

USE OF DETERGENT IN WOOL SCOURING

Wool scouring processes have been the subject of considerable analysis in recent years. However the necessary amount of detergent needed is still controlled by the personal judgement of experienced operators. No detergent measurement procedure, effective for commercial operation, is known. Optimal control of addition of detergent would naturally lead to reduced cost. This report is an attempt to analyse the detergent requirement of a wool scouring process with suggestions for further work.

1. Introduction

This problem seeks the estimation of the correct rate of detergent addition to a wool scouring machine under varying conditions.

Some detailed discussion of the scouring process can be found in the references, particularly Bateup (1986), Christoe (1986) and Warner (1986). A linear model describing the variation in time of dirt and grease content of a wool scour is discussed by Early (1978), and a simpler version by Wood (1967), while Warner (1981) considers low water flow using equilibrium equations.

The conventional method of aqueous wool scouring utilises a five bowl scour train (see figure 1). Wool, with dirt and grease, is added continuously to bowl 1, which also contains water and detergent. As the wool is moved through bowl 1, some dirt and grease is removed, and cleaner, less greasy wool is transferred continuously to bowl 2 where more detergent is added and more dirt and grease is removed from the wool. Grease laden liquor is removed from the first two bowls for woolgrease recovery, and the deficit of water in these bowls is made up by a flowback system of water from the subsequent bowls in the train. In the scouring system under consideration, the water flow in the scour has been modified to effectively isolate the first two bowls of the scour from the rest of the process, with make up water being relatively clean rinse water from the final rinse bowl. It is in these first two bowls that the bulk of the cleaning of the wool takes place, and the progressively cleaner wool then moves through bowls 3, 4, and 5.

Difficulties are experienced in accurately estimating the quantity of detergent required to adequately wash the wool, and this has economic and some environmental implications. Apart from the detergent cost, excess detergent tends to cause matting of the wool, thus lowering its value (*i.e.* ultimate profit), while insufficient detergent leaves dirty wool (of reduced value) which cannot be rewashed due to the matting problem.

There appears to be no published attempt to calculate the detergent requirement of a scour either under steady state conditions or under the effect of step changes in the feed rate of detergent consuming contaminants. This could be in part due to the difficulty of measuring these contaminants, in the long term, under process conditions. However, an understanding of the effects of these changes on the equilibrium of the system is a first step to allowing the making of considered decisions on the operation of the process.

There are several factors which are believed to contribute to the rate of detergent consumption by the scour:

- The rate of addition of dirt to the scour
- The particle size distribution of the dirt
- The rate of addition of woolgrease to the scour
- The particle size of the molten and emulsified woolgrease particles
- The rate of removal of “free” detergent from the system

Under ideal running conditions of a consistent wool blend, all of the above parameters could be considered to be constant, and by trial and error the removal of excess dirt and grease, and the addition of detergent, could be balanced to give a consistent product. This is the *art* of scouring. Unfortunately the *art* has been found lacking due largely to the fact that the removal of excess contaminants by the external woolgrease recovery loop does not appear to be sufficient at times, and, to compensate, large volumes of greasy, detergent bearing water are discharged instantaneously from the system. In addition, production is punctuated at regular intervals by a change of wool type. On a change of type the dirt content of the wool can vary within the range of 5.0% to 20.0% and the woolgrease content of the wool can be between 7.0% and 18.0% and almost all combinations of the two parameters. The production rate of the wool can vary also, although this may not be of great significance if sufficient detergent is present.

According to the *art*, there are one or two criteria which must be satisfied in order that the scour liquor is in a “condition” accepted as suitable to produce a clean grease free product of good colour.

- The detergent concentration must never fall below a critical micelle concentration
- The grease content of the first scour bowl should lie in the range 1.5% to 2.0%

- Excess “free” detergent can have a deleterious effect on the wool, specially in the second bowl

2. Some comments on the scouring process

A typical bowl arrangement is illustrated in figure 1. When wool enters bowl 1, up to 80% of the grease and dirt is removed in this bowl. After passage through a squeeze press the wool continues into the second bowl, taking with it the remaining adhering contaminants, plus up to 65% of its own weight of water, having the same composition as the first bowl liquor. This sequence is repeated down the scour train.

In the first bowl, woolgrease is liquefied by the elevated liquor temperature (65°C) of the scour liquor, and is stripped from the fibre by the emulsifying power of the detergent. Detergent is added continuously via metering pumps, at a nominal rate dependent upon the clean production rate of the machine. Dirt, once released from the materials causing it to adhere to the fibre surface, is dispersed by the detergent, and settles into hoppers below the bowls for removal.

Removal of dirt and greasy liquor from bowls 1 and 2 is via a series of automatic valves which allow the withdrawal of liquor in adjustable ratios between the two bowls for transport to the woolgrease recovery plant. Initially dirt, with associated absorbed grease and detergent is removed in a settling tank, and the settled sludge removed from the system. The supernatant liquor is passed to the centrifuges for recovering of woolgrease.

The woolgrease recovery centrifuges are 3-stage machines which produce an enriched oil in water emulsion, which passes to a further stage for dewatering, a solids rich phase which is discharged from the system, and a “middle phase” which is grease and solids deficient relative to the feed liquor. This liquor can be returned in whole or in part to the first bowl of the scour to aid in the control of the “condition” of the scour, and also to conserve energy, water and detergent. If the “condition” of the scour is judged subjectively to be unsatisfactory, then large quantities of water are dumped manually from the first two scour bowls and some detergent is added to compensate for the sudden dilution.

Manual intervention in the scouring process, especially with respect to patterns of water usage and operator induced changes in production rate, ensure that the process rarely achieves a state of equilibrium. Couple this with step changes in contaminant loading due to different wool-types (these can change as frequently as 2 hourly intervals), and you have a system in which the only constant is the rate of detergent addition. Ideally it would be nice to be able to manipulate the variables in such a way that equilibrium exists within the scour,

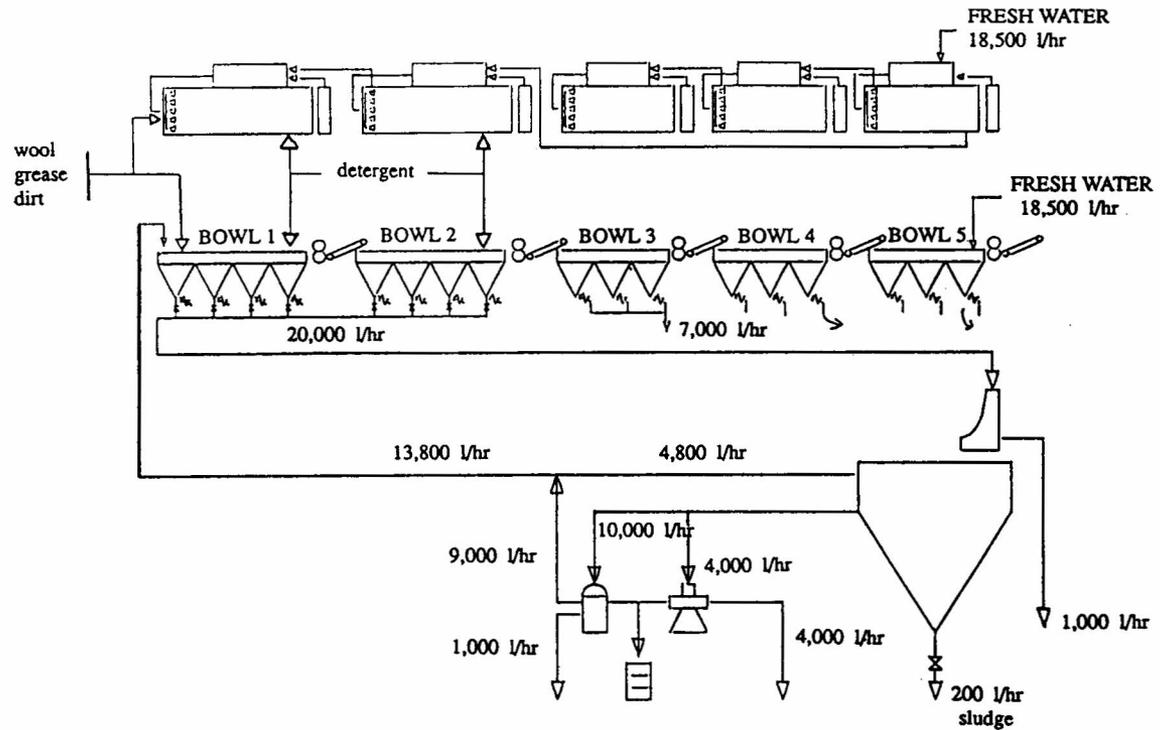


Figure 1: Illustration of the scouring process

with inputs balanced by outputs, whilst at the same time having some means of determining the correct rate of addition for the detergent.

3. Model of the scouring process

This model describes the rates at which wool, water, detergent, dirt and grease move between bowls centrifuge and recovery paths in the scouring process.

For simplicity we first consider bowls 1 and 2 where all the detergent is added and most of the "cleaning" occurs. Bowls 3, 4, 5 are more concerned with rinsing.

Assumptions:

- Wool enters and leaves both tanks at a constant rate with no loss.
- Wool contains a constant amount of grease and light grease per kg. Scouring efficiency h is the same for grease and light grease in each bowl.

- The grease content of the water leaving each bowl in the wool is negligible compared with the remaining grease in the wool itself.
- The delay involved in the extraction of the greasy liquor to the centrifuge and the return to bowl 1 is negligible.
- Detergent associated with grease and light grease, remains associated in the same proportions in the centrifuge operation.
- Detergent concentrations are sufficient such that there is “free” detergent as well as that associated with grease and light grease.

We use the following :

Constants

W	rate of wool feed (kg/hr)
γ_1	fraction of grease in wool (kg/kg)
γ_2	fraction of light grease in wool (kg/kg)
γ_3	fraction of dirt in wool (kg/kg)
a_i	rate of detergent entering bowl i (kg/hr)
V_i	volume of bowl i (litres)
F_{21}	flow rate from bowl 2 to bowl 1 (l/hr)
F_{ci}	flow rate of liquor from bowl i to centrifuge
FB_c	flow rate to bowl 1 from centrifuge (l/hr)
F_2	flow rate of clean water to bowl 2
r	water content in squeezed wool (l/kg)
η_1, η_2, η_3	grease, light grease and dirt scouring efficiency
s_1	detergent associated with grease (kg/kg)
s_2	detergent associated with light grease (kg/kg)
σ_0	fraction of centrifuge flow returned to bowl 1
σ_1	fraction of C.F. directly dumped
σ_2	fraction of C.F. dumped after grease extraction
$\sigma =$	$\sigma_1 + \sigma_2$
$\sigma_T =$	$\sigma_0 + \sigma_1 + \sigma_2$

Variables

C_{si}	concentration of detergent in bowl i (kg/l)
C_{Gi}	concentration of grease in bowl i
C_{gi}	concentration of light grease in bowl i

Entering bowl 1 is

<i>Wool</i>		W (kg/hr)
Containing:	grease	$\gamma_1 W$ (kg/hr)
	light grease	$\gamma_2 W$ (kg/hr)
	dirt	$\gamma_3 W$ (kg/hr)

Detergent a_1 (kg/hr)

Liquor from bowl 2 F_{21} (l/hr)

Containing:	detergent	$F_{21} C_{s2}$
	grease	$F_{21} C_{G2}$
	light grease	$F_{21} C_{g2}$

Centrifuge return FB_c (l/hr)

Containing:	detergent	
	grease	
	light grease	

Leaving bowl 1 is

<i>Wool</i>		W (kg/hr)
Containing:	water	rW (negligible?)
	detergent	$C_{s1} rW$ (negligible?)
	grease	$\eta_1 \gamma_1 W$
	light grease	$\eta_2 \gamma_2 W$
	dirt	$\eta_3 \gamma_3 W$

<i>Liquor</i>		F_{c1} (l/hr)
Containing:	detergent	$F_{c1} C_{s1}$ (kg/hr)
	grease	$F_{c1} C_{G1}$
	light grease	$F_{c1} C_{g1}$

Entering bowl 2 is

<i>Wool</i>		W (kg/hr)
Containing:	water	rW (negligible?)
	detergent	$C_{s1} rW$ (negligible?)
	grease	$\eta_1 \gamma_1 W$
	light grease	$\eta_2 \gamma_2 W$

Detergent a_2 (kg/hr)

Clean water F_2 (l/hr)

Leaving bowl 2 is

<i>Wool</i>		W (kg/hr)
Containing:	water	rW (negligible?)
	detergent	$C_{s2}rW$ (negligible?)
	grease	$\eta_1\gamma_1W$
	light grease	$\eta_2\gamma_2W$

Liquor to bowl 1

Containing:		F_{21} (l/hr)
	detergent	$F_{21}C_{s2}$ (kg/hr)
	grease	$F_{21}C_{G2}$
	light grease	$F_{21}C_{g2}$

Liquor to centrifuge

Containing:		F_{c2} (l/hr)
	detergent	$F_{c2}C_{s2}$ (kg/hr)
	grease	$F_{c2}C_{G2}$
	light grease	$F_{c2}C_{g2}$
Balance of flow rate		$F_2 = rW + F_{c1} + F_{c2} - FB_c$

Centrifuge operation

Input		$F_{c1} + F_{c2}$ (l/hr)
Containing:	detergent	$F_{c1}C_{s1} + F_{c2}C_{s2}$ (kg/hr)
	grease	$F_{c1}C_{G1} + F_{c2}C_{G2}$
	light grease	$F_{c1}C_{g1} + F_{c2}C_{g2}$

Of this, a fraction

σ_0 is returned directly to bowl 1
 σ_1 is dumped
 σ_2 has grease (and associated detergent) extracted and is dumped
 $1 - \sigma_T = 1 - \sigma_0 - \sigma_1 - \sigma_2$ has grease (and associated detergent) extracted and is returned to bowl 1.

Water $FB_c = (1 - \sigma)(F_{c1} + F_{c2})$ l/hr returned to bowl 1
 where $\sigma = \sigma_1 + \sigma_2$

Grease $(1 - \sigma_0)(F_{c1}C_{G1} + F_{c2}C_{G2})$ is extracted or dumped
 $\sigma_0(F_{c1}C_{G1} + F_{c2}C_{G2})$ is returned to bowl 1

Light grease $\sigma(F_{c1}C_{g1} + F_{c2}C_{g2})$ is dumped
 $(1 - \sigma)(F_{c1}C_{g1} + F_{c2}C_{g2})$ is returned to bowl 1

Detergent to bowl 1 from centrifuge
 $F_{c1}C_{s1} + F_{c2}C_{s2}$ leaves bowls 1 and 2

Of this, $s_1(F_{c1}C_{G1} + F_{c2}C_{G2})$ is associated with grease
 $s_2(F_{c1}C_{g1} + F_{c2}C_{g2})$ is associated with light grease

Free detergent =

$$F_{c1}C_{s1} + F_{c2}C_{s2} - s_1(F_{c1}C_{G1} + F_{c2}C_{G2}) - s_2(F_{c1}C_{g1} + F_{c2}C_{g2}) \geq 0$$

Detergent return is $(1 - \sigma) \times$ free detergent
 $+s_1 \times$ grease returned
 $+s_2 \times$ light grease returned

$$= (1 - \sigma)[F_{c1}C_{s1} + F_{c2}C_{s2} - s_1(F_{c1}C_{G1} + F_{c2}C_{G2}) - s_2(F_{c1}C_{g1} + F_{c2}C_{g2})] \\ + s_1\sigma_0(F_{c1}C_{G1} + F_{c2}C_{G2}) \\ + s_2(1 - \sigma)(F_{c1}C_{g1} + F_{c2}C_{g2})$$

$$= (1 - \sigma)[F_{c1}C_{s1} + F_{c2}C_{s2}] - (1 - \sigma_0 - \sigma)s_1(F_{c1}C_{G1} + F_{c2}C_{G2})$$

The concentration of detergent in bowls 1 and 2 satisfies

$$V_1 \frac{dC_{s1}}{dt} = a_1 + F_{21}C_{s2} + (1 - \sigma)[F_{c1}C_{s1} + F_{c2}C_{s2}] \\ - s_1(1 - \sigma_T)(F_{c1}C_{G1} + F_{c2}C_{G2}) - rWC_{s1} - F_{c1}C_{s1}$$

and

$$V_2 \frac{dC_{s2}}{dt} = a_2 + rWC_{s1} - rWC_{s2} - F_{21}C_{s2} - F_{c2}C_{s2}$$

If terms involving rW (the water content of squeezed wool) are neglected, these equations simplify to

$$V_1 \frac{dC_{s1}}{dt} = a_1 - \sigma F_{c1}C_{s1} + (F_{21} + (1 - \sigma)F_{c2})C_{s2} - s_1(1 - \sigma_T)F_{c1}C_{G1} - s_1(1 - \sigma_T)F_{c2}C_{G2} \quad (1)$$

$$V_2 \frac{dC_{s2}}{dt} = a_2 - (F_{21} + F_{c2})C_{s2} \quad (2)$$

Equation (2) can be solved directly, giving

$$C_{s2}(t) = A_2 e^{-(F_{21} + F_{c2})t/V_2} + \frac{a_2}{F_{21} + F_{c2}} \quad (3)$$

The concentration of grease in bowls 1 and 2 satisfies

$$V_1 \frac{dC_{G1}}{dt} = \gamma_1 W + C_{G2} F_{21} - \eta_1 \gamma_1 W - C_{G1} F_{c1} + \sigma_0 (C_{G1} F_{c1} + C_{G2} F_{c2})$$

$$V_2 \frac{dC_{G2}}{dt} = \eta_1 \gamma_1 W - \eta_2^2 \gamma_1 W - C_{G2} F_{21} - C_{G2} F_{c2}$$

We will assume $\eta_1 = \eta_2 = \eta_3 = \eta$ so that

$$V_1 \frac{dC_{G1}}{dt} = (1 - \eta) \gamma_1 W - F_{c1} (1 - \sigma_0) C_{G1} + (F_{21} + \sigma_0 F_{c2}) C_{G2} \quad (4)$$

$$V_2 \frac{dC_{G2}}{dt} = \eta (1 - \eta) \gamma_1 W - (F_{21} + F_{c2}) C_{G2} \quad (5)$$

Equation (5) thus yields

$$C_{G2}(t) = B_2 e^{-(F_{21} + F_{c2})t/V_2} + \frac{\eta(1 - \eta) \gamma_1 W}{F_{21} + F_{c2}} \quad (6)$$

whilst (6) and (4) give

$$C_{G1}(t) = B_1 e^{-F_{c1}(1 - \sigma_0)t/V_1} + B_3 e^{-(F_{21} + F_{c2})t/V_2} \quad (7)$$

and hence the solution for C_{s1}

The concentration of light grease in bowls 1 and 2 satisfies

$$V_1 \frac{dC_{g1}}{dt} = \gamma_2 W + C_{g2} F_{21} + (1 - \sigma)(C_{g1} F_{c1} + C_{g2} F_{c2}) - \eta \gamma_2 W - C_{g1} F_{c1}$$

$$V_2 \frac{dC_{g2}}{dt} = \eta \gamma_2 W - \eta^2 \gamma_2 W - C_{g2} F_{21} - C_{g2} F_{c2}$$

or, after re-arrangement,

$$V_1 \frac{dC_{g1}}{dt} = (1 - \eta) \gamma_2 W - \sigma F_{c1} C_{g1} + (F_{21} + (1 - \sigma) F_{c2}) C_{g2} \quad (8)$$

$$V_2 \frac{dC_{g2}}{dt} = \eta(1 - \eta) \gamma_2 W - (F_{21} + F_{c2}) C_{g2} \quad (9)$$

Equation (9) has the solution

$$C_{g2}(t) = A_2 e^{-(F_{21} + F_{c2})t/V_2} + \frac{\eta(1 - \eta) \gamma_2 W}{F_{21} + F_{c2}} \quad (10)$$

whilst (10) and (8) give

$$C_{g1}(t) = A_5 e^{-\sigma F_{c1}t/V_1} + A_3 e^{-(F_{21} + F_{c2})t/V_2} + A_4 \quad (11)$$

Equations (1, 2) represent the rate of change of concentrations of detergent in bowls 1 and 2. With constant input, these linear equations have an equilibrium solution which can be found as the limit of the time varying solution as t increases. Alternatively the equilibrium solution can be found from the solution of equations (1, 2, 4, 5, 8, 9) after the derivatives are replaced by zero.

4. Detergent requirement for removal of dirt and grease

This section contains a simple direct calculation of the detergent required at any time. The calculation is based on the mechanism of detergent action, and it gives an upper limit to the amount of grease that a volume of detergent can remove. The following data will be used.

Dirt particle size:

Geometric mean diameter	13.0 micrometers
standard deviation	2.0
distribution	log normal

Wool grease particle size:

Geometric diameter	3-8 micrometers
distribution	not known

Detergent molecules are bipolar with one end hydrophobic, the other hydrophilic. The detergent molecules "coat" dirt particles and grease globules and the hydrophilic ends float the particles "free". Consider a grease particle of diameter $8\mu m$ having surface area

$$4\pi r^2 = 4\pi(4 \times 10^{-6})^2(\text{m}^2) \simeq 2.01 \times 10^{-10}\text{m}^2$$

The area occupied by a detergent molecule on the surface of a particle is 50\AA^2 , that is $50 \times (10^{-10})^2 = 50 \times 10^{-20}(\text{m}^2)$. Thus the number of detergent molecules that can congregate around a grease particle of $8\mu m$ diameter is approximately $\frac{2.01 \times 10^{-10}}{50 \times 10^{-20}} = 4.02 \times 10^4$ molecules. The mass of detergent surrounding this grease particle is calculated from molecular weight (740) and Avogadro's number N :

1 molecule has mass $\frac{1.008}{N} \times 740$ gm so 4.02×10^8 molecules have total mass

$$\frac{1.008 \times 740 \times 4.02 \times 10^8}{6.025 \times 10^{23}} = 4.98 \times 10^{-13}\text{gm}$$

The mass of such a grease particle with specific gravity 0.97 is

$$\frac{4}{3}\pi(4 \times 10^{-6})^3 \times 0.97 \simeq 2.6 \times 10^{-10}\text{gm}$$

and thus the ratio {mass of grease: mass of detergent} $\simeq 525/1$

This high ratio is not achieved in practice: the ratios are generally found to be about 6/1 for greasy wool, 12/1 for clean wool, and 20/1 for best lambswool.

Our model of detergent action is oversimplified and does not take account of steric effects. We assumed each grease particle is surrounded by only one layer of detergent molecules, and we have not allowed for the required micelle concentration. The numerical result is an under estimate, but it raises the question of whether a more realistic model could lead to an effective simple calculation.

5. A simple non linear model

It is interesting to consider the effect of some nonlinear terms on the stability of solution of the state equations. The following simple nonlinear model, developed during the course of the meeting, does indeed exhibit stability.

Let x be the detergent concentration and y the concentration of dirty material (dirt and grease). If we assume that the removal of detergent is partly dependent on the proportion of dirty material removed and on the concentration of detergent available for the removal, then in bowl 1

$$\frac{dx}{dt} = a_1 - x(k_2 + k_3y) \quad (12)$$

$$\frac{dy}{dt} = k_4 - y(k_5 + k_3x) \quad (13)$$

where a_1 represents the rate of addition of detergent
 k_2x represents the nett rate of removal of detergent in liquor
 k_3y represents the nett rate of removal of detergent with dirty material
 k_4 represents the rate of addition of dirty material with wool
 k_5y represents the nett rate of removal of dirty material in liquor

Equilibrium occurs when $\frac{dx}{dt} = \frac{dy}{dt} = 0$, that is when

$$x(k_2 + k_3y) = a_1 \quad (14)$$

$$y(k_5 + k_3x) = k_4 \quad (15)$$

On eliminating y , we have

$$k_2k_3x^2 + (k_2k_5 + k_3k_4 - a_1k_3)x - a_1k_5 = 0 \quad (16)$$

with solution

$$x = \frac{-\beta}{2\alpha} \pm \sqrt{\left(\frac{\beta}{2\alpha}\right)^2 + \frac{\gamma}{\alpha}} \quad (17)$$

where

$$-\frac{\beta}{2\alpha} = \frac{1}{2} \left(\frac{a_1}{k_2} - \frac{k_5}{k_3} - \frac{k_4}{k_2} \right), \quad \frac{\gamma}{\alpha} = \frac{a_1 k_5}{k_2 k_3} \quad (18)$$

The corresponding results with x eliminated are

$$k_3 k_5 y^2 + (k_2 k_5 + k_3 a_1 - k_4 k_3) y - k_2 k_4 = 0 \quad (19)$$

$$y = -\frac{B}{2A} \pm \sqrt{\left(\frac{B}{2A}\right)^2 + \frac{C}{A}} \quad (20)$$

$$-\frac{B}{2A} = \frac{1}{2} \left(\frac{k_4}{k_5} - \frac{k_2}{k_3} - \frac{a_1}{k_5} \right), \quad \frac{C}{A} = \frac{k_4 k_2}{k_5 k_3} \quad (21)$$

The quadratic equations (16) and (19) each have one positive and one negative root and the positive pair of roots are physically significant. Denoting this equilibrium pair of values by (x_0, y_0) , and using a change of variable $X = x - x_0$, $Y = y - y_0$, equations (12) and (13) become:

$$\begin{aligned} \frac{dX}{dt} &= -k_2(X + x_0) - k_3(X + x_0)(Y + y_0) + a_1 \\ &= -k_2X - k_3y_0X - k_3x_0Y + (a_1 - k_2x_0 - k_3x_0y_0) - k_3XY \\ \frac{dY}{dt} &= -k_5(Y + y_0) - k_3(X + x_0)(Y + y_0) + k_4 \\ &= -k_3y_0X - (k_5 + k_3x_0)Y + (k_4 - k_5y_0 - k_3x_0y_0) - k_3XY \end{aligned}$$

Since $(X, Y) = (0, 0)$ is an equilibrium point, then

$$(a_1 - k_2x_0 - k_3x_0y_0) = 0 = (k_4 - k_5y_0 - k_3x_0y_0)$$

Therefore

$$\frac{dX}{dt} = -(k_2 + k_3y_0)X - k_3x_0Y - k_3XY \quad (22)$$

$$\frac{dY}{dt} = -(k_3y_0)X - (k_5 + k_3x_0)Y - k_3XY \quad (23)$$

Consider now the linear system

$$\frac{d\mathbf{v}}{dt} = A\mathbf{v} \quad (24)$$

where

$$\mathbf{v} = \begin{pmatrix} X \\ Y \end{pmatrix}, \quad A = \begin{pmatrix} -k_2 - k_3y_0 & -k_3x_0 \\ -k_3y_0 & -k_5 - k_3x_0 \end{pmatrix}$$

Since the trace of A is negative and the determinant of A is positive, then the eigenvalues of A are real and negative, or complex conjugate with negative real part. The system is therefore stable and the critical point $(0, 0)$ is a node or a focus. In addition

$$\begin{pmatrix} -k_2 - k_3y_0 & -k_3x_0 \\ -k_3y_0 & -k_5 - k_3x_0 \end{pmatrix}$$

is non-singular,

$$\frac{\partial}{\partial x} (-k_3XY) \quad \text{and} \quad \frac{\partial}{\partial Y} (-k_3XY) \quad \text{are continuous}$$

and

$$\lim_{X, Y \rightarrow 0, 0} \frac{-k_3XY}{\sqrt{x^2 + Y^2}} = 0$$

and therefore the nonlinear system (22) and (23) has the same behaviour near $(0,0)$ as the linear system (24). Therefore the nonlinear system (12) and (13) has a stable node or a stable focus at the equilibrium point (x_0, y_0)

6. A control model to predict detergent need

The result needed from analysis of this problem is to ensure the use of the optimal amount of detergent for the process. This section proposes a control process using the differential equation model of Section 3 to predict the amount of free detergent needed. Remember, the amount of free detergent in the bowls cannot be readily measured. The control scheme proposed is known as an observer based controller, and has the structure shown in figure 2.

The mass of clean wool being produced by the process is proposed as the measured variable to be used to correct the model for any inaccuracies. The mass flow rate of the clean wool being produced is available as a measured signal, so the total mass of clean wool produced for a given time period is available by integrating or summing this signal.

The system has been implemented in "SIMNON" by Dr. R. D. Bell (1991) of Macquarie University, with very promising results. The "process" was simulated by another version of the model equations. To gain some idea of the behaviour of the system, one simulation run had initial values for free detergent in the

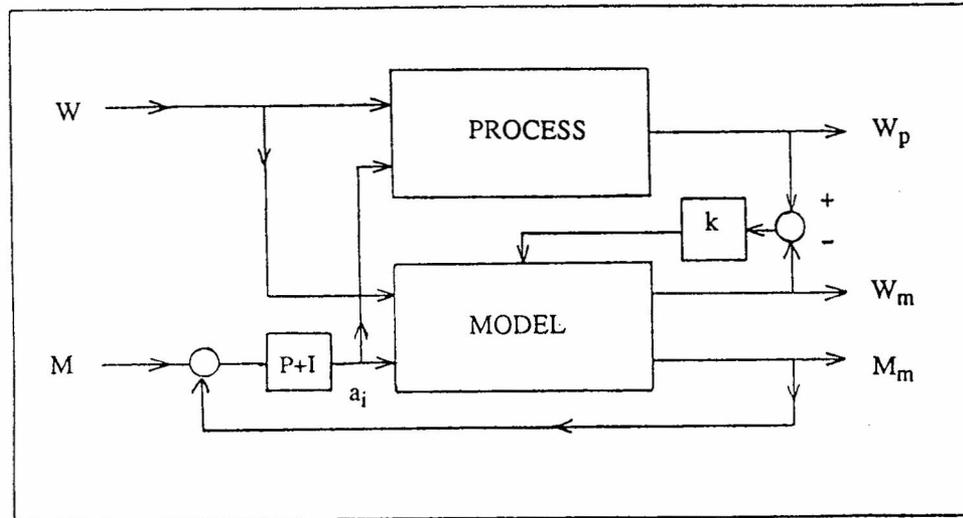


Figure 2: Observer based controller for free detergent

“process” different to that in the “model”. This is typical of the situation that occurs in practice since the amount of free detergent in the process is unknown. The results of the simulation showed that the mass of free detergent in the model eventually tracked the mass in the process. One of the useful features of the simulation is that, unlike the real process, there is easy access to variable values in the process for comparison with the behaviour of the model. It should be emphasised that the complexity of the model does not detract from the overall structure or feasibility of the controller. In fact, as more knowledge of the process is gained it can be incorporated in the model.

7. Conclusions

This report summarizes the combined work of numerous people interested in the wool scouring problem. Regular contributions were made by Peggy Adamson, Rodney Bell, Basil Benjamin, Eric Chu, John Hewitt, Patrick Howden, Duncan Roper, Walter Spunde, John Staniforth and Rod Weber.

Equations relevant to detergent need of a wool scouring process have been formulated. The system of linear ordinary differential equations of section 3

could be used to provide estimates of the concentrations of grease, dirt, and detergent at any time, given data for the various rates of addition of wool, grease, dirt and detergent. This somewhat tedious calculation presents no difficulty in principle. The solution of these linear equations is stable, and with constant input, a steady state solution could also be calculated.

An attempt to consider the effect on stability of some non linearity in the equations also leads to stable solutions. It would be useful to develop more realistic nonlinear models, although they would also be larger and more difficult to solve.

The control model of section 6 seems very promising and it is recommended that implementation of an experimental version begin.

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