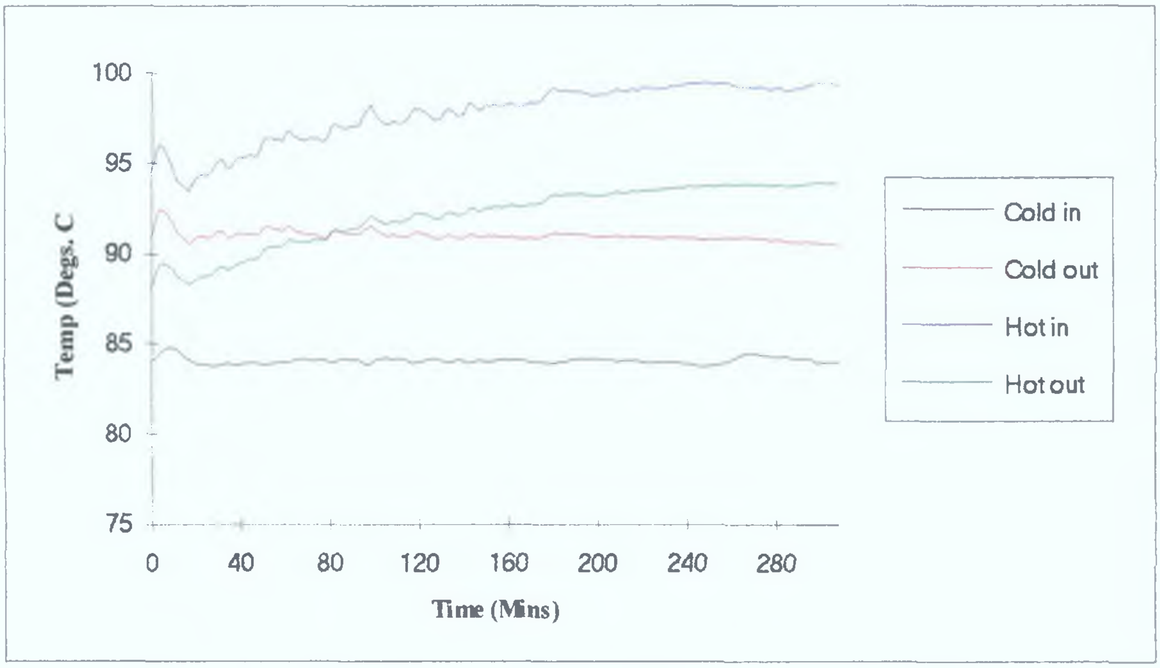


Fig 5.1 Temperature v's Time at 1% whey concentration and flowrate of 10 l/min

The effect of fouling was to gradually increase the inlet (and outlet) temperature of the heating fluid, particularly during the first two hours of the run. A higher heat input was necessary to hold the whey outlet temperature constant resulting in a hot inlet temperature rise of 6°C over the entire run. It is clear from this graph that fouling has a dramatic effect on the heat input necessary to hold the whey outlet temperature constant. The overall effect is to decrease the efficiency of the exchanger as the processing of the whey proceeds.

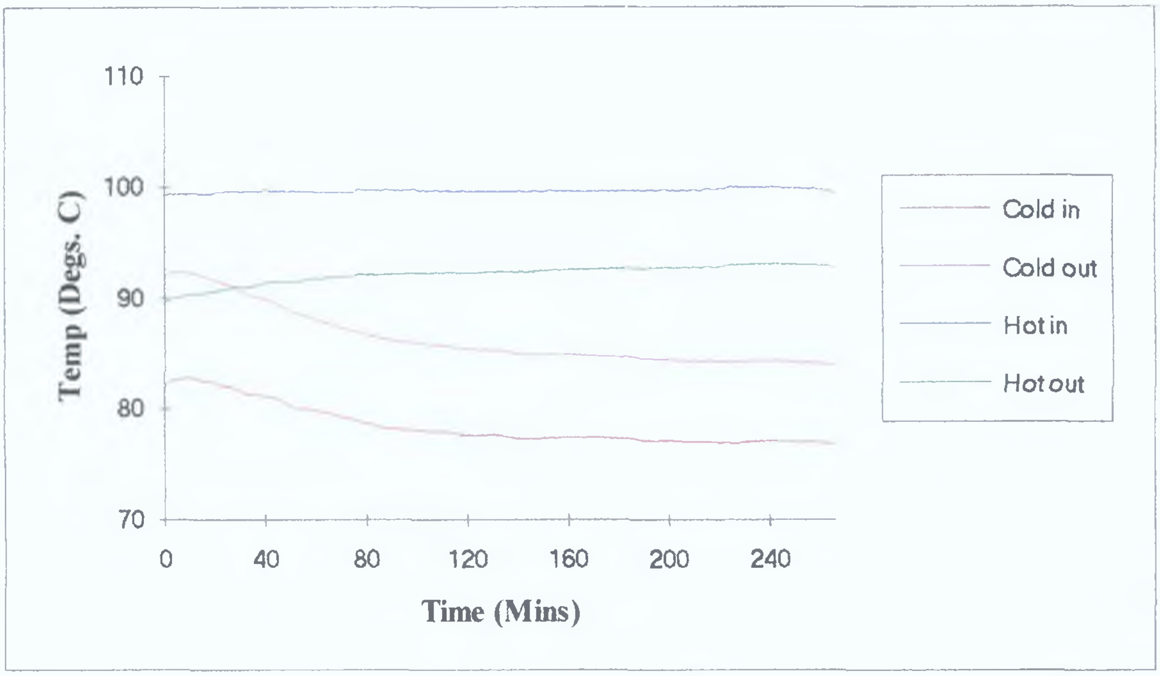


Fig 5.2 Temperature v's Time at 1% whey concentration and flowrate of 10 l/min using an alternative controller configuration

Alternative methods of controlling the exchanger were tested with the set-point thermometer placed in different positions. One configuration used was to place the probe in a position which held the hot water outlet temperature constant at 97°C (Fig 5.2). The effect of this configuration was a reduction in the whey outlet temperature due to fouling at the end of each experiment. This was not satisfactory because in an industrial situation this would result in lack of control of the product temperatures as the run proceeds.

5.3 The effect of fouling on the overall heat transfer coefficient

Figure 5.3a represents the evolution of the overall heat transfer coefficient (U), using an F-factor of 0.95 (Kandlikar & Shah, 1989), with time for a typical experimental run at 10 L/min. Belmar-Beiny and Fryer (1992) observed three phases of fouling;

A) *An Induction period* was noted during which the U-value was almost constant but sometimes increased slightly before decreasing.

B) *The Fouling period* during which the U-value decreased linearly with time to a minimum value

C) *The Post fouling period* during which the U-value increased slightly with time as described by Belmar-Beiny and Fryer (1992)

Only phases (A) and (B) were observed in these experiments The effect of fouling was to reduce the overall heat transfer coefficient by a factor of three An induction period lasting only 3-4 mins occurred in the early stages of the run

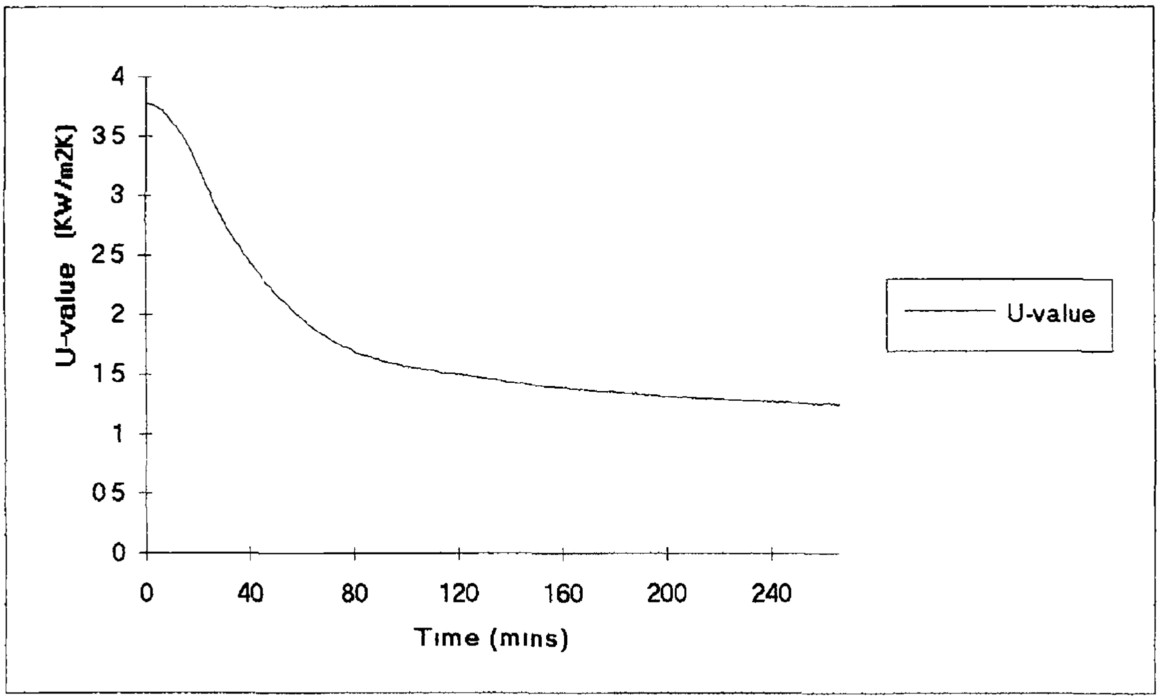


Fig 5.3a U-valve v's Time at 1% whey concentration and flowrate of 10 l/min

Just before a linear decrease in the heat transfer coefficient, the U-value appeared to increase on a number of occasions during the induction period at various flowrates (Fig 5 3b) This process may be due to increased turbulence due to deposition around the contact points of the plates (Photo A) as described by Bird and Fryer (1991) and Delplace and Leuliet (1994) This effect was most prevalent at lower flowrates and was completely eliminated at higher flowrates Delplace and Leuliet (1994) interpreted this effect as an increase in average velocity due to deposition which results in a change in local film coefficients This appears to counteract the decrease in U value due to fouling just before the linear decrease

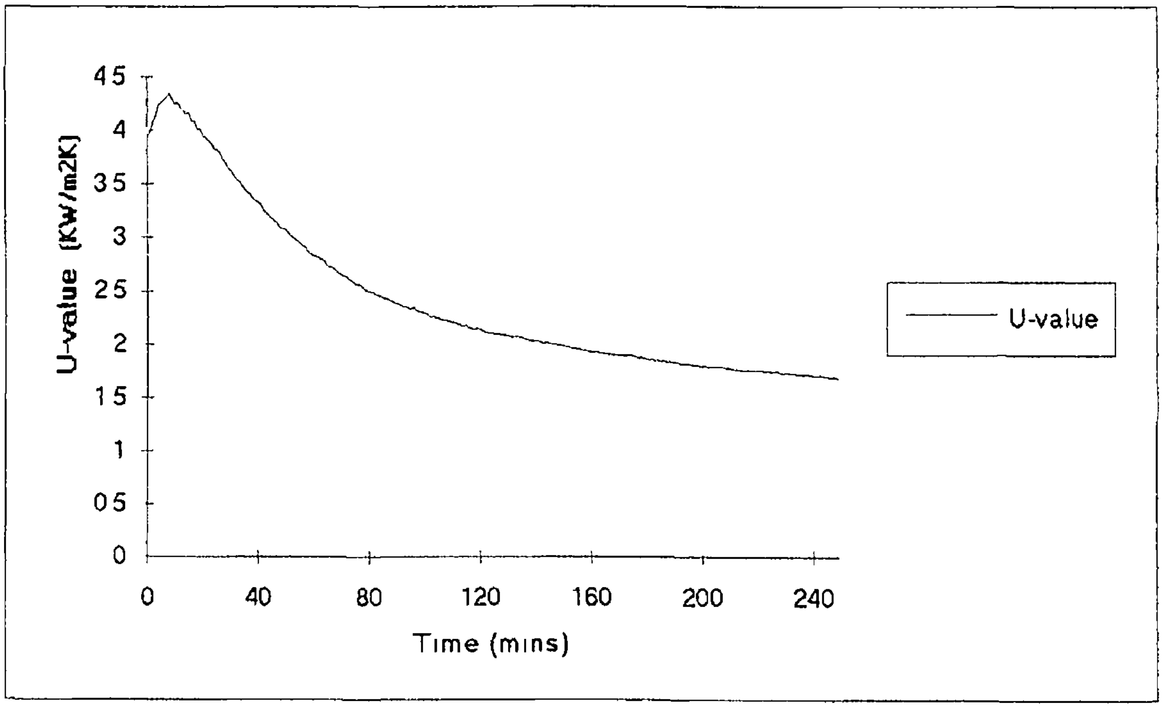


Fig 5 3b Graph demonstrating increase in U-value before linear decrease

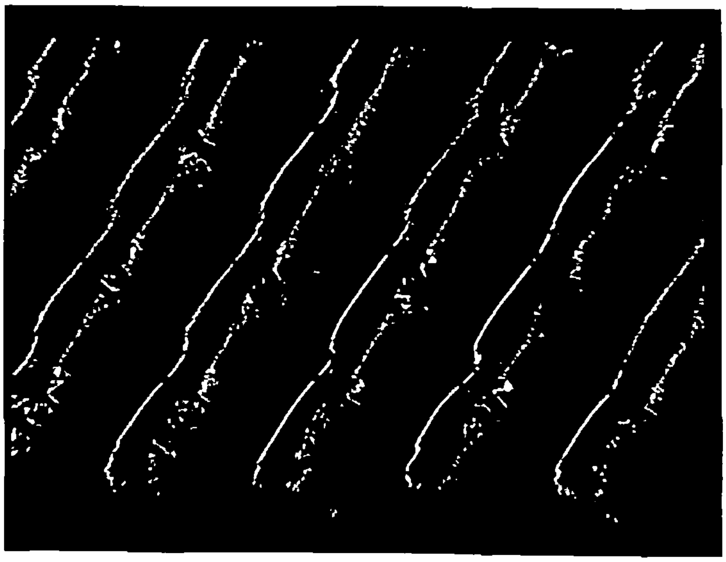


Photo A. Fouling at plate contact points

This rapid linear decrease lasted approximately 70 minutes during which time fouling progressed at a steady rate The graph then levelled off reflecting only a 6% reduction over the remaining 2 hours of the run During this stage the overall heat transfer coefficient was almost constant These phases of fouling correspond to phases (A) and (B) described by Fryer (1986)

5.4 The effect of deposition on fouling resistance

Figure 5 4 presents a plot of fouling resistance versus time, the measurement of which may be deduced from the overall heat transfer coefficient (Lund & Bixby, 1975) The overall heat transfer coefficient graph and fouling resistance graphs show inverse but corresponding behaviour The fouling resistance was found to increase to asymptotic level with time An induction period was noted which was small in relation to the overall experimental run, lasting only 4-5 minutes This was followed by a rapid linear increase lasting approximately 70 minutes after which asymptotic fouling occurs This decrease in deposition or falling rate continued for the remainder of the 4 hour run This observation was reported by numerous observers (Deplace & Leuliet, 1994, Bird & Fryer 1991) and is typical of whey fouling

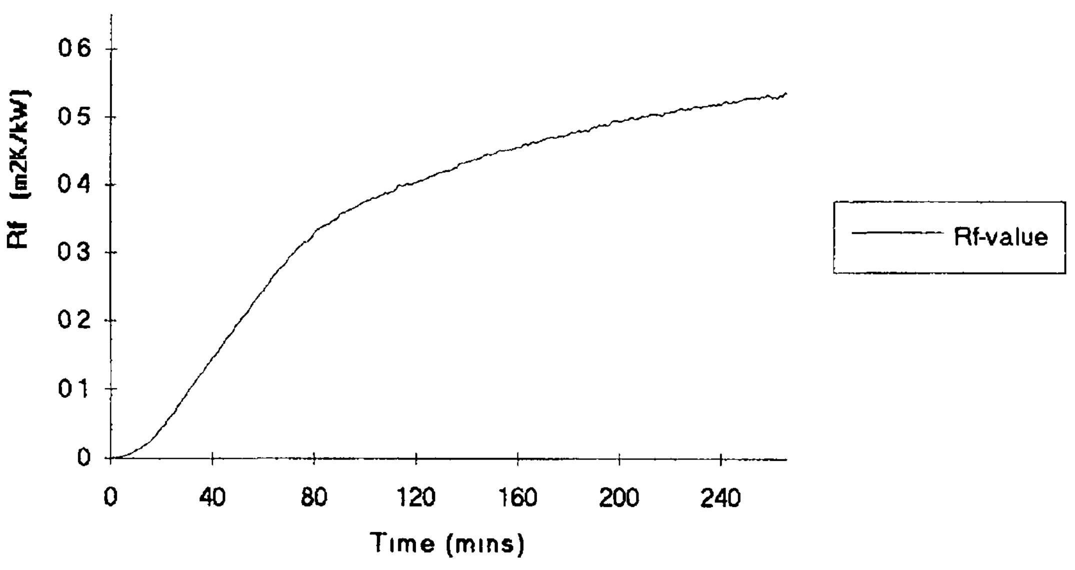


Fig 5 4 Fouling Resistance v's Time at 1% whey concentration and 10 l/min

The overall effect of fouling in each experiment was to increase the fouling resistance However the fouling resistance could be decreased by increasing the fluid flowrate This was attributed to turbulence induced by increasing shear stress (Belmar-Beiny & Fryer, 1992) Although the plate heat exchanger had a high number of contact points, high turbulence may hold the proteins in suspension reducing the laminar sub layer and decreasing deposit formation A decrease in fouling resistance was found in a number of runs during the induction period An explanation was offered by Crittenden and Alderman (1988) who found that the initial formation of deposits (Photo B) can lead to increased surface roughness which may increase local film heat transfer coefficients This can also lead to a reduction in cross sectional area which may result in an increase in velocity Whether either or both of these mechanisms can increase local heat transfer coefficients sufficiently to counteract the increase in thermal resistance due to fouling requires more detailed analysis

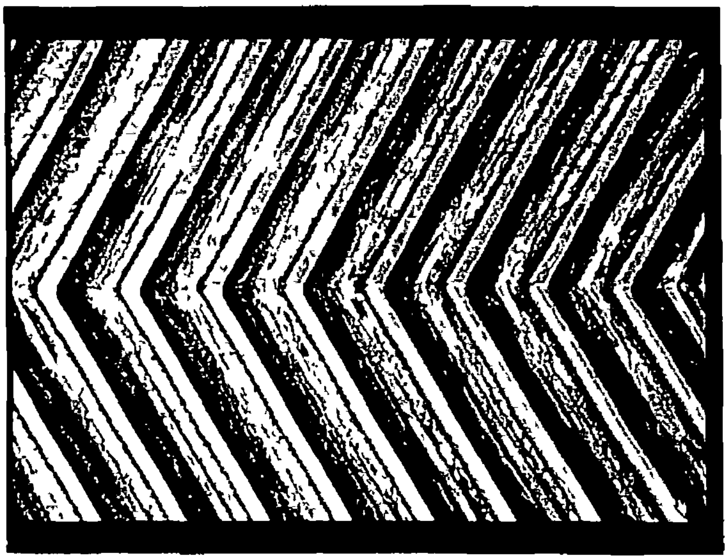


Photo B. Initial deposit formation on a heat exchanger plate

Lund and Bixby (1975) proposed that some benefit was to be gained by prefouling a plate heat exchanger with 'Type B' deposit before processing whey solutions With no prefouling over a 3 hour period the U-value decreased by 30% from clean Over the same period no decrease in U-value occurred for prefouled plates, but the initial U-value was approximately half that of the clean value. Although detailed experiments were not carried out in this area, poor cleaning results were compared with the above proposal. It was found that leaving 'Type B' deposit present rapidly increased fouling in disagreement with the above.

5.5 Effect of flowrate on fouling resistance

Figure 5.5 represents the effect of flowrate on fouling resistance for 1% whey protein solutions. Fouling resistances were calculated using the clean U-values evaluated during the preliminary tests and under identical flowrate combinations as those used to calculate the initial clean heat transfer coefficients (page 38). (See Appendix B.)

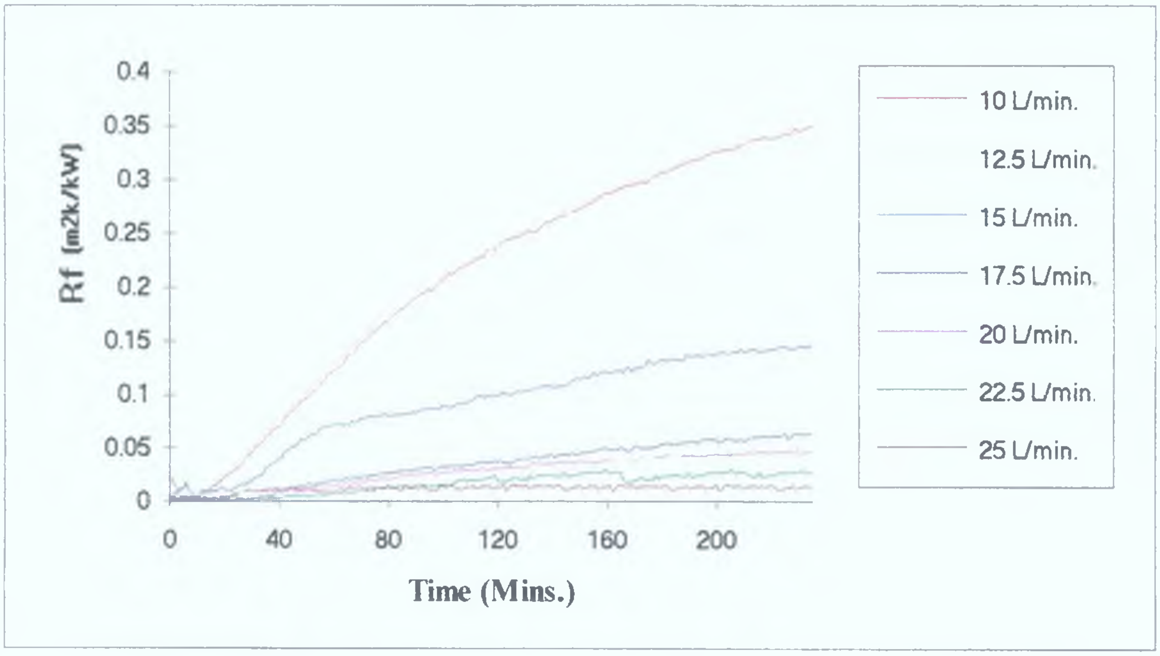


Fig 5.5 Graph of the effect of flowrate on fouling resistance

Flowrates ranged from 10 l/min to 25 l/min in steps of 2.5 l/min. At low flowrates (10-15 l/min) an asymptotic curve was observed which included a short induction period. However at flowrates above 17.5 l/min, an extended induction period occurs followed by a linear increase with no asymptote reached. The effect of flowrate on fouling resistance was to significantly affect the induction period, the slope of the linear period of the graphs and the asymptotic fouling resistance These areas will now be discussed in more detail

5 5 1 The effect of flowrate on the induction period

Before discussing the effect of the various parameters on the induction period it is worth defining the limits of this term Bird and Fryer (1991) carried out detailed analysis of the induction period on clean surfaces (Photo C) and found that deposits, even with natural water, formed immediately (within seconds) These deposits do not represent significant fouling in terms of fouling resistance and for the purpose of the following discussion the end of the induction period is defined as the point were the fouling resistance curve enters its linear phase The induction periods were evaluated by visually inspecting magnified sections of the graphs Accurate evaluation became more difficult at high flowrates

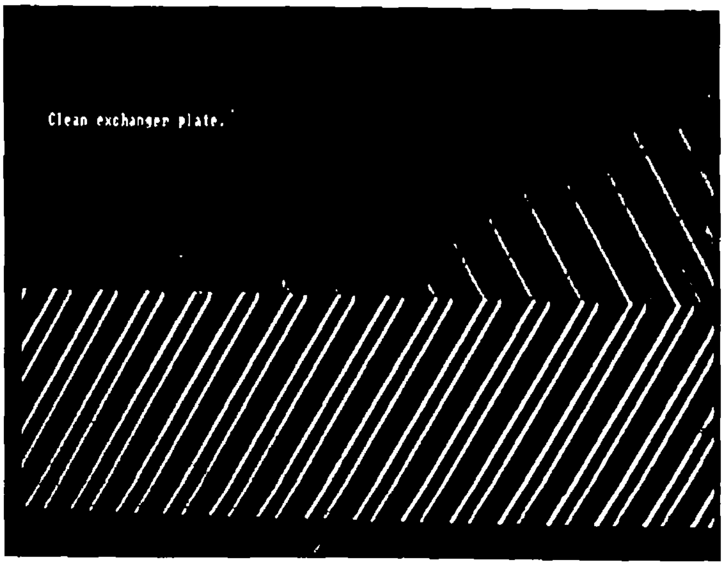


Photo C. Clean heat exchanger plate before processing

The induction period was found to vary significantly for different flowrates At low flowrates a short induction time ranging from 8-12 minutes was observed As stated previously it was noted that the Rf value during the induction period decreased before entering the linear phase of the fouling curve This effect was eliminated at higher flowrates and increased turbulence Whether or not the restriction of a flow channel by deposition of whey foulant causes an increase in thermal performance will depend on the deposit thermal conductivity and the effect on the channel area

Figure 5 6 demonstrates the effect of flowrate on the induction period for 1% whey protein solutions It should be noted that the fouling resistance graphs at the higher flowrates have such gradual slopes that it is difficult to determine exactly when the induction period starts For the present study the end of the induction period was taken as the point where the fouling resistance changed significantly A dramatic increase in the induction period occurred at higher flowrates with an increase from 10 - 20 l/min, effectively doubling the length of the induction period One solution to solving the problem of fouling would be to increase the induction period and prevent the fouling curve entering the rapid linear deposition stage The induction period was shown to increase with increasing velocity and was shown by Belmar-Bemy and Fryer (1992) to be strongly dependant on surface cleanliness Increased turbulence due to higher flowrates effectively cleans the exchanger plates by removing loose deposits and holding material in suspension, significantly extending the induction period

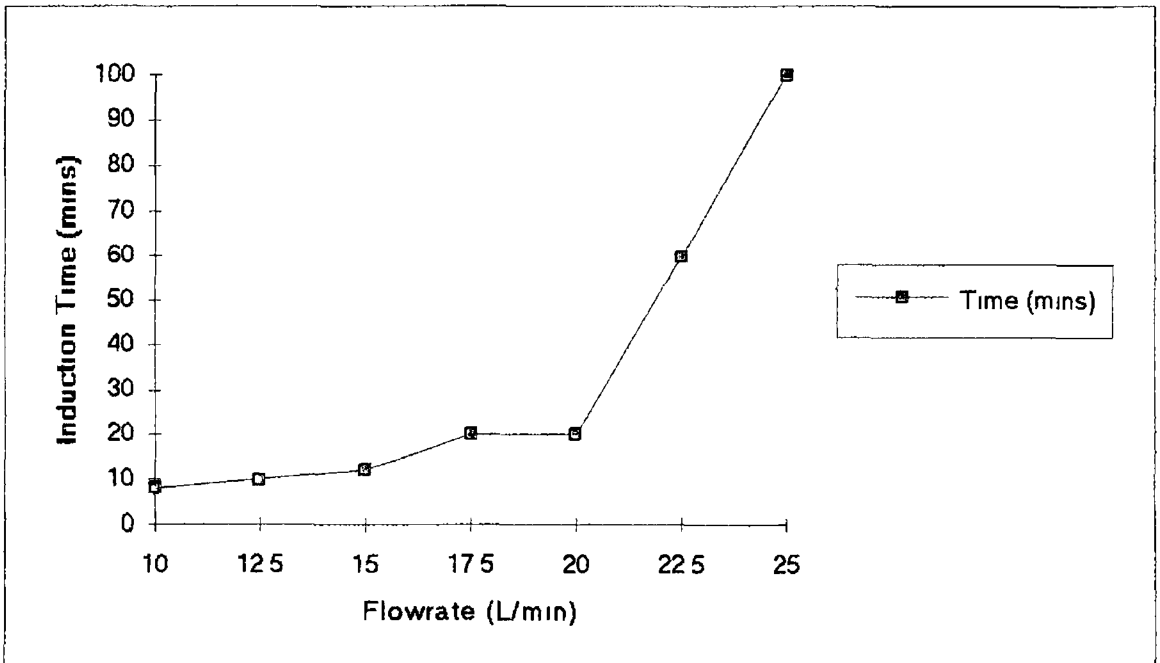


Fig 5.6 Graph of the effect of flowrate on the induction period

5.5.2 The effect of flowrate on fouling resistance

The maximum values of fouling resistance for each run, calculated by non-linear fit using Sigma Plot, are presented in Table A along with the corresponding flowrates, linear slopes, estimated induction periods and decrease in overall heat transfer coefficient. This table is based on information derived from results in Fig 5.5. From these observations it was noted that at lower flowrates the overall heat transfer coefficient decreases significantly due to increased fouling. Low flowrates were also responsible for short induction periods. Significant changes occurred between 15-17 L/min with reduced slopes of the linear portion of the fouling resistance graphs and increased induction periods. Higher turbulence held the solids in suspension reducing the laminar sub-layer and decreasing deposit formation (Bird & Fryer , 1991).

Table A.

Flowrate	**Rf(max).** (m^2K/kW)	**Induction time. (min)**	**Linear slope.** (m^2Kmin/kW)	**Decrease in U** (kW/m^2K)
10 l/min	0.35	8 mins	0.00246	2.78
12.5 l/min	0.28	10 mins	0.001764	2.75
15 l/min	0.15	12 mins	0.001756	2.27
17.5 l/min	0.06	20 mins	0.000313	1.25
20 l/min	0.046	20 mins	0.000254	0.72
22.5 l/min	0.04	60 mins	0.000216	0.47
25 l/min	0.014	100 mins	0.0000758	0.5

5.6 Kern-Seaton modelling.

The Kern-Seaton model (equation 3.7) was applied to the curves in figure 5.5 using Sigma Plot and the results are presented below. Considerable scatter was noted in both the deposition and removal rate terms (calculated by non-linear fit to the data using 180 points to establish the fit at each flowrate).

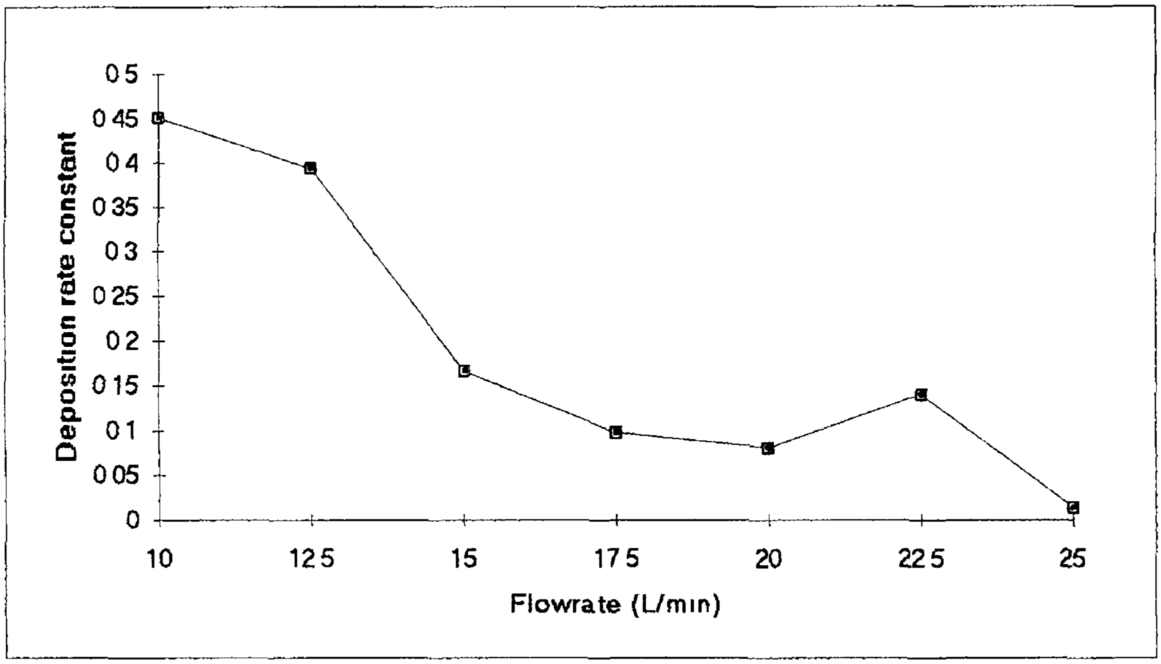


Fig 5.7 Graph of the deposition rate constant ($\frac{\phi_d}{\beta k}$)at various flowrates

The ratio $\frac{\phi_d}{\beta k}$ (Fig 5 7) was found to decrease with increasing flowrate as expected from Table A since R_f^{max} is equivalent to $\frac{\phi_d}{\beta k}$. A steady decrease in the rate constant was noted over the range of flowrates invertigated indicating a sensitivity to fluid velocity The maximum rate of deposition was found to occur at low flowrates with the corresponding fouling curves assuming an asymptotic form The Kern-Seaton model predicts that the the deposition rate constant should decrease with increasing flowrate and this is clearly demonstrated in Fig 5 7 Little change was found in the removal rate constant (calculated by non-linear fit to the data using 180 points to establish the fit at each flowrate) over the range of flowrates (Fig 5 8) At high flowrates the removal rate constant was found to be almost negligible which may account for the straight lines on the fouling curves At low flowrates the removal rates increased slightly accounting for the asymptotic form of fouling curve The Kern-Seaton model would suggest that the removal rate constant should increase with increasing flowrate due to its shear stress dependance This trend was identified at low flowrates only, with inconclusive trends noted at high flowrates It should be noted from figure 5 5 that only the lower flowrates exhibited asymptotic fouling curves and the application of the Kern-Seaton model to the remaining curves may account for the scatter observed in the removal rate constant graph From the data presented, at high flowrates the fouling time curve assumed an almost straight line function demonstrating that either the removal rate is negligible or the deposition and removal rates are constant with the deposition rate being predominant At low flowrates an asymptotic form of fouling time curve resulted suggesting that the removal rate increased with fouling layer thickness In this case the deposition and removal rates ultimately become equal An extension of the observation period at high flowrates until asymptotic fouling occured would generate more accurate results

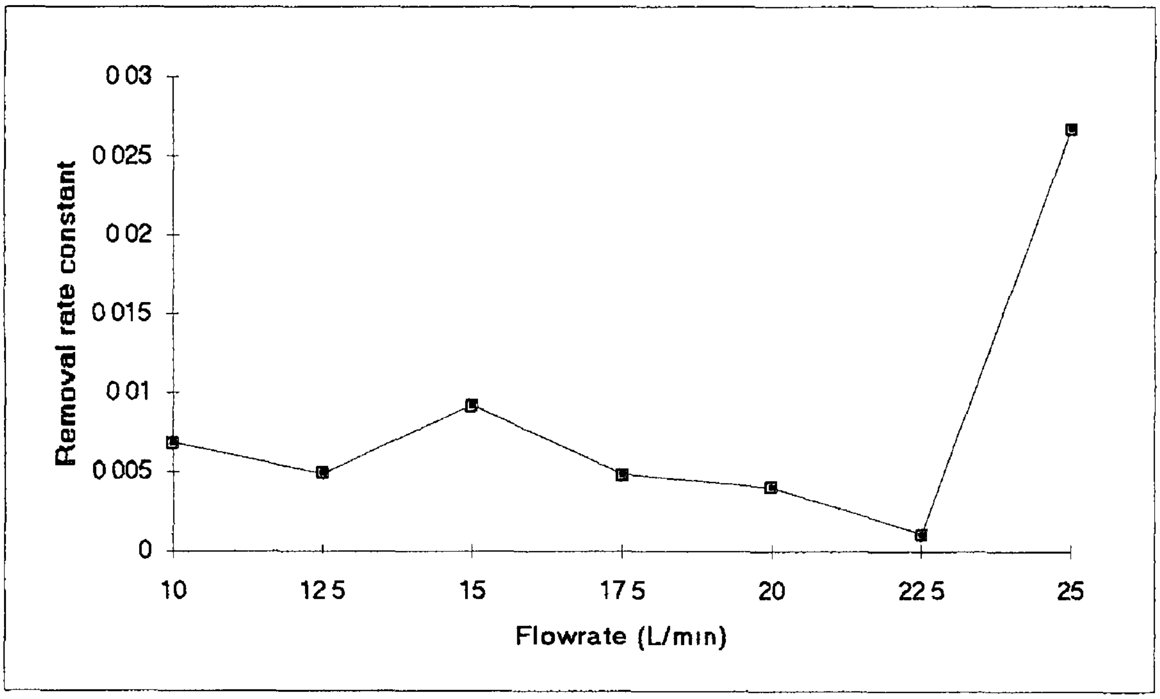


Fig 5.8 Graph of the removal rate constant (β)at various flowrates

During the induction period only negligible fouling was observed, as stated above The rate controlling step appears to change during each experiment and from run to run During fouling of whey products, reactions take place within the process fluid and also at the exchanger wall During the induction phase the process appears to be controlled by a reaction at the surface of the heat exchanger plates and the protein in the denatured fluid The bulk fluid temperature was above 80°C at this point and therefore contains plenty of depositable material However only a thin layer was found to be deposited on the heat transfer surface As the process continues it becomes easier for more material to deposit as the nature of the interface changes from metal to protein It is clear from our studies that at high flowrates this interface conditioning is much slower and not amenable to rapid deposition This is irrespective of the fact that the bulk fluid is carrying highly depositable material due to its temperature The rate controlling step at this point appears to be a surface reaction dependent on temperature and flowrate More experimental work is necessary in this area and an investigation of surface adsorption may be of interest

At low flowrates the linear velocity is a factor in deposition due to the fact that the thickness of the laminar sub layer adjacent to the heating surface is increased Therefore the volume of material subject to higher temperatures and the volume which remains near the heating surface are also increased Further investigation is necessary to determine the sensitivity of mass transportation on velocity and the possible sensitivity of the attachment/formation process to other variables such as temperature

5 7 The effect of concentration on fouling resistance

Figure 5 9 demonstrates the effect of concentration on fouling resistance at 10 and 20 l/min At low and high flowrates the effect of increasing concentration is to increase fouling resistance At higher flowrates the fouling resistance is also increased with increased concentration but the effect is less dramatic Increasing the concentration at low flowrates also reduced the length of the induction period By increasing the concentration from 1 to 3% at 10 l/min resulted in a 50% reduction in the induction period At higher flowrates an extended induction period was noted at all concentrations followed by a steady state period with little change in fouling resistance

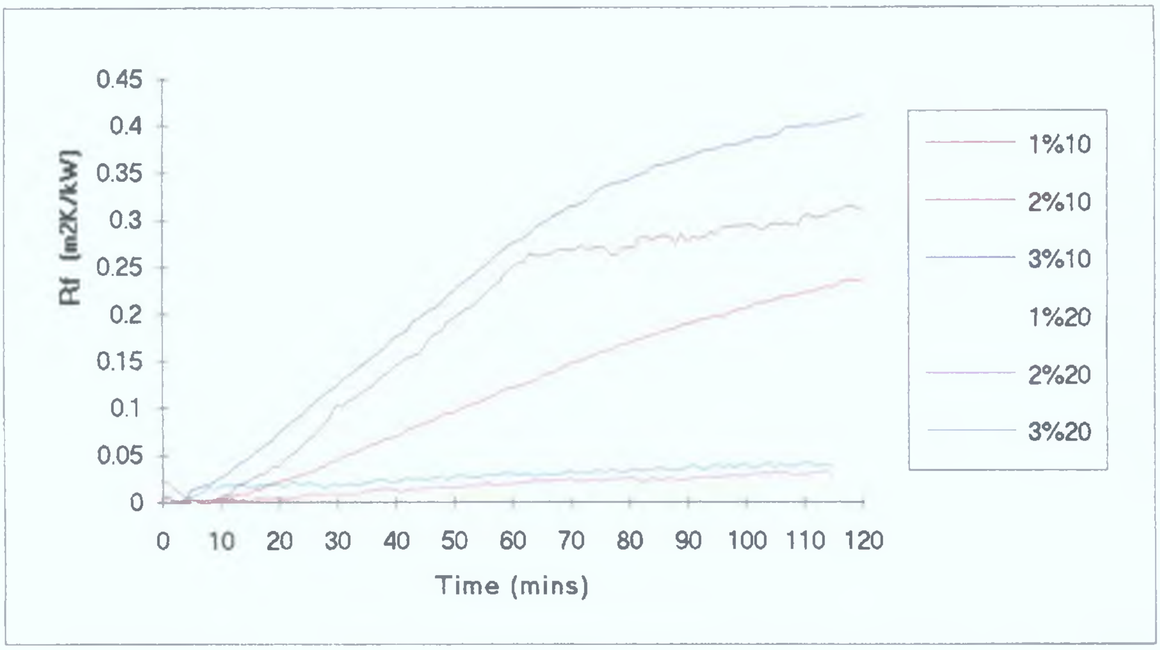


Fig 5.9 Graph of Fouling Resistance v's Time at various concentrations

Increased concentration was found to decrease the induction period particularly at low flowrates. At high concentrations and high flowrates a decrease was also found. However the effect on heat transfer was not as significant.

5.8 Effect of product temperature on fouling resistance

Figure 5.10 demonstrates the effect of temperature on a 1% whey solution at a flowrate of 10 l/min. An increase in temperature resulted in a corresponding increase in fouling resistance. The effect of temperature on the induction period was considerable. At 50°C the induction period lasted approximately 36 mins. However at 80° C using the same concentration and flowrate the induction period was reduced to 8 mins.

The shortest induction period was found to occur around the denaturation temperature of the whey protein in agreement with Belmar-Beiny and Fryer (1992). Decreasing the process temperature was found to increase the induction period due to lack of aggregates before reaching the denaturation temperature.

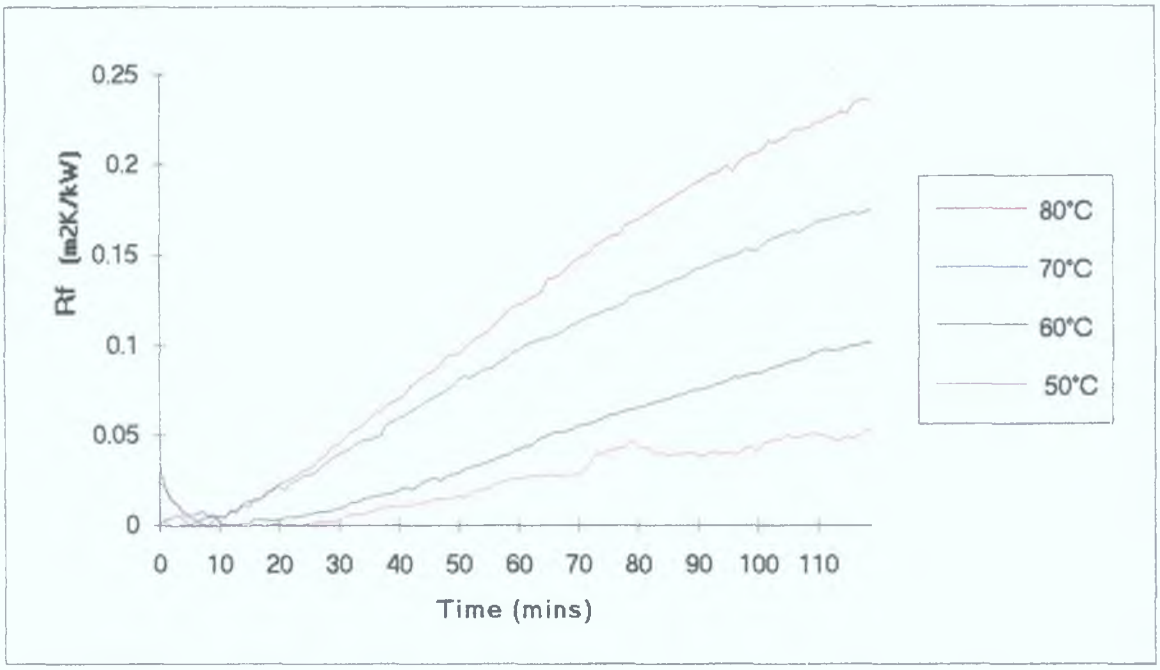


Fig 5.10 Graph of the effect of temperature on fouling resistance

5.9 Fouling deposits on heat exchanger plates

On completion of every run the plate heat exchanger was dismantled and each of the plates examined and individually weighed. Figure 5.11 presents the deposit per plate for a 1% whey protein solution at 92°C and a flowrate of 10 l/min. It should be noted that plate number 1 is not in contact with any whey stream and therefore is not affected by fouling. The remaining plates numbered 2 to 9 show considerable deposition. There was a marked decrease in deposit on plates 8 and 9. Both these plates are adjacent to the whey inlet and outlet ports (Schematic A, page 32). The average deposition per plate of the remaining plates is 25.28 grams per plate. However the average deposition for plates 8 and 9 is only 16.37 grams per plate, a reduction of 35%. During the separation of individual plates for examination it was found that fouled plates were stuck together. It is therefore more relevant to discuss the mass of deposit per channel rather than the mass per plate.

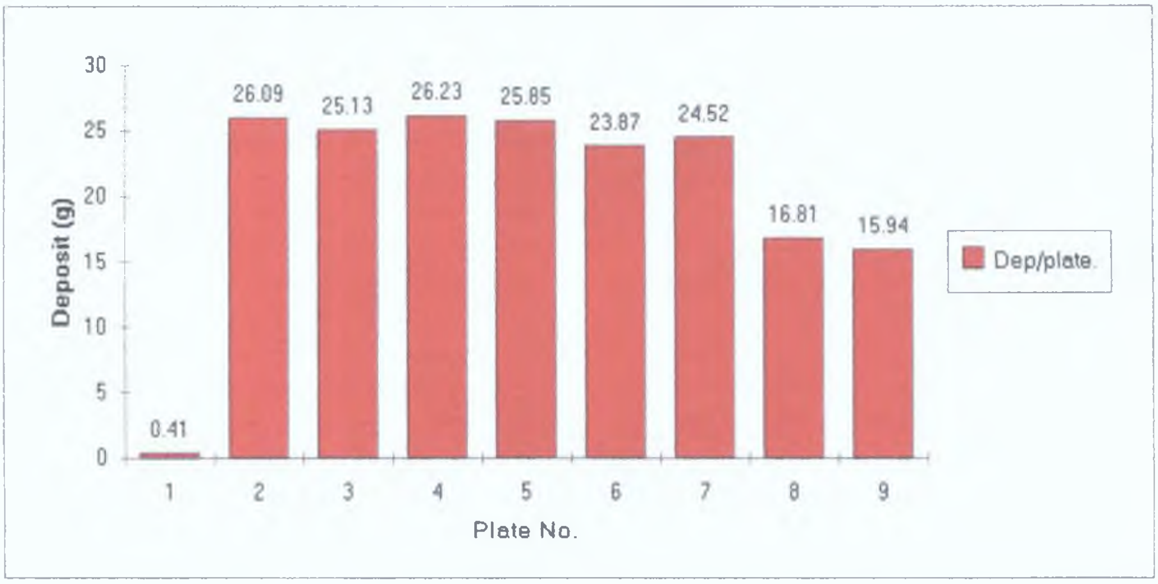


Fig 5.11 Deposition per plate at 1% whey concentration and 10 l/min

Figure 5.12 plots the deposition per channel for a 1% whey solution. Again a reduction in deposit is evident in channel number 4 which is bounded on each side by plates 8 and 9. This effect was present in all experimental runs with channel 4 consistently lower in deposition than any other channel. For this particular experiment there was almost 20 grams less deposit in channel 4 compared to any of the remaining 3 channels.

Fig 5.12. Graph of deposit per channel at 1% whey concentration and 10 l/min

Maximum deposition was found to take place at the base of each channel and also around the contact points within the heat exchanger Photo D demonstrated this deposition in channel four of the heat exchanger Before shooting this photograph the two adjacent plates were separated and placed in a drying oven over night

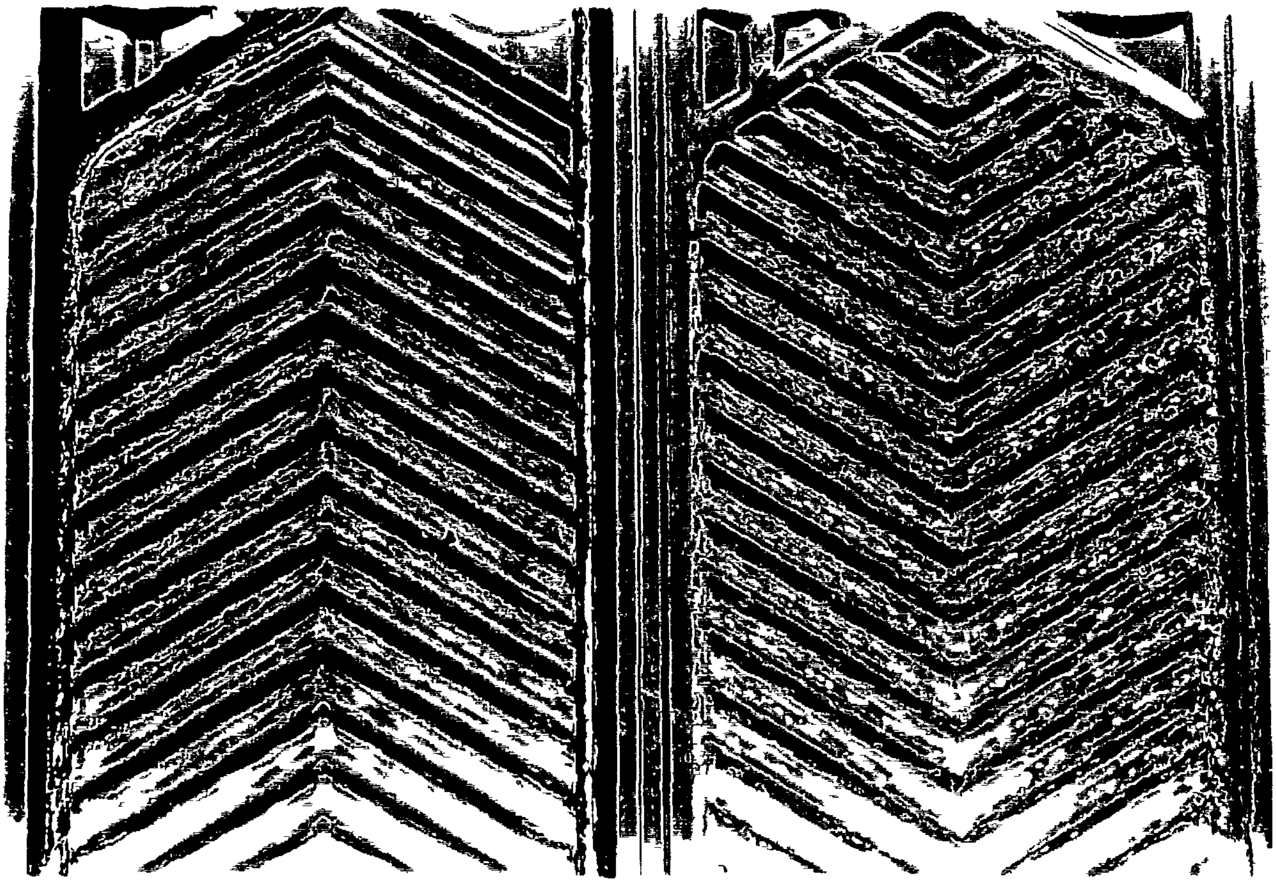


Photo D. Dried deposits on adjacent heat exchanger plates

5.10 Deposit formation

In agreement with Delplace and Leuliet (1994) it was found that comparison of wet and dry weights of fouling deposit demonstrated that approximately 70% water was present and that the weight of deposit on each plate of the same channel was not significantly different Deposits were found to form at the bottom of the channels and at the contact points corresponding to the presence of fouling in low velocity regions Initial deposition was found to occur around the contact points of alternate plates which was often predicted in literature (Belmar-Beiny *et al*, 1993) This may explain the increase in U-value during the induction period previously mentioned, with deposition inducing increased turbulence in channels as suggested by Bird and Fryer (1991)

Plates containing deposits which were most difficult to remove during cleaning operated at temperatures of 85-90°C These deposits consisted of both Type A and Type B as defined by Burton (1968) Type A protein deposit resulted from denaturation of proteins and was easily removed during the cleaning cycle Type B was composed mainly of minerals and formed a thin dense layer between Type A and the wall of the heat exchanger (Lalande & Corrieu, 1985) The product temperature within the heat exchanger is at its highest point at the heating surface which may explain the build up of Type B deposit which Lalande found to form at a higher temperature than Type A This would result in a higher level of supersaturation of mineral salt, a major constituent of Type B deposits The formation of Type A and B deposits is highly temperature dependent (Tissier & Lalande, 1986, Yoon, 1993) and worthy of additional detailed investigation

5.11 The effect of flowrate on deposition

Figure 5 13 demonstrates the effect of increasing flowrate on the total deposition within the heat exchanger for 1% whey solutions The total deposition, presented in grams, is the sum of that found in the four channels which make up the complete heat exchanger. At low flowrates (10 - 12.5 l/min) the deposition was found to be almost constant. This was followed by a rapid decrease in deposition as the flowrate increased with a minimum deposition at the highest flowrate of 25 L/min. There was an overall decrease in total deposit of 170 grams from the lowest to the highest flowrate.

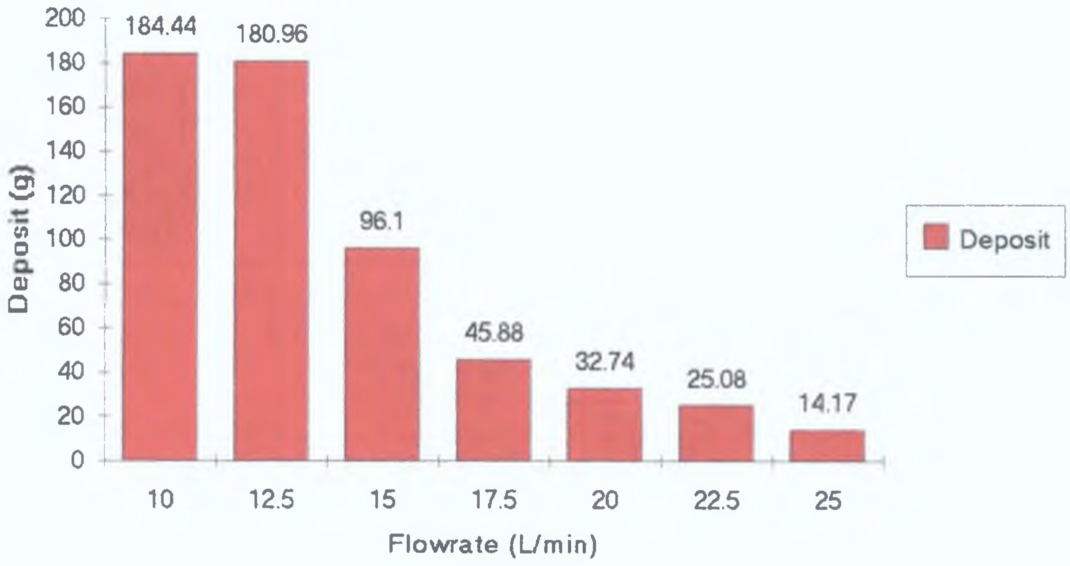


Fig 5.13 Graph of total exchanger deposition at various flowrates

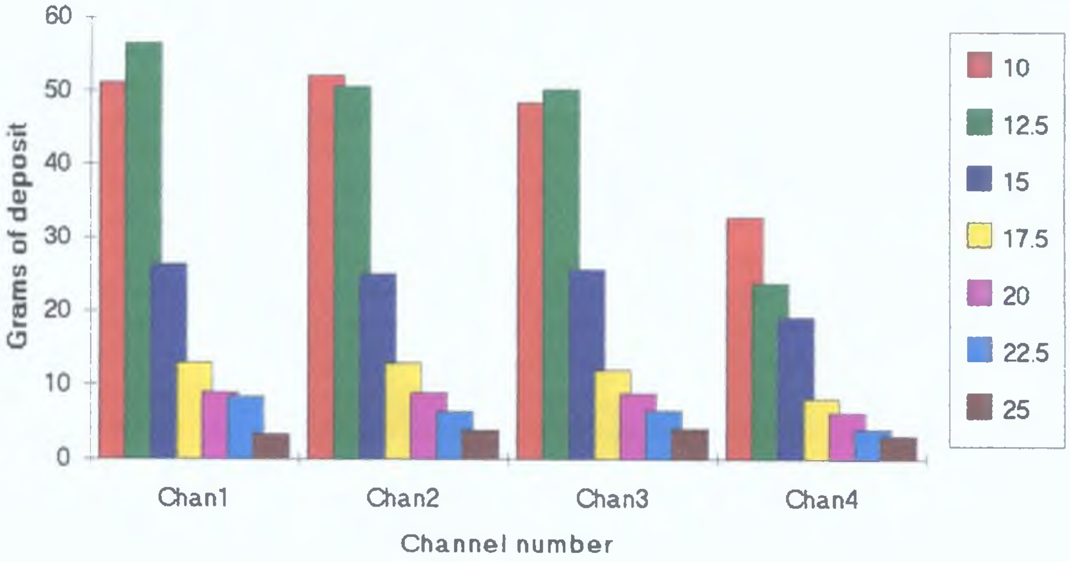


Fig 5.14 Graph of deposition per channel at various flowrates.

Figure 5 14 represents the total deposition per channel at different flowrates The trends per channel are almost identical irrespective of flowrate The maximum deposition occurs at lower flowrates with a rapid decrease in deposit after a flowrate of 12 5 l/min, to a minimum deposit ranging from 3 - 4 grams per channel Channels one, two and three all contain approximately the same amount of deposit at each flowrate with channel four consistently lower

5.12 The effect of temperature on deposition

In an attempt to quantify the effect of temperature on deposition and to take a closer look at the induction period, a series of experiments were run at high concentration during which the heat exchanger was dismantled every 15 minutes and the plates examined and weighed The exchanger was reassembled and the experiments continued for up to one hour Table B presents the deposit per plate within the exchanger measured every 15 minutes for a 3% whey protein solution circulated at 40°C

Table B

Plate No.	15 mins.	30 mins.	45 mins	60 mins.
1	2 18g	2 51g	2 76g	2 89g
2	4 01	4 42	4 39	4 7
3	3 89	4 42	4 94	5 03
4	3 59	4 33	3 77	4 3
5	3 67	4 72	5 33	5 75
6	3 4	4 07	3 77	4 12
7	3 15	3 99	3 66	4 26
8	6 84	3 09	2 99	3 24
9	1 79	1 63	1 54	1 49
Total weight	**30 34**	**30 67**	**30 39**	**32.89**

The total deposition was calculated from the above table and the results are presented in figure 5 15 The graph shows a slight increase in deposition after 45 minutes with considerable deposition within the first 15 minutes Approximately 30 grams of deposit occurred within the first 15 mins Only 3 additional grams were deposited over the next 45 mins

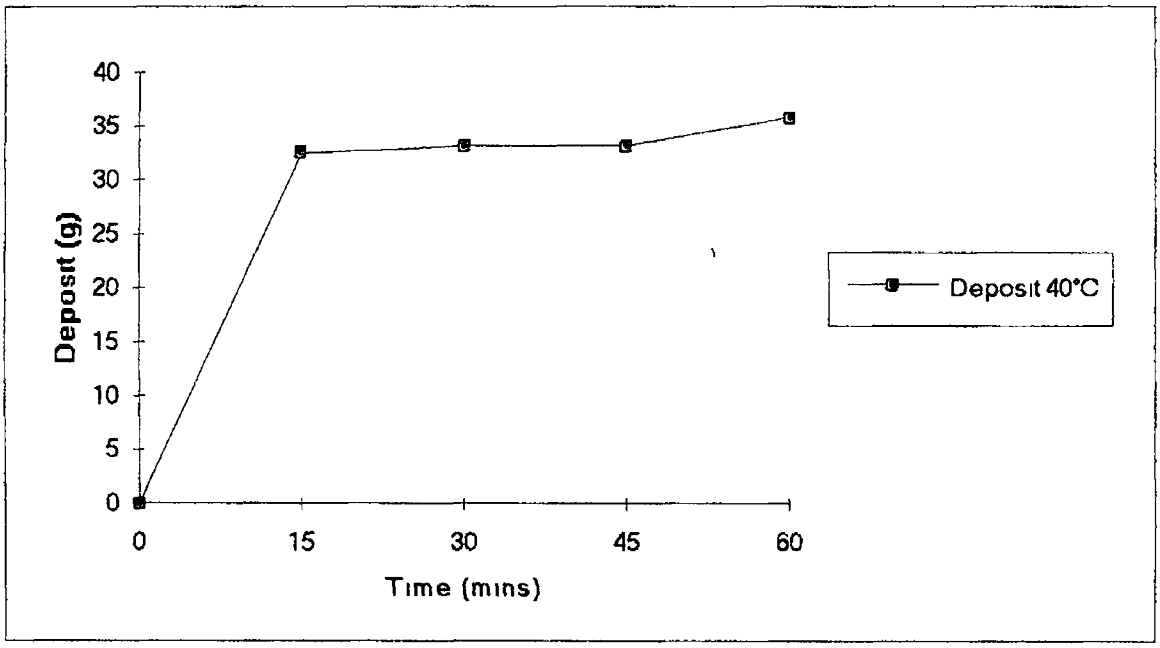


Fig 5.15. Graph of total deposition v's time at 40°C

These experiments were repeated at various temperatures up to 90°C and the results are presented in figure 5 16 Very little deposition occurs up to a temperature of 70°C At this point the graph shows a sudden and sustained increase in deposition From 70 - 80°C there is a three fold increase in deposit, however from 70 - 90°C this increases to ten fold This clearly demonstrates the effect of temperature on whey protein deposition and the key role played by denaturation as described by other authors (Lund & Bixby, 1975, Belmar-Beiny & Fryer, 1992)

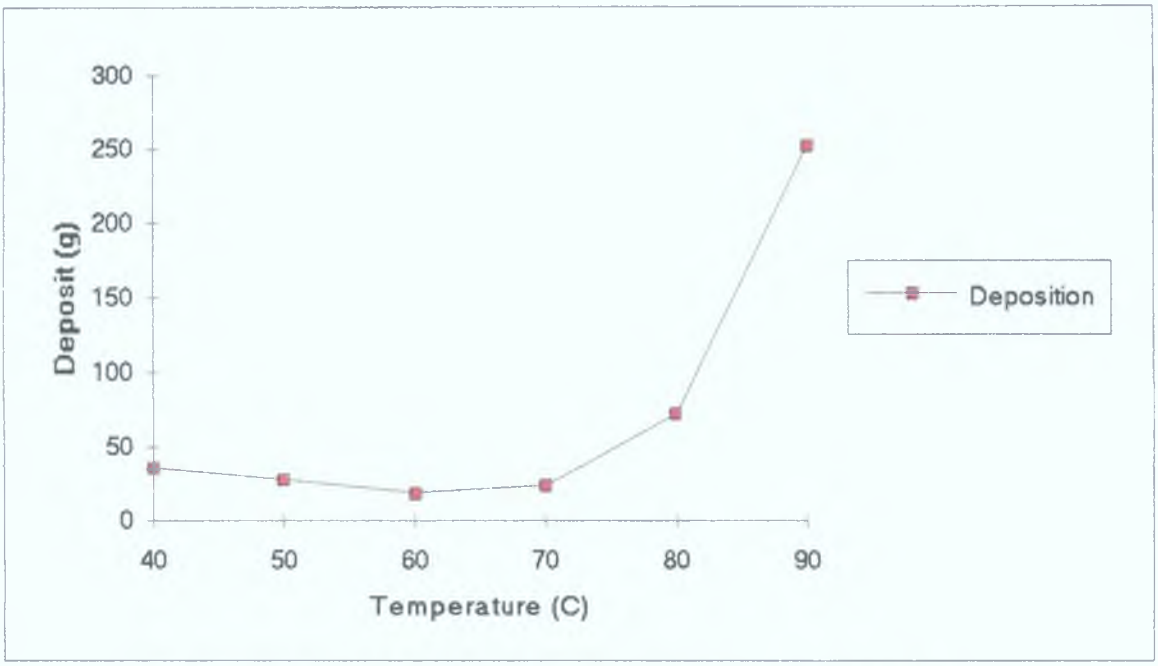


Fig 5.16. Graph of total deposition at various temperatures.

Deplace and Leuliet (1994) argued that little deposition occurred on plates before they reached a temperature of 70°C when experimenting with whey solutions. To explain why a thin layer of deposit was observed in regions below 70°C he stated that although the bulk fluid temperature was below 70°C the actual plate wall temperature may be sufficiently high to denature the proteins in solution. During our experiments even at bulk fluid temperatures of 80°C uneven distribution of deposits were found along the plates. In channels containing whey solutions deposition was found to increase along the plates from product inlet to outlet. Within a region of 10-15 mm around the inlet port of each of these channels (Photo F), very little deposition was found irrespective of temperature or concentration (Photo E & Photo F).The maximum deposition was localised at the outlet ports of these channels. It appears that turbulence due to entrance effects at the inlet ports is sufficient to reduce deposition in these regions and also this may be assisted by the fact that the heating fluid is at its lowest temperature at this point. Considering the fact that the exchanger is run in a counter current mode the increase in deposition at the outlets may be explained by the possible existence of a hot-spot in this region. The heating fluid is at its highest temperature at this point as its enters the heat exchanger.

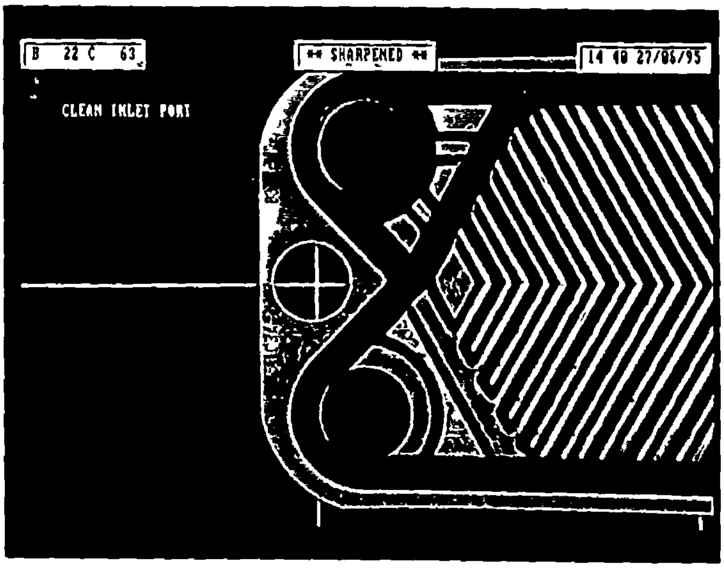


Photo E Inlet port of a clean plate from the heat exchanger

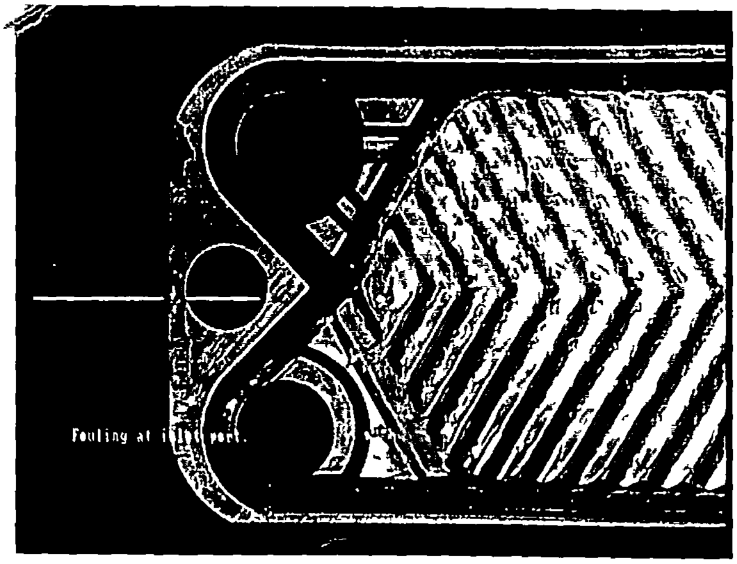


Photo F Fouling at the inlet port

The turbulent bursts concept of Cleaver and Yates (1973) states that the time required to form a bond at the heat transfer surface will decrease with increasing temperature Also from the above literature it was found that surface adsorption is significantly enhanced at higher temperature These results may be of significance if the above hot spot hypothesis is proven true Channel 4 on the rig was found to have consistently less deposit irrespective of run conditions On examination of this channel it was found that plate number 9 was a backing or end plate and is not heated by a hot fluid stream This resulted in a lower overall channel temperature which resulted in reduced channel deposits Detailed temperature mapping of the various channels is necessary to support the above hypothesis which was beyond the scope of this thesis

5 13 Effect of cleaning on the Induction Period

The induction period was found to increase with increasing velocity The ability to extend the induction period using high flowrates is of considerable interest and has been studied by several authors (Belmar-Beiny & Fryer, 1992, Baier, 1981, Lalande & Corrieu, 1985) One area of interest is that of cleaning heat exchangers using high velocity flush out in which the flowrate is increased rapidly during a production run to remove all loose deposits from the heat exchanger wall

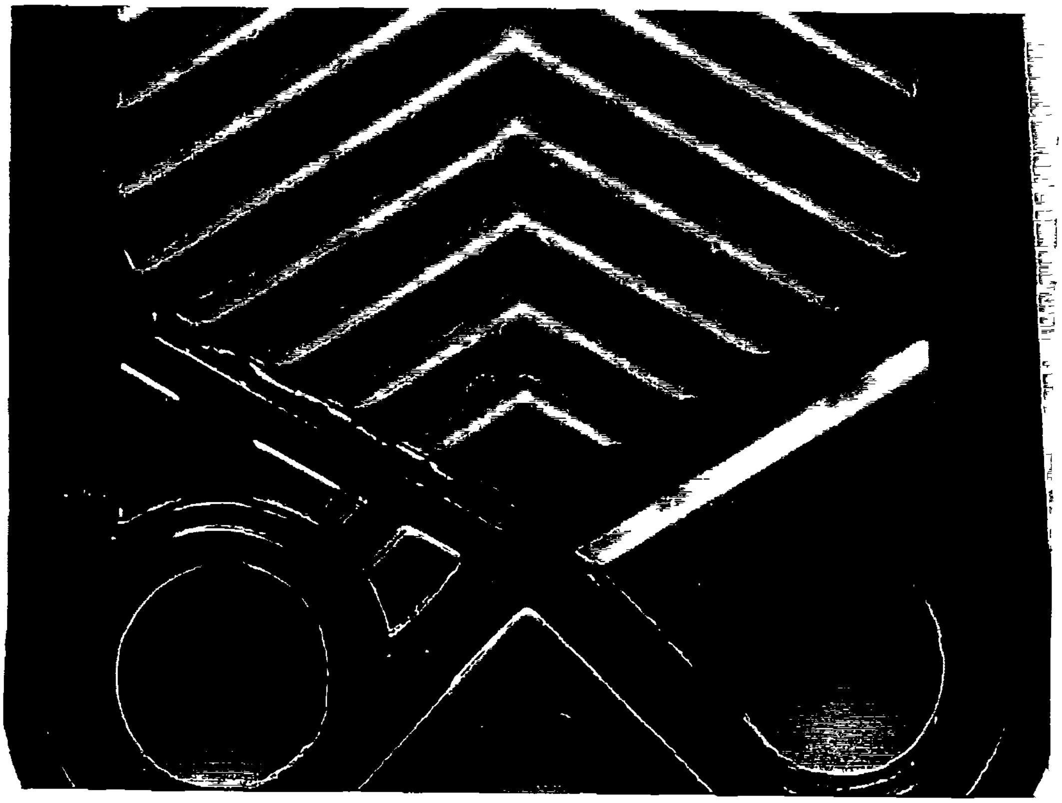


Photo G Deposits remaining after poor cleaning

It was found that when our rig was used in this way and returned to the original velocity, rapid build up of deposit occurred resulting in a fouling level higher than originally experienced had the process been allowed to continue undisturbed Removal of loose deposits reconditioned the surface leaving it rougher, resulting in increased fouling This points to the fact that surface cleanliness is of particular importance throughout the fouling process (Lund & Sandu, 1981) Chemical cleaning was found to be necessary to remove all deposits Deposits remaining following flushing alone enhanced the rate of fouling The induction period was found to be highly dependent on surface cleanliness during initial trials when plates were poorly cleaned (Photo G)

5.14 The effect of surface cleanliness on fouling

It was suggested in literature that a high surface finish on the plates is likely to reduce the tendency of fouling but the evidence is somewhat conflicting (Lund & Sandu, 1981) During the experiments surface cleanliness was found to have a significant effect on fouling If the plate was improperly cleaned, the initial layer which remained following cleaning acted as a surface on which subsequent layers of material particularly in low shear areas and around flow obstructions could easily deposit Lund and Sandu (1981) suggested that this rough surface was likely to increase fouling by providing a surface to which material can easily adsorb Lund also suggested that the induction period corresponds to the time taken to fill in all the surface roughness elements with deposits During the experiments with clean and dirty plates it was difficult to correlate the length of the induction period with any process variable except that it appeared to increase with increasing velocity Its length was strongly dependent on how clean the plates were Dirty plates were found to have a much shorter induction period During the cleaning process the adherence of Type A deposits to the heat transfer surface was not very strong and could be easily removed by increasing the flow velocity

Appendix A. Bibliograghy

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Appendix B. Raw Data

Raw Data From the Anville Series 410 Data Acquisition System

Heat Exchanger Date & Time	Temp Cold In (°C)	Temp Cold Out (°C)	Temp Hot In (°C)	Temp Hot Out (°C)	Pressure Cold In (Bar)	Pressure Cold Out (Bar)	Pressure Hot In (Bar)	Pressure Hot Out (Bar)
25/05/95 10:01	84.14	90.88	94.42	88.25	0.199	0.0137	0.0675	0.0258
25/05/95 10:02	84.16	91.16	94.78	88.4	0.196	0.012	0.068	0.024
25/05/95 10:03	84.25	91.8	95.48	88.85	0.1965	0.0162	0.067	0.024
25/05/95 10:04	84.4	92.29	95.99	89.25	0.2013	0.0182	0.0675	0.0235
25/05/95 10:05	84.55	92.5	96.05	89.43	0.1953	0.0178	0.067	0.024
25/05/95 10:06	84.66	92.51	95.95	89.51	0.1973	0.019	0.065	0.0235
25/05/95 10:07	84.73	92.43	95.75	89.51	0.199	0.0175	0.0653	0.0237
25/05/95 10:08	84.76	92.32	95.53	89.46	0.1933	0.0175	0.0637	0.0243
25/05/95 10:09	84.77	92.18	95.25	89.4	0.1935	0.018	0.0658	0.0243
25/05/95 10:10	84.77	91.94	94.97	89.28	0.1938	0.0182	0.0648	0.0237
25/05/95 10:11	84.73	91.69	94.67	89.14	0.189	0.0127	0.0645	0.0245
25/05/95 10:12	84.67	91.45	94.35	88.95	0.189	0.014	0.064	0.025
25/05/95 10:13	84.57	91.19	94.07	88.79	0.1915	0.0137	0.0658	0.0233
25/05/95 10:14	84.45	91.1	94	88.72	0.1947	0.0143	0.0675	0.024
25/05/95 10:15	84.34	90.95	93.86	88.61	0.1863	0.012	0.063	0.0235
25/05/95 10:16	84.27	90.89	93.8	88.52	0.189	0.0125	0.0677	0.023
25/05/95 10:17	84.19	90.72	93.66	88.45	0.19	0.0118	0.0648	0.0233
25/05/95 10:18	84.12	90.61	93.52	88.37	0.1875	0.0113	0.0645	0.0235
25/05/95 10:19	84.01	90.66	93.73	88.4	0.1912	0.012	0.0632	0.0227
25/05/95 10:20	83.94	90.81	93.98	88.48	0.1863	0.0132	0.0663	0.024
25/05/95 10:21	83.89	90.92	94.2	88.62	0.1895	0.0123	0.0653	0.0235
25/05/95 10:22	83.9	90.95	94.27	88.66	0.1883	0.0115	0.0645	0.0237
25/05/95 10:23	83.87	91.01	94.38	88.74	0.19	0.0118	0.0645	0.0233
25/05/95 10:24	83.87	91.02	94.41	88.79	0.186	0.0108	0.064	0.0237
25/05/95 10:25	83.87	90.99	94.42	88.79	0.1873	0.012	0.064	0.0227
25/05/95 10:26	83.85	90.99	94.43	88.83	0.1883	0.0123	0.0675	0.023
25/05/95 10:27	83.83	90.94	94.4	88.82	0.1935	0.012	0.064	0.024
25/05/95 10:28	83.79	90.95	94.51	88.85	0.1887	0.0123	0.065	0.023
25/05/95 10:29	83.77	91.08	94.77	88.95	0.1898	0.0123	0.064	0.0243
25/05/95 10:30	83.78	91.17	94.98	89.07	0.1885	0.0118	0.0625	0.0245
25/05/95 10:31	83.8	91.3	95.16	89.23	0.1885	0.0123	0.0645	0.0223
25/05/95 10:32	83.85	91.3	95.2	89.29	0.189	0.0127	0.0645	0.023
25/05/95 10:33	83.9	91.28	95.2	89.34	0.1928	0.0118	0.0648	0.0235
25/05/95 10:34	83.92	91.16	95.01	89.3	0.1918	0.0115	0.0635	0.0237
25/05/95 10:35	83.92	91.01	94.84	89.21	0.1925	0.012	0.0658	0.0233
25/05/95 10:36	83.91	90.89	94.69	89.18	0.189	0.0123	0.063	0.0237
25/05/95 10:37	83.88	90.95	94.89	89.23	0.1943	0.012	0.0635	0.0245
25/05/95 10:38	83.85	91.05	95.06	89.32	0.1912	0.012	0.0625	0.024
25/05/95 10:39	83.84	91.09	95.2	89.4	0.1908	0.0127	0.069	0.0235
25/05/95 10:40	83.85	91.16	95.33	89.49	0.1947	0.0123	0.0645	0.0237
25/05/95 10:41	83.86	91.19	95.39	89.54	0.1947	0.0123	0.0663	0.0245
25/05/95 10:42	83.91	91.15	95.32	89.57	0.1957	0.0125	0.0648	0.024
25/05/95 10:43	83.91	91.09	95.33	89.58	0.1973	0.013	0.065	0.0235
25/05/95 10:44	83.92	91.14	95.46	89.64	0.1925	0.0125	0.0675	0.0245
25/05/95 10:45	83.92	91.17	95.51	89.74	0.1918	0.0125	0.064	0.0243
25/05/95 10:46	83.94	91.16	95.52	89.78	0.195	0.014	0.066	0.024
25/05/95 10:47	83.94	91.08	95.4	89.76	0.1928	0.0137	0.062	0.024
25/05/95 10:48	83.95	91.07	95.43	89.78	0.197	0.0145	0.0635	0.024
25/05/95 10:49	83.91	91.07	95.55	89.82	0.1953	0.0118	0.0655	0.0247

25/05/95 10 50	83 86	91 19	95 8	89 93	0 1957	0 0125	0 0645	0 025
25/05/95 10 51	83 84	91 39	96 15	90 1	0 1978	0 0135	0 0625	0 0237
25/05/95 10 52	83 86	91 51	96 36	90 29	0 1968	0 0135	0 0648	0 0245
25/05/95 10 53	83 86	91 53	96 45	90 35	0 1957	0 0143	0 0645	0 0233
25/05/95 10 54	83 88	91 52	96 46	90 38	0 1957	0 0137	0 0645	0 024
25/05/95 10 55	83 91	91 51	96 46	90 41	0 1988	0 0127	0 064	0 0243
25/05/95 10 56	83 92	91 43	96 35	90 4	0 198	0 0118	0 0642	0 0245
25/05/95 10 57	83 95	91 41	96 36	90 43	0 1968	0 0123	0 0663	0 0245
25/05/95 10 58	83 98	91 43	96 43	90 46	0 1985	0 0123	0 0628	0 0243
25/05/95 10 59	84 01	91 31	96 27	90 45	0 197	0 0123	0 0663	0 0233
25/05/95 11 00	83 97	91 25	96 26	90 42	0 1975	0 0118	0 0637	0 024
25/05/95 11 01	83 95	91 41	96 58	90 55	0 198	0 0118	0 063	0 024
25/05/95 11 02	83 96	91 51	96 75	90 68	0 2002	0 0118	0 065	0 0245
25/05/95 11 03	83 98	91 56	96 83	90 8	0 1968	0 012	0 0642	0 025
25/05/95 11 04	84 04	91 51	96 72	90 81	0 2027	0 0127	0 067	0 025
25/05/95 11 05	84 1	91 4	96 55	90 72	0 2018	0 0125	0 0658	0 0247
25/05/95 11 06	84 13	91 3	96 5	90 7	0 2037	0 0115	0 064	0 0243
25/05/95 11 07	84 15	91 26	96 41	90 69	0 2005	0 0118	0 065	0 025
25/05/95 11 08	84 13	91 21	96 36	90 67	0 2018	0 0125	0 0642	0 0255
25/05/95 11 09	84 15	91 19	96 35	90 7	0 205	0 0118	0 0625	0 025
25/05/95 11 10	84 13	91 11	96 29	90 67	0 2035	0 011	0 0658	0 0245
25/05/95 11 11	84 12	91 11	96 35	90 7	0 2023	0 0118	0 0663	0 0253
25/05/95 11 12	84 08	91 12	96 44	90 73	0 2048	0 012	0 0635	0 0255
25/05/95 11 13	84 04	91 11	96 45	90 76	0 2045	0 0115	0 067	0 0245
25/05/95 11 14	84 09	91 09	96 43	90 81	0 2037	0 0123	0 0645	0 023
25/05/95 11 15	84 1	91 07	96 42	90 82	0 2023	0 0127	0 0642	0 0243
25/05/95 11 16	84 1	91 06	96 45	90 85	0 2058	0 0123	0 0632	0 0247
25/05/95 11 17	84 11	91	96 34	90 83	0 2045	0 012	0 065	0 024
25/05/95 11 18	84 12	90 94	96 25	90 76	0 2025	0 0118	0 0672	0 0247
25/05/95 11 19	84 07	90 9	96 28	90 8	0 2088	0 0115	0 0658	0 0243
25/05/95 11 20	83 96	90 93	96 46	90 85	0 2027	0 0137	0 065	0 025
25/05/95 11 21	83 94	91 06	96 72	91	0 2048	0 0115	0 065	0 0247
25/05/95 11 22	83 98	91 25	97 1	91 21	0 2058	0 0123	0 0658	0 0253
25/05/95 11 23	84	91 3	97 17	91 31	0 207	0 0125	0 0632	0 0245
25/05/95 11 24	84 03	91 3	97 17	91 38	0 207	0 0113	0 0663	0 025
25/05/95 11 25	84 12	91 25	97 08	91 31	0 207	0 0123	0 0637	0 025
25/05/95 11 26	84 13	91 2	97	91 3	0 2033	0 0123	0 065	0 025
25/05/95 11 27	84 15	91 18	96 98	91 3	0 208	0 0127	0 064	0 024
25/05/95 11 28	84 15	91 16	96 99	91 3	0 2037	0 011	0 0658	0 0247
25/05/95 11 29	84 13	91 17	97 02	91 37	0 2088	0 011	0 0658	0 0237
25/05/95 11 30	84 11	91 17	97 08	91 41	0 207	0 0125	0 0648	0 0245
25/05/95 11 31	84 13	91 18	97 12	91 44	0 2043	0 0115	0 0653	0 0243
25/05/95 11 32	84 13	91 16	97 09	91 45	0 209	0 0127	0 0648	0 0233
25/05/95 11 33	84 12	91 15	97 14	91 47	0 2072	0 0118	0 0655	0 0245
25/05/95 11 34	84 1	91 15	97 15	91 49	0 2093	0 012	0 0635	0 024
25/05/95 11 35	83 99	91 12	97 22	91 5	0 207	0 0127	0 066	0 0245
25/05/95 11 36	83 95	91 28	97 61	91 69	0 205	0 0127	0 0655	0 0247
25/05/95 11 37	83 88	91 41	97 83	91 81	0 2093	0 012	0 0648	0 0247
25/05/95 11 38	83 86	91 44	97 99	91 92	0 2088	0 0105	0 0642	0 0247
25/05/95 11 39	83 9	91 54	98 19	92 06	0 21	0 0115	0 0653	0 0245
25/05/95 11 40	83 98	91 6	98 27	92 15	0 2103	0 0115	0 0667	0 024
25/05/95 11 41	84 11	91 51	97 96	92 09	0 2062	0 0123	0 0648	0 0253
25/05/95 11 42	84 18	91 38	97 71	91 97	0 2103	0 0108	0 065	0 0253
25/05/95 11 43	84 2	91 26	97 58	91 87	0 2095	0 0123	0 0632	0 0263
25/05/95 11 44	84 24	91 23	97 44	91 85	0 2123	0 012	0 0635	0 0253

25/05/95 11 45	84 24	91 14	97 29	91 78	0 205	0 012	0 0658	0 0253
25/05/95 11 46	84 25	91 09	97 22	91 74	0 2107	0 0115	0 0675	0 0245
25/05/95 11 47	84 22	91 03	97 19	91 72	0 2123	0 0115	0 0635	0 0253
25/05/95 11 48	84 2	91 06	97 28	91 77	0 2115	0 0118	0 0667	0 0245
25/05/95 11 49	84 2	91 09	97 34	91 8	0 2107	0 0113	0 0645	0 0243
25/05/95 11 50	84 19	91 1	97 37	91 85	0 2095	0 0115	0 068	0 024
25/05/95 11 51	84 2	91 07	97 36	91 85	0 2107	0 0125	0 0645	0 0253
25/05/95 11 52	84 18	91 02	97 28	91 8	0 2105	0 0125	0 0658	0 0255
25/05/95 11 53	84 15	90 97	97 25	91 78	0 2115	0 012	0 067	0 0245
25/05/95 11 54	84 13	91	97 34	91 83	0 2138	0 0118	0 0663	0 0245
25/05/95 11 55	84 11	91 03	97 44	91 93	0 2145	0 0125	0 0658	0 0245
25/05/95 11 56	84 01	91	97 41	91 92	0 214	0 0118	0 0675	0 0253
25/05/95 11 57	83 95	91 02	97 65	91 97	0 21	0 012	0 0648	0 0245
25/05/95 11 58	83 93	91 12	97 88	92 13	0 2145	0 0113	0 0655	0 0253
25/05/95 11 59	83 97	91 23	98 09	92 25	0 2148	0 0115	0 0653	0 0255
25/05/95 12 00	83 99	91 24	98 03	92 27	0 212	0 0115	0 0675	0 0247
25/05/95 12 01	83 99	91 23	98 05	92 28	0 2145	0 011	0 0645	0 025
25/05/95 12 02	84 02	91 23	98 06	92 32	0 2145	0 0118	0 0663	0 0258
25/05/95 12 03	84 08	91 16	97 92	92 26	0 2132	0 0115	0 066	0 0243
25/05/95 12 04	84 11	91 14	97 89	92 26	0 2138	0 0118	0 065	0 0258
25/05/95 12 05	84 13	91 09	97 77	92 21	0 2128	0 0108	0 0683	0 0258
25/05/95 12 06	84 14	91 04	97 69	92 16	0 2155	0 0113	0 065	0 0243
25/05/95 12 07	84 16	90 99	97 6	92 09	0 2163	0 012	0 0653	0 0255
25/05/95 12 08	84 15	90 9	97 44	92	0 2113	0 0115	0 0658	0 0255
25/05/95 12 09	84 13	90 88	97 44	91 98	0 2153	0 0108	0 067	0 0245
25/05/95 12 10	84 12	90 88	97 48	91 99	0 2138	0 0125	0 0645	0 0258
25/05/95 12 11	84 07	90 88	97 55	92 02	0 2167	0 0115	0 0688	0 0253
25/05/95 12 12	83 99	90 89	97 69	92 07	0 2173	0 0113	0 0642	0 0247
25/05/95 12 13	83 99	90 99	97 89	92 19	0 2138	0 013	0 0653	0 0253
25/05/95 12 14	83 99	91 07	98 02	92 29	0 2177	0 0108	0 0667	0 0253
25/05/95 12 15	84	91 07	98	92 3	0 2183	0 0118	0 067	0 0258
25/05/95 12 16	84 03	91 06	97 98	92 3	0 2138	0 0118	0 07	0 0243
25/05/95 12 17	84 08	91	97 86	92 28	0 2153	0 0113	0 0663	0 0253
25/05/95 12 18	84 1	90 92	97 72	92 2	0 221	0 011	0 0653	0 0247
25/05/95 12 19	84 1	90 88	97 7	92 16	0 2163	0 011	0 0642	0 0253
25/05/95 12 20	84 08	90 9	97 73	92 2	0 2175	0 011	0 0663	0 0253
25/05/95 12 21	84 01	90 86	97 74	92 19	0 215	0 012	0 0658	0 0247
25/05/95 12 22	83 97	90 92	97 94	92 29	0 2173	0 0115	0 0658	0 025
25/05/95 12 23	83 95	91 02	98 19	92 4	0 218	0 011	0 067	0 026
25/05/95 12 24	83 96	91 1	98 37	92 58	0 2163	0 0123	0 065	0 025
25/05/95 12 25	83 99	91 13	98 36	92 61	0 217	0 0115	0 0653	0 024
25/05/95 12 26	84 02	91 05	98 19	92 53	0 214	0 0115	0 0653	0 0243
25/05/95 12 27	84 08	91 02	98 11	92 5	0 2175	0 0113	0 0655	0 0247
25/05/95 12 28	84 09	90 97	97 99	92 42	0 2193	0 011	0 0658	0 024
25/05/95 12 29	84 08	90 96	98 03	92 43	0 219	0 0113	0 065	0 025
25/05/95 12 30	84 02	90 95	98 04	92 44	0 217	0 012	0 0693	0 025
25/05/95 12 31	84 01	91 02	98 24	92 57	0 2185	0 0113	0 0683	0 0253
25/05/95 12 32	84 02	91 05	98 3	92 63	0 2195	0 0115	0 0645	0 0255
25/05/95 12 33	84 03	91 01	98 21	92 6	0 2212	0 0115	0 0675	0 0263
25/05/95 12 34	84 06	90 99	98 24	92 6	0 2175	0 011	0 067	0 025
25/05/95 12 35	84 08	91 06	98 3	92 66	0 215	0 0115	0 065	0 0247
25/05/95 12 36	84 1	91 02	98 27	92 65	0 223	0 0115	0 0677	0 0258
25/05/95 12 37	84 1	91	98 23	92 64	0 2183	0 012	0 0675	0 0255
25/05/95 12 38	84 12	90 95	98 18	92 6	0 2222	0 011	0 066	0 0255
25/05/95 12 39	84 11	90 96	98 19	92 63	0 222	0 0103	0 0667	0 0247

25/05/95 12 40	84 11	90 96	98 27	92 65	0 219	0 0113	0 0658	0 0255
25/05/95 12 41	84 09	90 96	98 28	92 68	0 2175	0 0113	0 0677	0 0255
25/05/95 12 42	84 11	91 01	98 37	92 73	0 221	0 0125	0 0667	0 0237
25/05/95 12 43	84 11	91 02	98 37	92 77	0 2205	0 011	0 0655	0 0263
25/05/95 12 44	84 12	90 95	98 26	92 71	0 223	0 0108	0 0672	0 026
25/05/95 12 45	84 12	90 92	98 21	92 67	0 2185	0 0113	0 068	0 026
25/05/95 12 46	84 12	90 89	98 16	92 65	0 2173	0 0123	0 0685	0 026
25/05/95 12 47	84 11	90 88	98 18	92 66	0 2183	0 012	0 0667	0 0255
25/05/95 12 48	84 08	90 87	98 19	92 67	0 2203	0 012	0 067	0 025
25/05/95 12 49	84 03	90 88	98 28	92 71	0 2212	0 0105	0 0663	0 026
25/05/95 12 50	84	90 88	98 31	92 72	0 2215	0 0118	0 0655	0 0253
25/05/95 12 51	83 99	90 9	98 37	92 77	0 2188	0 011	0 0658	0 026
25/05/95 12 52	84	90 92	98 4	92 8	0 2177	0 0105	0 0667	0 0253
25/05/95 12 53	84	90 87	98 33	92 74	0 2288	0 0258	0 065	0 0273
25/05/95 12 54	83 99	90 9	98 4	92 81	0 2263	0 0108	0 0655	0 0253
25/05/95 12 55	83 99	90 92	98 42	92 82	0 2253	0 0115	0 0658	0 0255
25/05/95 12 56	83 97	90 94	98 5	92 85	0 2243	0 0118	0 0658	0 026
25/05/95 12 57	83 95	90 97	98 66	92 93	0 2185	0 0115	0 0658	0 0255
25/05/95 12 58	83 96	91 05	98 85	93 08	0 2212	0 012	0 0658	0 0278
25/05/95 12 59	83 92	91 07	98 89	93 11	0 2233	0 0108	0 067	0 026
25/05/95 13 00	83 91	91 11	99 06	93 21	0 2238	0 0118	0 068	0 027
25/05/95 13 01	83 92	91 17	99 17	93 3	0 226	0 0115	0 0672	0 026
25/05/95 13 02	83 96	91 2	99 24	93 34	0 224	0 0125	0 0672	0 0268
25/05/95 13 03	84 01	91 2	99 11	93 35	0 2225	0 0108	0 0653	0 027
25/05/95 13 04	84 03	91 15	99 08	93 29	0 2212	0 012	0 068	0 0282
25/05/95 13 05	84 02	91 15	99 04	93 31	0 225	0 0108	0 0677	0 0278
25/05/95 13 06	84 02	91 12	99 07	93 29	0 2203	0 0115	0 0672	0 0275
25/05/95 13 07	84 03	91 16	99 11	93 34	0 2222	0 011	0 0677	0 0278
25/05/95 13 08	84 11	91 16	99 08	93 35	0 2253	0 012	0 0675	0 0278
25/05/95 13 09	84 13	91 15	99 02	93 34	0 2233	0 0115	0 0675	0 0278
25/05/95 13 10	84 14	91 15	99 04	93 35	0 223	0 0115	0 067	0 027
25/05/95 13 11	84 17	91 14	99	93 34	0 2228	0 0108	0 065	0 028
25/05/95 13 12	84 18	91 14	99 01	93 35	0 2253	0 0118	0 0655	0 0282
25/05/95 13 14	84 18	91 14	99 01	93 36	0 2235	0 0115	0 0675	0 029
25/05/95 13 15	84 2	91 14	99 02	93 38	0 2233	0 0118	0 0688	0 0288
25/05/95 13 16	84 21	91 13	98 96	93 36	0 2243	0 0125	0 0663	0 0292
25/05/95 13 17	84 21	91 09	98 91	93 32	0 2255	0 0115	0 0693	0 029
25/05/95 13 17	84 21	91 09	98 94	93 34	0 2228	0 0115	0 0672	0 0288
25/05/95 13 19	84 21	91 06	98 88	93 31	0 2273	0 011	0 067	0 0298
25/05/95 13 20	84 21	91 01	98 8	93 26	0 2228	0 011	0 067	0 028
25/05/95 13 21	84 19	90 96	98 77	93 22	0 2245	0 012	0 0675	0 0295
25/05/95 13 22	84 17	90 99	98 86	93 28	0 2225	0 011	0 0653	0 0298
25/05/95 13 23	84 16	91	98 84	93 29	0 2228	0 0113	0 0693	0 029
25/05/95 13 24	84 14	90 97	98 85	93 28	0 225	0 0108	0 0672	0 0298
25/05/95 13 25	84 15	90 98	98 85	93 29	0 2222	0 0103	0 0658	0 0295
25/05/95 13 26	84 14	90 98	98 88	93 32	0 2288	0 0108	0 0667	0 029
25/05/95 13 27	84 13	90 99	98 88	93 3	0 2247	0 0115	0 0672	0 0292
25/05/95 13 28	84 12	91	98 96	93 34	0 225	0 0127	0 068	0 0292
25/05/95 13 29	84 09	91 02	99 03	93 39	0 2273	0 012	0 0648	0 03
25/05/95 13 30	84 07	91 02	99 09	93 42	0 2238	0 0113	0 065	0 029
25/05/95 13 31	84 03	91 04	99 17	93 49	0 225	0 0105	0 0675	0 0298
25/05/95 13 32	84 07	91 04	99 17	93 5	0 2245	0 0125	0 0685	0 0313
25/05/95 13 33	84 09	90 98	99 02	93 42	0 229	0 0103	0 0642	0 0298
25/05/95 13 34	84 08	90 96	99 04	93 4	0 2278	0 0108	0 0675	0 0295
25/05/95 13 35	84 08	90 97	99 06	93 44	0 2313	0 0115	0 0655	0 03

25/05/95 13 36	84 08	90 95	99 02	93 43	0 2275	0 0115	0 0667	0 03
25/05/95 13 37	84 09	91	99 14	93 48	0 2282	0 0108	0 066	0 0298
25/05/95 13 38	84 1	91 02	99 17	93 52	0 227	0 0115	0 0675	0 0295
25/05/95 13 39	84 09	90 99	99 11	93 5	0 2292	0 0118	0 067	0 0298
25/05/95 13 40	84 07	90 95	99 08	93 45	0 229	0 0108	0 0685	0 0292
25/05/95 13 41	84 02	90 97	99 15	93 51	0 2257	0 0103	0 0675	0 0308
25/05/95 13 42	84	91 01	99 24	93 55	0 225	0 01	0 0663	0 0302
25/05/95 13 43	83 98	90 99	99 25	93 55	0 2288	0 0118	0 0675	0 0295
25/05/95 13 44	83 96	90 99	99 27	93 56	0 2327	0 0105	0 0672	0 0305
25/05/95 13 45	83 96	90 99	99 27	93 57	0 2298	0 0115	0 0683	0 0295
25/05/95 13 46	83 95	90 95	99 24	93 55	0 2278	0 0123	0 0658	0 0308
25/05/95 13 47	83 98	90 97	99 26	93 61	0 225	0 0118	0 0675	0 0302
25/05/95 13 48	83 99	90 94	99 14	93 53	0 2257	0 0113	0 0675	0 0295
25/05/95 13 49	83 98	90 93	99 14	93 53	0 2288	0 0108	0 0663	0 031
25/05/95 13 50	83 99	90 94	99 22	93 61	0 2268	0 0118	0 0648	0 0302
25/05/95 13 51	83 99	90 92	99 21	93 61	0 2298	0 0113	0 0653	0 0323
25/05/95 13 52	83 99	90 94	99 17	93 61	0 227	0 0113	0 0688	0 0323
25/05/95 13 53	83 99	90 93	99 17	93 61	0 2282	0 0108	0 0703	0 0323
25/05/95 13 54	83 99	90 95	99 27	93 65	0 227	0 0115	0 0703	0 0318
25/05/95 13 55	83 99	90 96	99 31	93 66	0 2275	0 012	0 0703	0 0327
25/05/95 13 56	83 99	90 96	99 31	93 69	0 2292	0 0115	0 0655	0 0327
25/05/95 13 57	83 99	90 95	99 3	93 67	0 2308	0 0113	0 07	0 0335
25/05/95 13 58	83 96	90 95	99 36	93 7	0 226	0 0108	0 0698	0 033
25/05/95 13 59	83 94	90 94	99 36	93 7	0 2298	0 0108	0 068	0 0323
25/05/95 14 00	83 92	90 93	99 38	93 7	0 23	0 0103	0 0637	0 0335
25/05/95 14 01	83 9	90 91	99 39	93 7	0 23	0 0103	0 066	0 0323
25/05/95 14 02	83 91	90 92	99 43	93 73	0 2308	0 0103	0 0655	0 0325
25/05/95 14 03	83 9	90 93	99 45	93 76	0 2233	0 0108	0 0693	0 032
25/05/95 14 04	83 88	90 93	99 46	93 76	0 2325	0 0108	0 0655	0 0323
25/05/95 14 05	83 86	90 92	99 47	93 76	0 2303	0 0105	0 0648	0 0338
25/05/95 14 06	83 82	90 88	99 46	93 74	0 2295	0 0103	0 0703	0 032
25/05/95 14 07	83 78	90 88	99 5	93 77	0 229	0 011	0 0683	0 0335
25/05/95 14 08	83 78	90 84	99 48	93 75	0 2325	0 0113	0 0645	0 033
25/05/95 14 09	83 77	90 84	99 48	93 74	0 226	0 0115	0 0642	0 0335
25/05/95 14 10	83 76	90 85	99 54	93 78	0 2243	0 012	0 0658	0 0318
25/05/95 14 11	83 78	90 84	99 53	93 79	0 232	0 0115	0 0685	0 032

Calculation of 'U' values at a flowrate of 10 L/min

Temp Cold In (°C)	Temp Cold out (°C)	Temp Hot in (°C)	Temp Hot out (°C)	Temp Co - Ci (°C)	Temp Log mean	mcp/AF	U-Value	Time (mins)
84.14	90.88	94.42	88.25	6.74	3.817911	2.228	3.933229	0
84.16	91.16	94.78	88.4	7	3.921835	2.228	3.976709	1
84.25	91.8	95.48	88.85	7.55	4.122907	2.228	4.079986	2
84.4	92.29	95.99	89.25	7.89	4.249095	2.228	4.137098	3
84.55	92.5	96.05	89.43	7.95	4.179792	2.228	4.237675	4
84.66	92.51	95.95	89.51	7.85	4.104717	2.228	4.260903	5
84.73	92.43	95.75	89.51	7.7	4.005753	2.228	4.28274	6
84.76	92.32	95.53	89.46	7.56	3.907771	2.228	4.310304	7
84.77	92.18	95.25	89.4	7.41	3.796735	2.228	4.348336	8
84.77	91.94	94.97	89.28	7.17	3.721075	2.228	4.29305	9
84.73	91.69	94.67	89.14	6.96	3.648412	2.228	4.25031	10
84.67	91.45	94.35	88.95	6.78	3.54535	2.228	4.260747	11
84.57	91.19	94.07	88.79	6.62	3.507442	2.228	4.205162	12
84.45	91.1	94	88.72	6.65	3.540938	2.228	4.184258	13
84.34	90.95	93.86	88.61	6.61	3.546647	2.228	4.152395	14
84.27	90.89	93.8	88.52	6.62	3.537805	2.228	4.169071	15
84.19	90.72	93.66	88.45	6.53	3.559299	2.228	4.087558	16
84.12	90.61	93.52	88.37	6.49	3.537805	2.228	4.087201	17
84.01	90.66	93.73	88.4	6.65	3.690742	2.228	4.014423	18
83.94	90.81	93.98	88.48	6.87	3.81408	2.228	4.01312	19
83.89	90.92	94.2	88.62	7.03	3.960864	2.228	3.9544	20
83.9	90.95	94.27	88.66	7.05	3.996859	2.228	3.929936	21
83.87	91.01	94.38	88.74	7.14	4.074081	2.228	3.904665	22
83.87	91.02	94.41	88.79	7.15	4.107618	2.228	3.878208	23
83.87	90.99	94.42	88.79	7.12	4.130304	2.228	3.840725	24
83.85	90.99	94.43	88.83	7.14	4.16263	2.228	3.821603	25
83.83	90.94	94.4	88.82	7.11	4.178418	2.228	3.791167	26
83.79	90.95	94.51	88.85	7.16	4.26614	2.228	3.739324	27
83.77	91.08	94.77	88.95	7.31	4.392966	2.228	3.707445	28
83.78	91.17	94.98	89.07	7.39	4.509596	2.228	3.651086	29
83.8	91.3	95.16	89.23	7.5	4.600437	2.228	3.632264	30
83.85	91.3	95.2	89.29	7.45	4.627369	2.228	3.587049	31
83.9	91.28	95.2	89.34	7.38	4.638567	2.228	3.544767	32
83.92	91.16	95.01	89.3	7.24	4.572416	2.228	3.527833	33
83.92	91.01	94.84	89.21	7.09	4.520775	2.228	3.494206	34
83.91	90.89	94.69	89.18	6.98	4.49501	2.228	3.459712	35
83.88	90.95	94.89	89.23	7.07	4.609111	2.228	3.41757	36
83.85	91.05	95.06	89.32	7.2	4.702285	2.228	3.411448	37
83.84	91.09	95.2	89.4	7.25	4.798543	2.228	3.36623	38
83.85	91.16	95.33	89.49	7.31	4.868065	2.228	3.345617	39
83.86	91.19	95.39	89.54	7.33	4.902826	2.228	3.330985	40
83.91	91.15	95.32	89.57	7.24	4.877125	2.228	3.307424	41
83.91	91.09	95.33	89.58	7.18	4.920416	2.228	3.251156	42
83.92	91.14	95.46	89.64	7.22	4.987293	2.228	3.225429	43
83.92	91.17	95.51	89.74	7.25	5.043863	2.228	3.202506	44

83 94	91 16	95 52	89 78	7 22	5 064006	2 228	3 176568	45
83 94	91 08	95 4	89 76	7 14	5 032799	2 228	3 160849	46
83 95	91 07	95 43	89 78	7 12	5 059458	2 228	3 135387	47
83 91	91 07	95 55	89 82	7 16	5 16203	2 228	3 09035	48
83 86	91 19	95 8	89 93	7 33	5 306568	2 228	3 077552	49
83 84	91 39	96 15	90 1	7 55	5 475801	2 228	3 071952	50
83 86	91 51	96 36	90 29	7 65	5 60292	2 228	3 042021	51
83 86	91 53	96 45	90 35	7 67	5 668811	2 228	3 014523	52
83 88	91 52	96 46	90 38	7 64	5 684368	2 228	2 994514	53
83 91	91 51	96 46	90 41	7 6	5 689857	2 228	2 975963	54
83 92	91 43	96 35	90 4	7 51	5 664242	2 228	2 954019	55
83 95	91 41	96 36	90 43	7 46	5 680701	2 228	2 92585	56
83 98	91 43	96 43	90 46	7 45	5 708058	2 228	2 907924	57
84 01	91 31	96 27	90 45	7 3	5 667831	2 228	2 869598	58
83 97	91 25	96 26	90 42	7 28	5 699715	2 228	2 845728	59
83 95	91 41	96 58	90 55	7 46	5 855929	2 228	2 8383	60
83 96	91 51	96 75	90 68	7 55	5 94935	2 228	2 827435	61
83 98	91 56	96 83	90 8	7 58	6 011734	2 228	2 809213	62
84 04	91 51	96 72	90 81	7 47	5 955989	2 228	2 794357	63
84 1	91 4	96 55	90 72	7 3	5 854273	2 228	2 77821	64
84 13	91 3	96 5	90 7	7 17	5 858326	2 228	2 726847	65
84 15	91 26	96 41	90 69	7 11	5 817349	2 228	2 723075	66
84 13	91 21	96 36	90 67	7 08	5 817349	2 228	2 711586	67
84 15	91 19	96 35	90 7	7 04	5 827397	2 228	2 691617	68
84 13	91 11	96 29	90 67	6 98	5 833602	2 228	2 665838	69
84 12	91 11	96 35	90 7	6 99	5 884594	2 228	2 646524	70
84 08	91 12	96 44	90 73	7 04	5 960289	2 228	2 631604	71
84 04	91 11	96 45	90 76	7 07	6 003589	2 228	2 623757	72
84 09	91 09	96 43	90 81	7	6 003589	2 228	2 597779	73
84 1	91 07	96 42	90 82	6 97	6 008993	2 228	2 58432	74
84 1	91 06	96 45	90 85	6 96	6 044522	2 228	2 565444	75
84 11	91	96 34	90 83	6 89	6 003589	2 228	2 556957	76
84 12	90 94	96 25	90 76	6 82	5 950247	2 228	2 553669	77
84 07	90 9	96 28	90 8	6 83	6 029834	2 228	2 523658	78
83 96	90 93	96 46	90 85	6 97	6 1851	2 228	2 510737	79
83 94	91 06	96 72	91	7 12	6 334235	2 228	2 504384	80
83 98	91 25	97 1	91 21	7 27	6 515661	2 228	2 485943	81
84	91 3	97 17	91 31	7 3	6 563694	2 228	2 477934	82
84 03	91 3	97 17	91 38	7 27	6 582292	2 228	2 460778	83
84 12	91 25	97 08	91 31	7 13	6 486254	2 228	2 449124	84
84 13	91 2	97	91 3	7 07	6 460809	2 228	2 438078	85
84 15	91 18	96 98	91 3	7 03	6 451476	2 228	2 427792	86
84 15	91 16	96 99	91 3	7 01	6 467565	2 228	2 414862	87
84 13	91 17	97 02	91 37	7 04	6 520325	2 228	2 405573	88
84 11	91 17	97 08	91 41	7 06	6 580551	2 228	2 390329	89
84 13	91 18	97 12	91 44	7 05	6 601324	2 228	2 379432	90
84 13	91 16	97 09	91 45	7 03	6 600625	2 228	2 372933	91
84 12	91 15	97 14	91 47	7 03	6 646827	2 228	2 356439	92
84 1	91 15	97 15	91 49	7 05	6 670881	2 228	2 354621	93
83 99	91 12	97 22	91 5	7 13	6 780584	2 228	2 342813	94
83 95	91 28	97 61	91 69	7 33	7 011386	2 228	2 329245	95

83 88	91 41	97 83	91 81	7 53	7 148439	2 228	2 346923	96
83 86	91 44	97 99	91 92	7 58	7 278915	2 228	2 320159	97
83 9	91 54	98 19	92 06	7 64	7 379269	2 228	2 306722	98
83 98	91 6	98 27	92 15	7 62	7 394661	2 228	2 295894	99
84 11	91 51	97 96	92 09	7 4	7 187881	2 228	2 29375	100
84 18	91 38	97 71	91 97	7 2	7 034767	2 228	2 280331	101
84 2	91 26	97 58	91 87	7 06	6 973234	2 228	2 255722	102
84 24	91 23	97 44	91 85	6 99	6 886298	2 228	2 261552	103
84 24	91 14	97 29	91 78	6 9	6 821413	2 228	2 253668	104
84 25	91 09	97 22	91 74	6 84	6 787306	2 228	2 245297	105
84 22	91 03	97 19	91 72	6 81	6 808035	2 228	2 228643	106
84 2	91 06	97 28	91 77	6 86	6 872917	2 228	2 223813	107
84 2	91 09	97 34	91 8	6 89	6 903013	2 228	2 2238	108
84 19	91 1	97 37	91 85	6 91	6 941822	2 228	2 217787	109
84 2	91 07	97 36	91 85	6 87	6 94783	2 228	2 203042	110
84 18	91 02	97 28	91 8	6 84	6 917733	2 228	2 202964	111
84 15	90 97	97 25	91 78	6 82	6 933108	2 228	2 191652	112
84 13	91	97 34	91 83	6 87	6 997988	2 228	2 187251	113
84 11	91 03	97 44	91 93	6 92	7 091653	2 228	2 174071	114
84 01	91	97 41	91 92	6 99	7 133736	2 228	2 183109	115
83 95	91 02	97 65	91 97	7 07	7 302966	2 228	2 156926	116
83 93	91 12	97 88	92 13	7 19	7 456841	2 228	2 148272	117
83 97	91 23	98 09	92 25	7 26	7 54775	2 228	2 14306	118
83 99	91 24	98 03	92 27	7 25	7 510382	2 228	2 150756	119
83 99	91 23	98 05	92 28	7 24	7 531104	2 228	2 14188	120
84 02	91 23	98 06	92 32	7 21	7 541136	2 228	2 130167	121
84 08	91 16	97 92	92 26	7 08	7 447451	2 228	2 118072	122
84 11	91 14	97 89	92 26	7 03	7 428024	2 228	2 108615	123
84 13	91 09	97 77	92 21	6 96	7 357815	2 228	2 107539	124
84 14	91 04	97 69	92 16	6 9	7 313627	2 228	2 101994	125
84 16	90 99	97 6	92 09	6 83	7 249983	2 228	2 098934	126
84 15	90 9	97 44	92	6 75	7 17508	2 228	2 096005	127
84 13	90 88	97 44	91 98	6 75	7 185712	2 228	2 092903	128
84 12	90 88	97 48	91 99	6 76	7 216384	2 228	2 087095	129
84 07	90 88	97 55	92 02	6 81	7 291284	2 228	2 080934	130
83 99	90 89	97 69	92 07	6 9	7 421612	2 228	2 07141	131
83 99	90 99	97 89	92 19	7	7 53131	2 228	2 070822	132
83 99	91 07	98 02	92 29	7 08	7 60504	2 228	2 074182	133
84	91 07	98	92 3	7 07	7 594416	2 228	2 07415	134
84 03	91 06	97 98	92 3	7 03	7 574961	2 228	2 067712	135
84 08	91	97 86	92 28	6 92	7 510086	2 228	2 05294	136
84 1	90 92	97 72	92 2	6 82	7 431058	2 228	2 044791	137
84 1	90 88	97 7	92 16	6 78	7 422746	2 228	2 035074	138
84 08	90 9	97 73	92 2	6 82	7 456411	2 228	2 037838	139
84 01	90 86	97 74	92 19	6 85	7 51126	2 228	2 031856	140
83 97	90 92	97 94	92 29	6 95	7 651603	2 228	2 023707	141
83 95	91 02	98 19	92 4	7 07	7 792487	2 228	2 021429	142
83 96	91 1	98 37	92 58	7 14	7 925847	2 228	2 007094	143
83 99	91 13	98 36	92 61	7 14	7 904642	2 228	2 012478	144
84 02	91 05	98 19	92 53	7 03	7 804971	2 228	2 006778	145
84 08	91 02	98 11	92 5	6 94	7 735954	2 228	1 99876	146

84 09	90 97	97 99	92 42	6 88	7 656331	2 228	2 002087	147
84 08	90 96	98 03	92 43	6 88	7 692259	2 228	1 992736	148
84 02	90 95	98 04	92 44	6 93	7 735954	2 228	1 99588	149
84 01	91 02	98 24	92 57	7 01	7 870998	2 228	1 984282	150
84 02	91 05	98 3	92 63	7 03	7 910525	2 228	1 98	151
84 03	91 01	98 21	92 6	6 98	7 865124	2 228	1 977266	152
84 06	90 99	98 24	92 6	6 93	7 877404	2 228	1 960042	153
84 08	91 06	98 3	92 66	6 98	7 891047	2 228	1 97077	154
84 1	91 02	98 27	92 65	6 92	7 882141	2 228	1 956037	155
84 1	91	98 23	92 64	6 9	7 86683	2 228	1 95418	156
84 12	90 95	98 18	92 6	6 83	7 838395	2 228	1 941372	157
84 11	90 96	98 19	92 63	6 85	7 857359	2 228	1 942358	158
84 11	90 96	98 27	92 65	6 85	7 909066	2 228	1 929659	159
84 09	90 96	98 28	92 68	6 87	7 938075	2 228	1 928221	160
84 11	91 01	98 37	92 73	6 9	7 973414	2 228	1 928057	161
84 11	91 02	98 37	92 77	6 91	7 987103	2 228	1 927542	162
84 12	90 95	98 26	92 71	6 83	7 932796	2 228	1 918269	163
84 12	90 92	98 21	92 67	6 8	7 903267	2 228	1 916979	164
84 12	90 89	98 16	92 65	6 77	7 883225	2 228	1 913374	165
84 11	90 88	98 18	92 66	6 77	7 908543	2 228	1 907249	166
84 08	90 87	98 19	92 67	6 79	7 938075	2 228	1 905767	167
84 03	90 88	98 28	92 71	6 85	8 022989	2 228	1 902259	168
84	90 88	98 31	92 72	6 88	8 057797	2 228	1 902336	169
83 99	90 9	98 37	92 77	6 91	8 107368	2 228	1 898949	170
84	90 92	98 4	92 8	6 92	8 122131	2 228	1 898241	171
84	90 87	98 33	92 74	6 87	8 083116	2 228	1 893621	172
83 99	90 9	98 4	92 81	6 91	8 142175	2 228	1 890831	173
83 99	90 92	98 42	92 82	6 93	8 146914	2 228	1 895201	174
83 97	90 94	98 5	92 85	6 97	8 202305	2 228	1 893268	175
83 95	90 97	98 66	92 93	7 02	8 318336	2 228	1 880251	176
83 96	91 05	98 85	93 08	7 09	8 442809	2 228	1 871003	177
83 92	91 07	98 89	93 11	7 15	8 486578	2 228	1 877105	178
83 91	91 11	99 06	93 21	7 2	8 607362	2 228	1 863707	179
83 92	91 17	99 17	93 3	7 25	8 671707	2 228	1 862724	180
83 96	91 2	99 24	93 34	7 24	8 692793	2 228	1 855643	181
84 01	91 2	99 11	93 35	7 19	8 605206	2 228	1 861585	182
84 03	91 15	99 08	93 29	7 12	8 577822	2 228	1 849346	183
84 02	91 15	99 04	93 31	7 13	8 570952	2 228	1 853428	184
84 02	91 12	99 07	93 29	7 1	8 593109	2 228	1 84087	185
84 03	91 16	99 11	93 34	7 13	8 61211	2 228	1 84457	186
84 11	91 16	99 08	93 35	7 05	8 56305	2 228	1 834323	187
84 13	91 15	99 02	93 34	7 02	8 52245	2 228	1 835219	188
84 14	91 15	99 04	93 35	7 01	8 53299	2 228	1 830341	189
84 17	91 14	99	93 34	6 97	8 498179	2 228	1 827352	190
84 18	91 14	99 01	93 35	6 96	8 503445	2 228	1 8236	191
84 18	91 14	99 01	93 36	6 96	8 508198	2 228	1 822581	192
84 2	91 14	99 02	93 38	6 94	8 513464	2 228	1 81622	193
84 21	91 13	98 96	93 36	6 92	8 47287	2 228	1 819662	194
84 21	91 09	98 91	93 32	6 88	8 448592	2 228	1 814342	195
84 21	91 09	98 94	93 34	6 88	8 473894	2 228	1 808925	196
84 21	91 06	98 88	93 31	6 85	8 443837	2 228	1 807449	197

84 21	91 01	98 8	93 26	6 8	8 404264	2 228	1 802704	198
84 19	90 96	98 77	93 22	6 77	8 405249	2 228	1 794541	199
84 17	90 99	98 86	93 28	6 82	8 474886	2 228	1 79294	200
84 16	91	98 84	93 29	6 84	8 468631	2 228	1 799526	201
84 14	90 97	98 85	93 28	6 83	8 494431	2 228	1 791437	202
84 15	90 98	98 85	93 29	6 83	8 489173	2 228	1 792547	203
84 14	90 98	98 88	93 32	6 84	8 523988	2 228	1 787839	204
84 13	90 99	98 88	93 3	6 86	8 51397	2 228	1 795177	205
84 12	91	98 96	93 34	6 88	8 574576	2 228	1 787685	206
84 09	91 02	99 03	93 39	6 93	8 638954	2 228	1 787258	207
84 07	91 02	99 09	93 42	6 95	8 694302	2 228	1 781006	208
84 03	91 04	99 17	93 49	7 01	8 778214	2 228	1 779209	209
84 07	91 04	99 17	93 5	6 97	8 763936	2 228	1 771939	210
84 09	90 98	99 02	93 42	6 89	8 669009	2 228	1 770781	211
84 08	90 96	99 04	93 4	6 88	8 685252	2 228	1 764904	212
84 08	90 97	99 06	93 44	6 89	8 709573	2 228	1 762534	213
84 08	90 95	99 02	93 43	6 87	8 694302	2 228	1 760505	214
84 09	91	99 14	93 48	6 91	8 750124	2 228	1 759458	215
84 1	91 02	99 17	93 52	6 92	8 769679	2 228	1 758076	216
84 09	90 99	99 11	93 5	6 9	8 749156	2 228	1 757107	217
84 07	90 95	99 08	93 45	6 88	8 740107	2 228	1 753827	218
84 02	90 97	99 15	93 51	6 95	8 81879	2 228	1 755865	219
84	91 01	99 24	93 55	7 01	8 873643	2 228	1 760075	220
83 98	90 99	99 25	93 55	7 01	8 898936	2 228	1 755073	221
83 96	90 99	99 27	93 56	7 03	8 923735	2 228	1 755189	222
83 96	90 99	99 27	93 57	7 03	8 928496	2 228	1 754253	223
83 95	90 95	99 24	93 55	7	8 92899	2 228	1 74667	224
83 98	90 97	99 26	93 61	6 99	8 943275	2 228	1 741389	225
83 99	90 94	99 14	93 53	6 95	8 853105	2 228	1 749059	226
83 98	90 93	99 14	93 53	6 95	8 863124	2 228	1 747082	227
83 99	90 94	99 22	93 61	6 95	8 933256	2 228	1 733366	228
83 99	90 92	99 21	93 61	6 93	8 938515	2 228	1 727361	229
83 99	90 94	99 17	93 61	6 95	8 906931	2 228	1 738489	230
83 99	90 93	99 17	93 61	6 94	8 9122	2 228	1 734961	231
83 99	90 95	99 27	93 65	6 96	8 973331	2 228	1 728107	232
83 99	90 96	99 31	93 66	6 97	8 993861	2 228	1 72664	233
83 99	90 96	99 31	93 69	6 97	9 008147	2 228	1 723902	234
83 99	90 95	99 3	93 67	6 96	8 998625	2 228	1 72325	235
83 96	90 95	99 36	93 7	6 99	9 058733	2 228	1 719194	236
83 94	90 94	99 36	93 7	7	9 073515	2 228	1 718849	237
83 92	90 93	99 38	93 7	7 01	9 098805	2 228	1 71652	238
83 9	90 91	99 39	93 7	7 01	9 124092	2 228	1 711763	239
83 91	90 92	99 43	93 73	7 01	9 149375	2 228	1 707032	240
83 9	90 93	99 45	93 76	7 03	9 173695	2 228	1 707364	241
83 88	90 93	99 46	93 76	7 05	9 188477	2 228	1 709467	242
83 86	90 92	99 47	93 76	7 06	9 208513	2 228	1 708167	243
83 82	90 88	99 46	93 74	7 06	9 233801	2 228	1 703489	244
83 78	90 88	99 5	93 77	7 1	9 288167	2 228	1 703113	245
83 78	90 84	99 48	93 75	7 06	9 289137	2 228	1 693341	246
83 77	90 84	99 48	93 74	7 07	9 289137	2 228	1 69574	247
83 76	90 85	99 54	93 78	7 09	9 339222	2 228	1 691417	248

RFLT110.CSV

Calculation of 'Rf' values at a flowrate of 10 L/min

Uc	Uf	1/Uc	1/Uf	Rf	Time
4.365	3.933229	0.229095	0.254244	0.025149	0
4.365	3.976709	0.229095	0.251464	0.022369	1
4.365	4.079986	0.229095	0.245099	0.016004	2
4.365	4.137098	0.229095	0.241715	0.01262	3
4.365	4.237675	0.229095	0.235978	0.006883	4
4.365	4.260903	0.229095	0.234692	0.005597	5
4.365	4.28274	0.229095	0.233495	0.0044	6
4.365	4.310304	0.229095	0.232002	0.002907	7
4.365	4.348336	0.229095	0.229973	0.000878	8
4.365	4.29305	0.229095	0.232935	0.00384	9
4.365	4.25031	0.229095	0.235277	0.006182	10
4.365	4.260747	0.229095	0.234701	0.005606	11
4.365	4.205162	0.229095	0.237803	0.008708	12
4.365	4.184258	0.229095	0.238991	0.009896	13
4.365	4.152395	0.229095	0.240825	0.01173	14
4.365	4.169071	0.229095	0.239862	0.010767	15
4.365	4.087558	0.229095	0.244645	0.01555	16
4.365	4.087201	0.229095	0.244666	0.015571	17
4.365	4.014423	0.229095	0.249102	0.020007	18
4.365	4.01312	0.229095	0.249183	0.020088	19
4.365	3.9544	0.229095	0.252883	0.023788	20
4.365	3.929936	0.229095	0.254457	0.025362	21
4.365	3.904665	0.229095	0.256104	0.027009	22
4.365	3.878208	0.229095	0.257851	0.028756	23
4.365	3.840725	0.229095	0.260368	0.031272	24
4.365	3.821603	0.229095	0.26167	0.032575	25
4.365	3.791167	0.229095	0.263771	0.034676	26
4.365	3.739324	0.229095	0.267428	0.038333	27
4.365	3.707445	0.229095	0.269728	0.040632	28
4.365	3.651086	0.229095	0.273891	0.044796	29
4.365	3.632264	0.229095	0.27531	0.046215	30
4.365	3.587049	0.229095	0.278781	0.049686	31
4.365	3.544767	0.229095	0.282106	0.053011	32
4.365	3.527833	0.229095	0.28346	0.054365	33
4.365	3.494206	0.229095	0.286188	0.057093	34
4.365	3.459712	0.229095	0.289041	0.059946	35
4.365	3.41757	0.229095	0.292606	0.06351	36
4.365	3.411448	0.229095	0.293131	0.064036	37
4.365	3.36623	0.229095	0.297068	0.067973	38
4.365	3.345617	0.229095	0.298899	0.069803	39
4.365	3.330985	0.229095	0.300212	0.071116	40
4.365	3.307424	0.229095	0.30235	0.073255	41
4.365	3.251156	0.229095	0.307583	0.078488	42
4.365	3.225429	0.229095	0.310036	0.080941	43
4.365	3.202506	0.229095	0.312255	0.08316	44
4.365	3.176568	0.229095	0.314805	0.08571	45
4.365	3.160849	0.229095	0.316371	0.087276	46
4.365	3.135387	0.229095	0.31894	0.089845	47
4.365	3.09035	0.229095	0.323588	0.094493	48
4.365	3.077552	0.229095	0.324934	0.095838	49
4.365	3.071952	0.229095	0.325526	0.096431	50

4 365	3 042021	0 229095	0 328729	0 099634	51
4 365	3 014523	0 229095	0 331727	0 102632	52
4 365	2 994514	0 229095	0 333944	0 104849	53
4 365	2 975963	0 229095	0 336026	0 106931	54
4 365	2 954019	0 229095	0 338522	0 109427	55
4 365	2 92585	0 229095	0 341781	0 112686	56
4 365	2 907924	0 229095	0 343888	0 114793	57
4 365	2 869598	0 229095	0 348481	0 119386	58
4 365	2 845728	0 229095	0 351404	0 122309	59
4 365	2 8383	0 229095	0 352324	0 123229	60
4 365	2 827435	0 229095	0 353677	0 124582	61
4 365	2 809213	0 229095	0 355972	0 126877	62
4 365	2 794357	0 229095	0 357864	0 128769	63
4 365	2 77821	0 229095	0 359944	0 130849	64
4 365	2 726847	0 229095	0 366724	0 137629	65
4 365	2 723075	0 229095	0 367232	0 138137	66
4 365	2 711586	0 229095	0 368788	0 139693	67
4 365	2 691617	0 229095	0 371524	0 142429	68
4 365	2 665838	0 229095	0 375117	0 146021	69
4 365	2 646524	0 229095	0 377854	0 148759	70
4 365	2 631604	0 229095	0 379996	0 150901	71
4 365	2 623757	0 229095	0 381133	0 152038	72
4 365	2 597779	0 229095	0 384944	0 155849	73
4 365	2 58432	0 229095	0 386949	0 157854	74
4 365	2 565444	0 229095	0 389796	0 160701	75
4 365	2 556957	0 229095	0 39109	0 161995	76
4 365	2 553669	0 229095	0 391593	0 162498	77
4 365	2 523658	0 229095	0 39625	0 167155	78
4 365	2 510737	0 229095	0 398289	0 169194	79
4 365	2 504384	0 229095	0 3993	0 170205	80
4 365	2 485943	0 229095	0 402262	0 173167	81
4 365	2 477934	0 229095	0 403562	0 174467	82
4 365	2 460778	0 229095	0 406376	0 17728	83
4 365	2 449124	0 229095	0 408309	0 179214	84
4 365	2 438078	0 229095	0 410159	0 181064	85
4 365	2 427792	0 229095	0 411897	0 182802	86
4 365	2 414862	0 229095	0 414102	0 185007	87
4 365	2 405573	0 229095	0 415701	0 186606	88
4 365	2 390329	0 229095	0 418352	0 189257	89
4 365	2 379432	0 229095	0 420268	0 191173	90
4 365	2 372933	0 229095	0 421419	0 192324	91
4 365	2 356439	0 229095	0 424369	0 195274	92
4 365	2 354621	0 229095	0 424697	0 195602	93
4 365	2 342813	0 229095	0 426837	0 197742	94
4 365	2 329245	0 229095	0 429324	0 200229	95
4 365	2 346923	0 229095	0 42609	0 196995	96
4 365	2 320159	0 229095	0 431005	0 20191	97
4 365	2 306722	0 229095	0 433516	0 204421	98
4 365	2 295894	0 229095	0 43556	0 206465	99
4 365	2 29375	0 229095	0 435967	0 206872	100
4 365	2 280331	0 229095	0 438533	0 209438	101
4 365	2 255722	0 229095	0 443317	0 214222	102
4 365	2 261552	0 229095	0 442174	0 213079	103
4 365	2 253668	0 229095	0 443721	0 214626	104
4 365	2 245297	0 229095	0 445375	0 21628	105

4 365	2 228643	0 229095	0 448704	0 219608	106
4 365	2 223813	0 229095	0 449678	0 220583	107
4 365	2 2238	0 229095	0 449681	0 220586	108
4 365	2 217787	0 229095	0 4509	0 221805	109
4 365	2 203042	0 229095	0 453918	0 224823	110
4 365	2 202964	0 229095	0 453934	0 224839	111
4 365	2 191652	0 229095	0 456277	0 227182	112
4 365	2 187251	0 229095	0 457195	0 2281	113
4 365	2 174071	0 229095	0 459967	0 230871	114
4 365	2 183109	0 229095	0 458062	0 228967	115
4 365	2 156926	0 229095	0 463623	0 234528	116
4 365	2 148272	0 229095	0 46549	0 236395	117
4 365	2 14306	0 229095	0 466623	0 237527	118
4 365	2 150756	0 229095	0 464953	0 235858	119
4 365	2 14188	0 229095	0 46688	0 237785	120
4 365	2 130167	0 229095	0 469447	0 240352	121
4 365	2 118072	0 229095	0 472127	0 243032	122
4 365	2 108615	0 229095	0 474245	0 24515	123
4 365	2 107539	0 229095	0 474487	0 245392	124
4 365	2 101994	0 229095	0 475739	0 246644	125
4 365	2 098934	0 229095	0 476432	0 247337	126
4 365	2 096005	0 229095	0 477098	0 248003	127
4 365	2 092903	0 229095	0 477805	0 24871	128
4 365	2 087095	0 229095	0 479135	0 25004	129
4 365	2 080934	0 229095	0 480553	0 251458	130
4 365	2 07141	0 229095	0 482763	0 253668	131
4 365	2 070822	0 229095	0 4829	0 253805	132
4 365	2 074182	0 229095	0 482118	0 253023	133
4 365	2 07415	0 229095	0 482125	0 25303	134
4 365	2 067712	0 229095	0 483626	0 254531	135
4 365	2 05294	0 229095	0 487106	0 258011	136
4 365	2 044791	0 229095	0 489048	0 259952	137
4 365	2 035074	0 229095	0 491383	0 262287	138
4 365	2 037838	0 229095	0 490716	0 261621	139
4 365	2 031856	0 229095	0 492161	0 263066	140
4 365	2 023707	0 229095	0 494143	0 265048	141
4 365	2 021429	0 229095	0 494699	0 265604	142
4 365	2 007094	0 229095	0 498233	0 269138	143
4 365	2 012478	0 229095	0 4969	0 267805	144
4 365	2 006778	0 229095	0 498311	0 269216	145
4 365	1 99876	0 229095	0 50031	0 271215	146
4 365	2 002087	0 229095	0 499479	0 270384	147
4 365	1 992736	0 229095	0 501823	0 272728	148
4 365	1 99588	0 229095	0 501032	0 271937	149
4 365	1 984282	0 229095	0 503961	0 274866	150
4 365	1 98	0 229095	0 50505	0 275955	151
4 365	1 977266	0 229095	0 505749	0 276654	152
4 365	1 960042	0 229095	0 510193	0 281098	153
4 365	1 97077	0 229095	0 507416	0 278321	154
4 365	1 956037	0 229095	0 511238	0 282143	155
4 365	1 95418	0 229095	0 511724	0 282629	156
4 365	1 941372	0 229095	0 5151	0 286005	157
4 365	1 942358	0 229095	0 514838	0 285743	158
4 365	1 929659	0 229095	0 518226	0 289131	159
4 365	1 928221	0 229095	0 518613	0 289518	160

4 365	1 928057	0 229095	0 518657	0 289562	161
4 365	1 927542	0 229095	0 518795	0 2897	162
4 365	1 918269	0 229095	0 521303	0 292208	163
4 365	1 916979	0 229095	0 521654	0 292559	164
4 365	1 913374	0 229095	0 522637	0 293542	165
4 365	1 907249	0 229095	0 524315	0 29522	166
4 365	1 905767	0 229095	0 524723	0 295628	167
4 365	1 902259	0 229095	0 525691	0 296596	168
4 365	1 902336	0 229095	0 525669	0 296574	169
4 365	1 898949	0 229095	0 526607	0 297512	170
4 365	1 898241	0 229095	0 526804	0 297708	171
4 365	1 893621	0 229095	0 528089	0 298994	172
4 365	1 890831	0 229095	0 528868	0 299773	173
4 365	1 895201	0 229095	0 527649	0 298553	174
4 365	1 893268	0 229095	0 528187	0 299092	175
4 365	1 880251	0 229095	0 531844	0 302749	176
4 365	1 871003	0 229095	0 534473	0 305378	177
4 365	1 877105	0 229095	0 532735	0 30364	178
4 365	1 863707	0 229095	0 536565	0 30747	179
4 365	1 862724	0 229095	0 536848	0 307753	180
4 365	1 855643	0 229095	0 538897	0 309802	181
4 365	1 861585	0 229095	0 537177	0 308082	182
4 365	1 849346	0 229095	0 540732	0 311637	183
4 365	1 853428	0 229095	0 539541	0 310446	184
4 365	1 84087	0 229095	0 543221	0 314126	185
4 365	1 84457	0 229095	0 542132	0 313037	186
4 365	1 834323	0 229095	0 54516	0 316065	187
4 365	1 835219	0 229095	0 544894	0 315799	188
4 365	1 830341	0 229095	0 546346	0 317251	189
4 365	1 827352	0 229095	0 54724	0 318145	190
4 365	1 8236	0 229095	0 548366	0 319271	191
4 365	1 822581	0 229095	0 548672	0 319577	192
4 365	1 81622	0 229095	0 550594	0 321499	193
4 365	1 819662	0 229095	0 549553	0 320458	194
4 365	1 814342	0 229095	0 551164	0 322069	195
4 365	1 808925	0 229095	0 552814	0 323719	196
4 365	1 807449	0 229095	0 553266	0 324171	197
4 365	1 802704	0 229095	0 554722	0 325627	198
4 365	1 794541	0 229095	0 557246	0 328151	199
4 365	1 79294	0 229095	0 557743	0 328648	200
4 365	1 799526	0 229095	0 555702	0 326607	201
4 365	1 791437	0 229095	0 558211	0 329116	202
4 365	1 792547	0 229095	0 557865	0 32877	203
4 365	1 787839	0 229095	0 559334	0 330239	204
4 365	1 795177	0 229095	0 557048	0 327953	205
4 365	1 787685	0 229095	0 559383	0 330288	206
4 365	1 787258	0 229095	0 559516	0 330421	207
4 365	1 781006	0 229095	0 561481	0 332385	208
4 365	1 779209	0 229095	0 562047	0 332952	209
4 365	1 771939	0 229095	0 564354	0 335258	210
4 365	1 770781	0 229095	0 564722	0 335627	211
4 365	1 764904	0 229095	0 566603	0 337508	212
4 365	1 762534	0 229095	0 567365	0 33827	213
4 365	1 760505	0 229095	0 568019	0 338924	214
4 365	1 759458	0 229095	0 568357	0 339262	215

4 365	1 758076	0 229095	0 568804	0 339709	216
4 365	1 757107	0 229095	0 569117	0 340022	217
4 365	1 753827	0 229095	0 570182	0 341086	218
4 365	1 755865	0 229095	0 56952	0 340425	219
4 365	1 760075	0 229095	0 568158	0 339062	220
4 365	1 755073	0 229095	0 569777	0 340682	221
4 365	1 755189	0 229095	0 569739	0 340644	222
4 365	1 754253	0 229095	0 570043	0 340948	223
4 365	1 74667	0 229095	0 572518	0 343423	224
4 365	1 741389	0 229095	0 574254	0 345159	225
4 365	1 749059	0 229095	0 571736	0 342641	226
4 365	1 747082	0 229095	0 572383	0 343288	227
4 365	1 733366	0 229095	0 576912	0 347817	228
4 365	1 727361	0 229095	0 578918	0 349823	229
4 365	1 738489	0 229095	0 575212	0 346117	230
4 365	1 734961	0 229095	0 576382	0 347287	231
4 365	1 728107	0 229095	0 578668	0 349573	232
4 365	1 72664	0 229095	0 57916	0 350064	233
4 365	1 723902	0 229095	0 580079	0 350984	234
4 365	1 72325	0 229095	0 580299	0 351204	235
4 365	1 719194	0 229095	0 581668	0 352573	236
4 365	1 718849	0 229095	0 581785	0 35269	237
4 365	1 71652	0 229095	0 582574	0 353479	238
4 365	1 711763	0 229095	0 584193	0 355098	239
4 365	1 707032	0 229095	0 585812	0 356717	240
4 365	1 707364	0 229095	0 585698	0 356603	241
4 365	1 709467	0 229095	0 584978	0 355883	242
4 365	1 708167	0 229095	0 585423	0 356328	243
4 365	1 703489	0 229095	0 58703	0 357935	244
4 365	1 703113	0 229095	0 58716	0 358065	245
4 365	1 693341	0 229095	0 590548	0 361453	246
4 365	1 69574	0 229095	0 589713	0 360618	247
4 365	1 691417	0 229095	0 59122	0 362125	248
4 365	1 685121	0 229095	0 593429	0 364334	249
4 365	1 683014	0 229095	0 594172	0 365077	250
4 365	1 687966	0 229095	0 592429	0 363334	251
4 365	1 683815	0 229095	0 593889	0 364794	252
4 365	1 685841	0 229095	0 593176	0 364081	253
4 365	1 684684	0 229095	0 593583	0 364488	254
4 365	1 680731	0 229095	0 594979	0 365884	255
4 365	1 677048	0 229095	0 596286	0 367191	256
4 365	1 678002	0 229095	0 595947	0 366852	257
4 365	1 673434	0 229095	0 597574	0 368478	258
4 365	1 672232	0 229095	0 598003	0 368908	259
4 365	1 66222	0 229095	0 601605	0 37251	260
4 365	1 658022	0 229095	0 603128	0 374033	261
4 365	1 64925	0 229095	0 606336	0 377241	262
4 365	1 652218	0 229095	0 605247	0 376152	263
4 365	1 645195	0 229095	0 607831	0 378736	264
4 365	1 639673	0 229095	0 609878	0 380782	265
4 365	1 640333	0 229095	0 609632	0 380537	266
4 365	1 631393	0 229095	0 612973	0 383878	267
4 365	1 630722	0 229095	0 613225	0 38413	268
4 365	1 631259	0 229095	0 613023	0 383928	269
4 365	1 626366	0 229095	0 614868	0 385773	270

Calculation of clean 'U' values at a flowrate of 10 L/min

Temp Cold in (°C)	Temp Cold out (°C)	Temp Hot in (°C)	Temp Hot out (°C)	Temp Co - Ci (°C)	Temp Log mean	mcp/AF	U-value	Time
18.56	22.31	26.07	21.67	3.75	3.424726	2.228	2.439612	1
20.34	25.44	30.5	24.55	5.1	4.621981	2.228	2.458426	2
23.24	29.06	34.73	27.95	5.82	5.175168	2.228	2.505611	3
26.25	32.7	38.84	31.41	6.45	5.635806	2.228	2.549875	4
29.48	36.15	42.38	34.72	6.67	5.72073	2.228	2.597703	5
32.84	39.9	46.11	38.33	7.06	5.842608	2.228	2.692236	6
36.15	43.29	49.67	41.64	7.14	5.923861	2.228	2.685397	7
39.31	46.83	53.31	44.97	7.52	6.060758	2.228	2.764433	8
42.51	50.33	57.15	48.3	7.82	6.290953	2.228	2.769526	9
45.74	53.88	60.92	51.7	8.14	6.485019	2.228	2.796587	10
48.93	57.35	64.39	54.97	8.42	6.527238	2.228	2.874073	11
52.02	60.3	67.19	57.89	8.28	6.366387	2.228	2.897694	12
54.84	63.15	69.96	60.67	8.31	6.307316	2.228	2.935429	13
57.51	65.79	72.48	63.22	8.28	6.18707	2.228	2.981676	14
59.83	68.06	74.65	65.47	8.23	6.102681	2.228	3.004653	15
62.07	70.29	76.85	67.64	8.22	6.051509	2.228	3.026379	16
64.15	72.27	78.66	69.64	8.12	5.928619	2.228	3.05153	17
65.98	73.92	80.12	71.35	7.94	5.775063	2.228	3.063226	18
67.57	75.39	81.45	72.81	7.82	5.640069	2.228	3.08914	19
68.91	77.27	81.69	73.86	8.36	4.679999	2.228	3.979932	20
69.86	77.28	81.1	74.19	7.42	4.069675	2.228	4.062181	21
70.38	77.53	81.2	74.49	7.15	3.885849	2.228	4.099542	22
70.61	77.69	81.26	74.72	7.08	3.833664	2.228	4.114665	23
70.85	77.87	81.27	74.89	7.02	3.710806	2.228	4.214868	24
70.93	77.95	81.36	74.89	7.02	3.678149	2.228	4.252291	25
70.93	77.75	80.93	74.81	6.82	3.518402	2.228	4.318711	26
71	78.11	81.4	75.01	7.11	3.638134	2.228	4.354178	27
71.05	78.07	81.35	74.95	7.02	3.581059	2.228	4.367579	28
71.11	78	81.02	74.98	6.89	3.427451	2.228	4.478815	29
71.07	78.01	81.3	74.99	6.94	3.595806	2.228	4.300098	30
71.09	78.03	81.21	74.93	6.94	3.499634	2.228	4.418268	31
71.12	78.05	81.2	75.02	6.93	3.511662	2.228	4.39679	32
71.12	78.14	81.39	75.03	7.02	3.569837	2.228	4.381309	33
71.21	77.98	81.05	74.99	6.77	3.412699	2.228	4.419833	34
71.16	78.02	81.21	75.02	6.86	3.514362	2.228	4.349034	35
71.11	77.9	81.04	74.93	6.79	3.468899	2.228	4.361073	36
71.17	78.1	81.43	75.09	6.93	3.616984	2.228	4.268762	37
71.28	78.04	81.07	75.02	6.76	3.372553	2.228	4.465839	38
71.29	78.15	81.48	75.19	6.86	3.607498	2.228	4.236754	39
71.36	78.12	81.21	75.16	6.76	3.432771	2.228	4.387499	40
71.37	78.16	81.18	75.16	6.79	3.39044	2.228	4.461994	41
71.31	78.01	81.14	75.05	6.7	3.425954	2.228	4.35721	42
71.28	78.02	81.17	75.04	6.74	3.446006	2.228	4.357717	43
71.21	78.06	81.22	75.05	6.85	3.488963	2.228	4.374309	44

Average U- value 4.365