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Heat Exchanger Fouling and Cleaning:

Fundamentals and Applications

The Balance Between in the Cleaning of Milk Fouling Deposits

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THE BALANCE BETWEEN CHEMICAL AND PHYSICAL EFFECTS
IN THE CLEANING OF MILK FOULING DEPOSITS

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ABSTRACT

Deposits formed on the surface of heat treatment equipment in the dairy industry compromise product quality and process efficiency. Frequent cleaning is needed to ensure consumer safety and optimal process operation. Cleaning solutions generally have a high environmental impact; the need is to minimize their use. We have studied the physics and chemistry of cleaning at two length scales of measurement: (i) the effect of cleaning chemical and water on deposits within a plate heat exchanger (PHE), and (ii) the effect of process variables on small fouled disks. The chemical nature of cleaning of dairy deposits is shown clearly by the effect of using pulses of water within a PHE cleaning cycle: cleaning stops for proteins, in contrast to the cleaning of starch pastes from surfaces. Different modes of cleaning can be identified from cleaning of the disks, and effects of physics and chemistry can be separated to some extent.

INTRODUCTION

Milk Fouling

Dairy products, and milk in particular, have received much attention from researchers, due to the problems caused in both the operation of plant and the possible contamination of product. The chemical composition of the deposit is very different to the composition of the fluid. Two types of deposit are formed when milk undergoes heat treatment; these were termed Type A and Type B deposit by Burton (1988). The former is high in protein content and forms at temperatures of 85°C to 110°C, due to the denaturation and aggregation of proteins (mainly β-lactoglobulin, β-lg). Type B deposit (110-140°C) is mainly composed of calcium and phosphorus, which form inversely soluble salts. Smaller pressure drop increases result from this deposit as the minerals form a thin scale on the surface, but a reduction in heat transfer is observed. Natural fluctuations in fluid composition throughout the year are known to significantly alter the extent and nature of fouling.

The difficulty of storage and cost of using raw milk in research has lead to the use of whey protein concentrate (WPC) by a number of authors (such as Robbins et al, 1999), who obtained reproducible fouling behaviour. The suitability of these solutions to recreate milk fouling experiments over the full temperature range is however debatable since, although a deposit similar to type A from milk is formed, heavy fouling of this type occurs at all temperatures in the range 85-140°C. Robbins et al (1999) reported that, in contrast to WPC processing, milk does not produce a deposit between 100 and 120°C. Also, unlike milk, WPC does not produce a mineral scale at UHT temperatures. Christian et al (2002) studied the influence of composition on fouling, and found that adding calcium and phosphate to WPC significantly changed the fouling pattern, making it similar to milk. However, the relationship between process chemistry and the cleaning of deposits is significantly less well understood.

Cleaning of Dairy Deposits

Deposits formed by milk and other dairy products cannot be removed by water alone. Protein rich deposits are mainly removed by alkaline cleaning solutions and mineral scale by acidic solutions. Industrial equipment is cleaned either using traditional two stage cleaner or more modern single stage cleaners (detergent based alkaline solutions, see Timperley and Smeulders, 1987). The costs incurred through loss of production mean that previous research has been aimed towards optimising cleaning to increase production. However, environmental concerns are increasingly important; effluent disposal is becoming more expensive. Of equal importance is to minimise the waste produced by food process plant.

Investigations on bench scale equipment (Gillham, 1997; Bird, 1993) have established the sequence of steps involved in WPC deposit removal. Three phases are seen: (1) swelling, (2) uniform removal of the swollen deposit and (3) decay; removal of remaining patchy deposits from the surface. During cleaning of a pilot scale PHE pressure values can aid in determination of the cleaning process: (1) often there is a rapid initial decrease in pressure drop (ΔP) when blockages from ports are removed, (2) swelling of the deposit results in an increase is pressure drop, before (3) pressure drop decreases to the clean value. The resulting swollen deposit is more susceptible to fluid shear than the un-swollen deposit, and can be removed from the system. Gillham et al (1999, 2000) studied the effects of flow rate and temperature on each

stage of deposit removal, and showed that flow pulsing could reduce the cleaning time.

Concentration of cleaning chemical affects removal rates, in general increasing the concentration decreases the time to clean (for example, see Gallot-Lavalee et al, 1984). Optimum concentrations have however been reported, as high concentrations (<0.5wt% NaOH) result in a deposit that is less open and more difficult to remove by fluid shear.

Changani (2000) states that, for cleaning WPC deposits from pilot scale PHE, above a certain concentration (0.7wt% NaOH) no significant increase in cleaning rate occurs, so increasing the chemical concentration has no benefit. In industrial cases however, the extent of fouling is often greater and formed over a longer time, therefore these optima may not be relevant after scale-up to industrial equipment.

The aim of the work described here is to develop an understanding of how cleaning occurs, and whether it is possible to optimise it to minimize the amount of environmental impact that cleaning has. Although it is clear from many studies that both physical (flow rate) and chemical effects (cleaning concentration) affect the rate of cleaning, little has been done to separate them. Here we have tried to understanding both types of process using experiments on two length scales.

PLATE HEAT EXCHANGER EXPERIMENTS

Fouling
Initial studies used the pilot scale PHE described in detail in previous work (Robbins et al, 1999) using WPC and modified WPC solutions (with mineral added) as a process fluid to simulate milk fouling. The PHE can heat product at up to UHT conditions and is capable of flow rates up to ca. 210 l/hr. Temperature and pressure sensors at the outlet/inlet of each exchanger section allow measurement of pressure drop and heat transfer coefficient in each section as a function of time. WPC35 powder was obtained from the Carbery Group (Ireland). Initial experiments showed that the experimental procedure resulted in WPC fouling comparable with previous studies.

The PHE was brought to thermal equilibrium at the desired process temperatures and after a minimum of 10 minutes the process flow was diverted to the chosen WPC solution using a three-way valve. Runs were carried out for a maximum of one hour (70 minutes for cleaning concentration and pulse flow investigations) or until the maximum pressure of the system exceeded 6.5 bar.

Cleaning
Standard cleaning runs were carried out using a 0.54 wt% NaOH solution of a single stage cleaner (LQ 32, DiverseyLever), and a fluid outlet temperature of 92 to 103°C. The single stage cleaner contains surfactants and wetting agents, but on protein deposits behaves like sodium hydroxide alone. Cleaning solution was circulated (100 l/hr) until the pressure drop values decreased to approximately 0.3 bar and remained constant to 2 decimal places for 10 minutes. These conditions have been shown successfully to remove a WPC deposit giving repeatedly reproducibly clean results.

In a number of cases, switched flow cleaning was carried out: here the solution passing through the exchanger was varied between cleaning fluid and water. All other factors were kept the same as in the standard protocol for cleaning. During these experiments fluid was switched (by three-way valve) between cleaning agent (0.54wt% NaOH) and water either every 30 minutes or every 10 minutes for two hours, unless the system was clean before this time.

Monitoring
The extent of fouling and cleaning was monitored using pressure and temperature sensors. The data was then interpreted as change in normalised change in pressure drop and the normalised change in fouling resistance for the overall run, in each section of the PHE. Change in pressure drop was calculated by taking the initial and final pressure drop of each section from the fouling graphs and determining the pressure drop for each section.

Effect of switching cleaning agent and water
Christian et al (2002) study the effect of adding mineral to fouling. For modified WPC processed at 150 l/hr, the majority of fouling is essentially proteinaceous, and occurs in the pasteuriser. On cleaning, deposit swells which results in a temporary increase in the pressure drop. Figure 1 shows detailed results, in terms of the pressure drops through the three sections of the heat exchanger: the highest pressure drop is seen in the pasteurizer. During cleaning of the PHE, as shown in Figure 1(a), pressure drop increase occurs in both the pasteuriser and intermediate sections, which are not significantly fouled. Cleaning is complete after about 40 minutes (confirmed by dismantling the equipment). No pressure drop increase occurs in the UHT section: the viscosity of the cleaning agent is not responsible for the pressure increase. It was considered that this effect could be due to:

- chemical effects: i.e. swelling of deposit present in the intermediate section or
- physical effects, rinsing of deposits removed from the pasteuriser section through the rest of the exchanger.

The action of chemical to produce swelling is clear: depending on which of the above ideas is true, it was felt that cleaning chemical might not be necessary throughout the process. If cleaning chemical produces a deposit that is susceptible to fluid shear alone, then reduction in pressure drop will continue even when cleaning chemical is replaced by water. If removal is controlled by fluid shear, the effect of switching to water, after the deposit has become swollen, would be expected to be zero, i.e. cleaning will continue. Equally, any effects will not depend on the fluid type.

Experiments were conducted in which flows of cleaning chemical (0.54wt% NaOH) and water were alternated through the exchanger for periods of 30 minutes and 10 minutes. Results are shown in Figure 1.. Switching of chemicals and water at 30 minute intervals clearly shows the dependence of the cleaning process on chemical action. After the initial 30 minutes circulation of chemicals the pasteuriser section is 87% clean and the intermediate section is 50% clean, in terms of the pressure drop recovery. When, between 30 and 60 minutes, water is circulated through the PHE, Figure 1(b) shows a clear plateau in the intermediate section during this time: the pressure drop reduction stops, i.e. cleaning effectively stops. The deposit remaining at 30 minutes is therefore not removed by fluid shear of water alone and still requires chemical action. Reintroduction of cleaning chemicals at t = 60 minutes restarts cleaning, resulting in a pressure drop decrease in both the pasteuriser and intermediate section.

The behaviour of the system when the fluids are changed after 10 minutes is more difficult to see. In contrast to the 30:30 measurements, the pasteuriser section is not clean after the initial 10 minutes circulation of cleaning chemical. In the first 10 minutes the pressure drop in the pasteuriser increases and then decreases, suggesting that 10 minutes is long enough for swelling and some removal to occur. In this case, during the circulation of water from 10 to 20 minutes, the pressure drop continues to decrease and the percentage clean increases (from 52 to 61%) suggesting that in this stage deposit can be removed by the mechanical action of water.

In contrast, the 10 minutes flow of water between 30 and 40 minutes does not increase the percentage clean: pressure drop remains essentially constant. Some cleaning also occurs during the water rinse between 50 and 60 minutes. The intermediate section is slow to clean; percentage clean values remain below 90% for the first 90 minutes cleaning, increases and decreases in the percentage clean may be due to repeated swelling and removal of deposit during the pulsed regime.

Switching water and cleaning chemical shows clearly that chemical effects predominate during cleaning of this type of deposit from the plate heat exchanger.

OBSERVATION OF THE CLEANING OF DISKS

Experimental method

In parallel work the cleaning of circular disks (26 mm diameter upper diameter and 30mm lower diameter) made of 316 stainless steel was studied: these disks have also being used to study the adhesive and cohesive forces involved in deposition (Liu et al, 2003). Disks were fouled within an insert within the PHE rig. The main section of the insert consisted of a rectangular flow channel (length: 350mm, height: 5mm, width: 50mm), with six holes in one face. A ridge (1mm by 1mm) was milled around the edge of the holes so the disks could be slotted in and easily removed. The disk surface lay flush with the inside surface of the channel.

Clean disks were placed into the PHE insert and connected to the UHT outlet port of the PHE by removing the pipe section that connects the UHT outlet to the cooling section. Fouling runs lasted 120 minutes; the fouling fluid was at 85 C in the test section, giving a deposit that was representative of pasteurizer deposits (Type A). After a run, the fouling rig was carefully disconnected and the disk-containing section isolated. Disks fouled with WPC deposits were removed from the fouling rig. Deposits appeared to be approximately 2 mm thick and formed an even coverage of the disk; they were cream in colour and fluffy in nature. The chemical composition of this deposit was 70-80% protein, 2% calcium and 1% phosphorus (Analytichem, Birmingham), with respect to the dry sample.

The disks were then cleaned within a separate apparatus. The main part of the cleaning rig was a horizontal rectangular flow channel, (height 7 mm and width 32 mm). Type 316 stainless steel, 2mm thickness, was used to for the construction of the rig. The test section, containing the fouled disk, was near the middle of the flow channel. The fouled stainless steel disk fitted into the test section so that the clean surface was flush with the lower inside surface of the channel. The disk was visible through a 3-sided glass section (100 mm length) of the channel; this was permanently fixed to the flow channel with silicon glue. A heat flux sensor, type 20457-3, supplied by Rhopoint Components, Oxted, was fixed in contact with the reverse side of this disk

throughout the experiments. The dimensions of the sensor used were 25mm by 20mm; it therefore covered the majority of the fouled disk area (disk diameter 26 mm). The cleaning of the disk could thus be simultaneously followed optically and by the recovery of heat transfer.

Results

Removal of proteinacous dairy deposits is influenced by a variety of factors: temperature, fluid flow, chemical concentration, chemical type and the amount of deposit present. The complex inter-relationship makes the exact role of each difficult to determine. The force of water alone will not remove these deposits and expensive chemicals are required to remove the deposits. However, fluid motion is required

- to bring the chemical to the deposit surface interface,
- provide shear to detach the soil from the surface and
- to carry the detached deposit out of the system.

Temperature is also an important consideration as increasing the temperature increases the rate of reaction and diffusion as well as altering the viscosity of the liquid.

A series of cleaning experiments were carried in a 3 factorial matrix, (Christian, 2003), the combined influence of the following conditions was investigated:

- temperature (30, 50 and 70°C),
- concentration (0.1, 0.5 and 1.0 wt% NaOH) of a single stage cleaner and
- flow rate (0.7, 1.5 and 2.3 l/min).

The experiments carried out aid in the understanding of deposit removal mechanisms and fully characterise the cleaning behaviour of the WPC deposits produced. Here, only key results are presented. At t = 0 the deposits was contacted with the cleaning solution. There is a reduction in heat transfer coefficient (HTC) due to swelling of the deposit. A minimum HTC is observed in each case. The HTC then recovers back to the initial value and continues to increase to a constant value (U_o). Results in the Figures are expressed as the fouling resistance, R_F, with the standard definition:

$$\frac{1}{U} = \frac{1}{U_o} + R_F \qquad (1)$$

save that the system starts dirty (U) and ends up clean (U_o).

Typical results are shown here to illustrate the effects that are seen. Experiments were found to be reproducible: detail is given in Christian (2004). Figure 2 shows, in terms of the decrease in fouling resistance measured by the heat flux sensor, the effect of both temperature and flow rate. The heat transfer coefficients begin from about

the same point in each Figure; there is often an increase in fouling resistance, due to swelling, followed by decrease to the clean state.

The effect of cleaning temperature is greater than that of flow; at all flow rates the cleaning time decreases from more than 2000 seconds to less than 500 when the temperature is increased from 30 to 70 C. Increasing the flow rate also reduces the cleaning time, but to a lesser amount. Again this demonstrates how the effect of chemistry exceeds that of physical factors in this case.

Closer observation of the types of removal suggests different types of behaviour. Two distinct groups of removal mechanisms are found in visual observation of experiments:

- deposit removal after swelling is chemically dependant, the entire deposit is dissolved into the cleaning solution, and little or no removal of isolated islands is observed
- deposit removal after swelling is dependant on physical factors. Large pieces of the deposit are removed in chunks; here the action of chemical is to weaken the deposit so that it fractures and breaks away from the surface.

Chemical removal dominates above 0.5wt% NaOH (for all flow rate) at temperatures of 50°C and above. However, the lowest flow rate at 30°C also appears to exhibit chemical removal for all concentrations. Physical processes dominate when the chemical concentration is low (or when the reaction is limited by low temperatures) and sufficient forces are applied from the fluid flow.

Examples of the deposit appearance during the two different removal processes are given in Figure 3. The contrast between the deposit and the metal surface makes it difficult to quantify removal, but the different patterns of removal can be seen, in terms of the behavior of chunks in the system. In Figure 3(a) the deposit is shown being removed gradually, whilst in Figure 3(b) cleaning occurs through the removal of large chunks of material. The strength of the deposit is affected by chemical; some quantification of this has been attempted, both by Liu et al (2003) and, using indentation methods, by Ozkan et al (2002). More work will be needed to relate deposit strength to removal.

CONCLUSIONS

A series of experiments have been carried out on different length scales to study the cleaning of proteinaceous deposits formed from whey proteins. On a whole-plant scale, experiments studied whether the action of cleaning chemical could lead to the formation of a deposit which could be removed by fluid shear alone. It was found that cleaning ceased when cleaning chemical was replaced by

water; physical action alone is not able to induce removal in this case.

In separate experiments on the cleaning of small disks, recovery of heat flux was measured at the same time as the surface was observed and filmed. A complex relationship was found between the cleaning behaviour and different process parameters: it is clear that for some circumstances the removal of deposit is via the removal of large chunks by fluid shear, whilst some deposits are removed essentially by chemical dissolution. Further experiments are reported in Christian and Fryer (2004).

Work is underway to study the forces which occur in deposits during cleaning using the micromanipulation method described in Liu et al (2003). Better understanding, both of the factors which influence cleaning and of the forces holding deposits onto surfaces, will be of value to the designers of both process plant and cleaning techniques.
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ACKNOWLEDGEMENTS

REFERENCES

Bird, M. R., (1993), Cleaning of food process plant, *Ph.D. Thesis*, University of Cambridge, U.K.

Burton, H., (1968), Reviews of the progress of dairy science, *Journal of Dairy Research*, 35, 317-330.

Changani, S. D., (2000), An investigation into the fouling and cleaning behavior of dairy deposits , *Ph.D. Thesis*, University of Birmingham, U.K.

Christian, G.K., (2004) *PhD Thesis*, University of Birmingham, U.K.

Christian, G.K., Changani, S.D. and Fryer, P.J. (2002) The effect of adding minerals on fouling from whey protein concentrate: development of a model fouling fluid for a plate heat exchanger. *Transactions of the Institution of Chemical Engineers Part C.*, 80, 231-239

Christian, G.K., and Fryer, P.J. (2004) Investigation in the reduction of chemical waste during cleaning of dairy pasteurisation plants, to be presented at ICEF 9, Montpellier, March 2004.

Gallot-Lavallee, T. Lalande M. & Corrieu G., (1984), Cleaning kinetics modeling of holding tubes fouled during milk pasteurization, *Journal of Food Process Engineering*, 7: 123-142.

Gillham, C. R., (1997), Enhanced cleaning of surfaces fouled by whey protein, *Ph.D. Thesis*, University of Cambridge, UK.

Gillham, C. R., Fryer P. J., Hasting A. M. P & Wilson D. I., (1999), Cleaning-in-place of whey protein fouling deposits: mechanisms controlling cleaning, *Trans IChemE*, 77, C: 127-135.

Gillham, C. R., Fryer P. J. Hasting A. P. M. & Wilson D. I., (2000), Enhanced cleaning of whey proteins soils using pulsed flows, *Journal of Food Engineering*, 46: 199-209.

Liu, W., Christian, G.K., Zhang, Z. and Fryer, P.J. (2002) Development and use of a novel method for measuring the force required to disrupt and remove fouling deposits. *Transactions of the Institution of Chemical Engineers Part C.*, 80, 286-291.

Liu, W., Christian, G.K., Zhang, Z. and Fryer, P.J. (2003) Direct measurement of the forces required to disrupt and remove fouling deposits. *This conference.*

Ozkan, N., Xin, H., and Chen, X.D., (2002) Application of a depth sensing indentation tool to evaluate the mechanical properties of food materials, *Journal of Food Science*, 67: 1814-1820.

Robbins, P. T. Elliot B. L. Fryer P. J. Belmar M. T. & Hasting A. P. M., (1999), A comparison of milk and whey fouling in a pilot scale plate heat exchanger: Implications for modeling and mechanistic studies, *Trans IChemE*, 77, C: 97-106.

Timperley, D. A. & Smeulders C. N. M., (1987), Cleaning of dairy HTST plate heat exchangers: comparison of single- and two-stage procedures, *Journal of the Society of Dairy Technology*, 40, 1: 4-7.
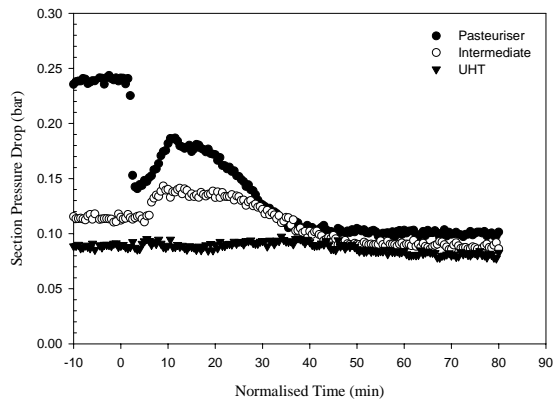
Figure 1(a): Typical pressure drop for the cleaning of WPC deposit with added mineral (Christian et al, 2002) (flow :150 l/hr) from the PHE with 0.54wt% NaOH
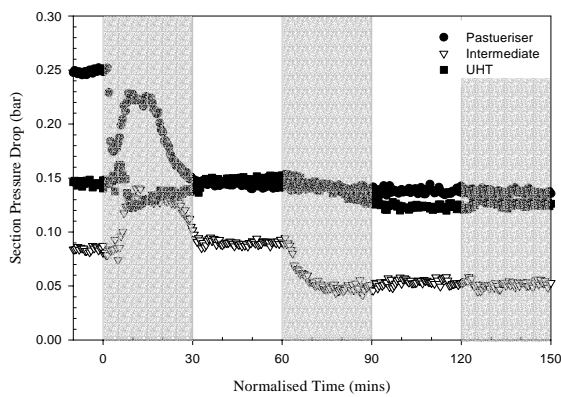

Figure 1 (b): 30:30 switched flow cleaning of deposit with added mineral (Christian et al, 2002) (flow:150 l/hr) from each section of the PHE with 0.54wt% NaOH. Grey areas denote chemical flow.
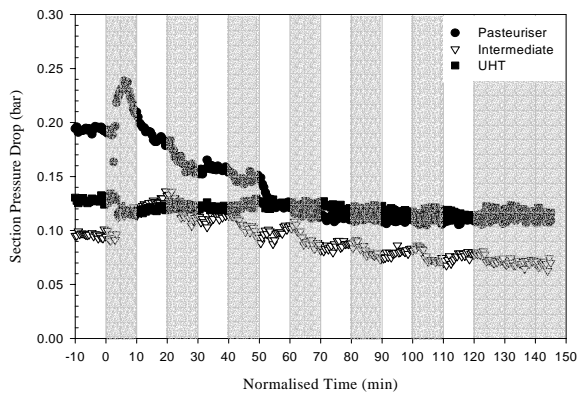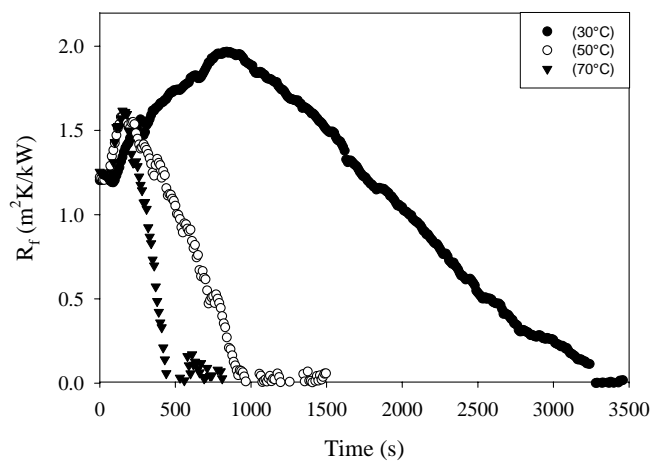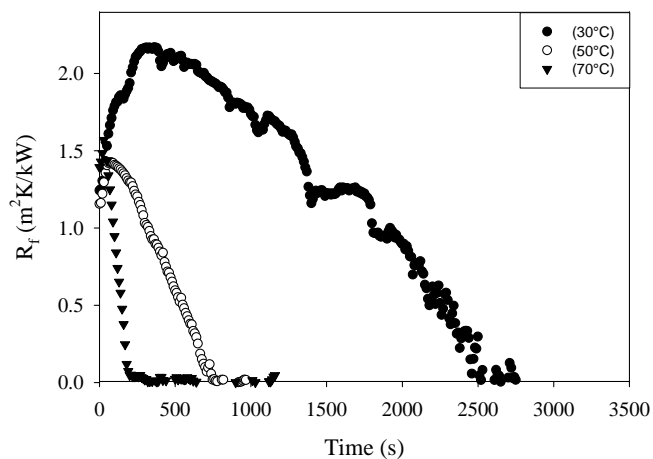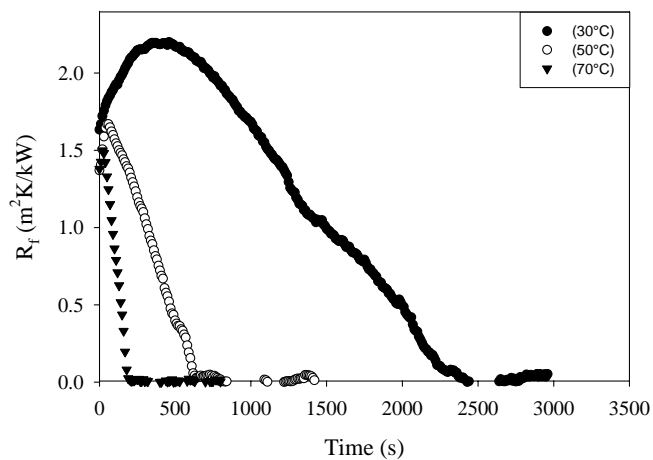

Figure 1(c): 10:10 pulse flow cleaning of deposit with added mineral (Christian et al, 2002) (flow:150 l/hr)from each section of the PHE with 0.54wt% NaOH. Grey areas denote chemical flow.

(a)

(b)

(c)

Figure 2: The effect of temperature on the cleaning of WPC deposits with 0.5 wt% NaOH, at different flow rates (a) 0.7 l/min, (b) 1.5 l/min and (c) 2.3 l/min
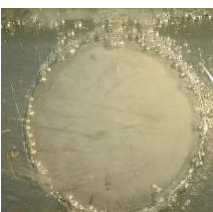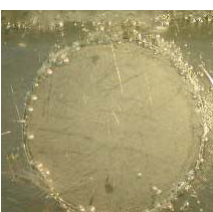
(a)	'Dissolving'		(b)	'Chunk'	
Time (s)	Image	Description	Time (s)	Image	Description
-40		Prior to chemical contact	-40		Prior to chemical contact
90		Action of the chemical uncertain at this point	650		The deposit had thinned and become more gel like
120		The deposit has thinned and a more open structure is visible. Erosion at the edges visible	750		'Chunk' removal has occurred at the front edge
140		A gel-like deposit is formed	780		Further 'chunk' removal
160		Deposit has thinned. A gel layer remains over the majority of the surface	840		A large island of deposit remains
180		Clean	890		Clean

Figure 3 : Images of WPC deposit during cleaning, showing two different classifications: (a) 70C, 2.3 l/min, 1.0 wt% NaOH, (b) 70C, 2.3 l/min, 0.1 wt% NaOH. Deposit first contacts cleaning chemical at t = 0; Flow from left to right