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Challenges in Cleaning: Recent Developments and Future Prospects

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CHALLENGES IN CLEANING: RECENT DEVELOPMENTS AND FUTURE PROSPECTS

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ABSTRACT

There is considerable scope for optimisation of processes subject to fouling by effective management of cleaning. The cleaning cycle starts with the (often-complex) material generated during the fouling cycle. The nature of the deposit determines the most appropriate cleaning method, which can often be optimised significantly via knowledge of the key mechanisms involved in deposit removal. Links between deposit ageing and cleanability need to be established and quantified. There is a wide range of cleaning methods available, and attention is focused here on cleaning-in-place (CIP) techniques. Modern instrumentation allows cleaning (and deposit materials behaviour) to be probed to greater degree than ever before, but the removal technology is only part of the cleaning process. Monitoring and validation of cleaning are equally important, particularly for process plant used in flexible manufacture or subject to batch assurance requirements. Individual sensors are unlikely to meet all monitoring criteria, so future approaches will require reconciliation and interpretation of on-line data from multiple devices. Many industries stand to learn from practice and approaches the food, pharmaceuticals and electronics sectors, where these concepts are well established. The definition of 'cleanliness' will vary from sector to sector, but the needs of minimising environmental impact, accurate monitoring, assurance and suitable training for operators are common to all.

INTRODUCTION - 'CLEANLINESS'

Cleaning, the removal of deposit layers from equipment surfaces, is an essential operation for many industrial processes subject to fouling. Exceptions arise where the surface is replaced rather than renewed for subsequent processing, either because (*i*) the risks posed by re-use are too great, (*ii*) the down-time required for cleaning too large, or (*iii*) the cost of achieving the required state of cleanliness is greater than a replacement strategy. Replacement strategies are seldom employed in the process industries, which indicates that the aim of the cleaning process may simply be to restore process efficiency in terms of heat transfer efficiency or pressure drop. In other sectors, such as the food, biotech and high value chemicals manufacture, issues such as cross-contamination of products, separation of products in flexible manufacturing operations, microbial impacts on hygiene, batch integrity and traceability are extremely important, so that 'cleanliness' includes chemical and biological aspects, usually at the micro-scale. Nano-scale criteria for cleanliness are found in the medical and micro-electronic sectors, where avoidance of molecular contamination (*e.g.* allergen carryover) is the principal aim.

These examples are quoted in order to illustrate that any discussion of cleaning must incorporate a definition of the associated degree of cleanliness desired, as this will dictate the choice of technologies and determine the extent to which cleaning can be verified. The latter point raises the issue of *assurance*, which a major part of validated cleaning processes - defined as

A procedure whose effectiveness has been proved by a documented programme providing a high degree of assurance that a specific cleaning procedure, when performed appropriately, will consistently clean a particular piece of equipment to a pre-determined level of cleanliness. (Crockford, 2003)

In sectors where the aim of cleaning is to restore process performance, assurance may not be ranked strongly: in others, it is essential for compliance with quality criteria. Assurance therefore requires the use of monitors or testing, which need to be planned as a cleaning protocol is developed, as quantitative data will be required in order to prove compliance. Likewise, operators will need to be trained to interpret the data generated - both qualitative and quantitative - in order to identify problems and/or solutions.

Figure 1 illustrates some of the factors to be considered during development of validated cleaning processes in many food and biotech operations. It assumes that the nature of the foulant to be cleaned can be identified *and* is generated consistently, which is not always the case. In the food industry, for instance, seasonal variations create deposit inconsistency, while product changeovers in multi-product plant may require different cleaning strategies for the same equipment.

Furthermore, the technologies employed and emphasis given to particular factors will be determined by the application, the stated 'cleanliness' aims, reproducibility and reliability. A key feature of the Figure is that cleaning, possibly even more than fouling, involves more than technology: effective cleaning is about effective management.

This paper does not seek to present a definitive account of existing cleaning technologies, as these are covered in detail elsewhere (*e.g.* Müller-Steinhagen, 2000; Graβhoff, 1997). Rather, the intention is to identify where challenges and opportunities exist in implementing effective cleaning management, and suggest areas where progress is being made, or attention needs to be directed. Moreover, cleaning is understood to mean the removal of existing fouling layers in dedicated stages, as opposed to those mitigation or antifouling techniques whereby foulant is removed continuously during processing, without interrupting manufacturing.

Particular attention is directed towards cleaning-in-place technologies, which are highly favoured in the food and biotech sectors owing to their suitability for verification as they avoid contamination arising from opening equipment. Several of the references are drawn from a recent conference on this topic in the food industry (Wilson *et al.*, 2002). The emphasis lies on applications to heat transfer equipment. It must be noted that related cleaning problems occur in non-heated systems and deposition need not always be heat transfer induced: biofilms, for example, which are not considered in detail, give rise to cleaning (and sterilisation) problems in both.

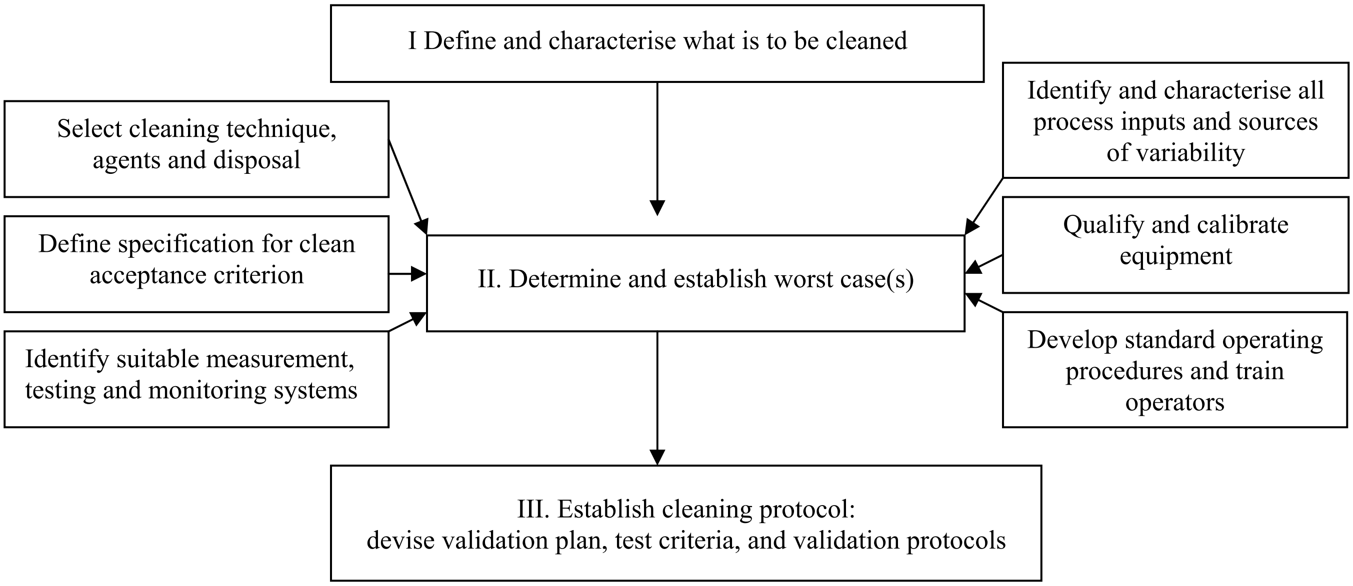

Figure 1 Factors to be considered in developing cleaning methods (*after* Crockford, 2003)

FOULING – SETTING INITIAL CONDITIONS

The view of cleaning as a necessary chore, when fouling mitigation methods prove unable to prevent deposit build-up, ignores the inherent symbiosis between fouling and cleaning. The first aspect is of *initial states*: the surface layers generated during the fouling process obviously form the starting material for any cleaning protocol, and likewise the state of the surface remaining after any cleaning stage is of crucial importance in later operation, as it will dictate the ability of foulants to attach. The extent of fouling is rarely uniform in heat exchangers, either due to surface temperature and shear stress distributions arising from the flow pattern in the unit, or variations in chemical reaction with bulk or surface temperature and composition. As fouling proceeds, this variation in distribution will cause a variation in fouling level (*e.g.* high fouling coverage giving rise to lower local flow rates and therefore higher fouling rates) and in fouling properties – particularly those linked to ageing. The second aspect concerns *process operating conditions*, as a design selected to give optimal mass transfer, heat transfer, temperatures or reactions during a cleaning stage may not be able to operate at the conditions needed to mitigate fouling most effectively. The nature of the foulant can is also likely to be affected by operating conditions, apart from temperature (and ageing): biofilm characteristics are well known to vary with flow conditions and oxygen concentration, while at a finer scale, Lelièvre *et al.* (2002a) reported that the removal rate of *Bacillus* spores was affected by the flow conditions applied during both the soiling (attachment) procedure and the cleaning stage. This aspect is particularly important when equipment is used for different products, where it will have not been optimized for either stage.

Ageing

Ageing has long been recognized as an important stage in fouling – indeed, discussed for crude oil exchangers by Atkins in 1962 – is an essential feature in dairy operations (Visser *et al.*, 1997). Ageing was classified as one of the fundamental steps in Epstein's 5×5 fouling mechanism matrix (1981) and was described by Müller-Steinhagen (2000) as the most poorly understood aspect of fouling**,** yet is a key factor in linking fouling and cleaning processes as one seeks to optimize potential mitigation routes. Ageing arises in many fouling mechanisms, and almost always yields a stronger, more resistant deposit, *e.g.* reaction to bind heterogeneous food matrices together (Liu *et al.* 2002): 'consolidation' of particulate deposits (Turner and Klimas, 2001). Several mathematical models of fouling now feature ageing considerations (scaling – Bohnet *et al.*, 1997; waxes – Singh *et al.*, 2000), which have been made possible by the availability of measurement techniques to quantify ageing effects and the recognition of the importance of this factor.

There is considerable scope for further work in this field, particularly in linking the effectiveness of cleaning stages to the extent and nature of fouling. The rate and type of cleaning will be linked to the amount and nature of deposition, and it is likely to result in an optimal set of operating and cleaning times. Current scheduling optimization approaches do not feature this linkage, although this may be due to other considerations such as (*i*) cleaning requiring off-line action, where the cleaning time is not very sensitive to foulant factors; (*ii*) ageing effects are weak; (*iii*) cleaning is determined by other quantitative or qualitative criteria. An important example of the latter is hygiene considerations in the food sector, whereby microbial activity often determines operating periods, yet recent work on thermophile survival in fouling layers by Hinton *et al.* (2002) indicates that such criteria are again intimately linked to fouling. It should be noted that incorporating ageing models into scheduling optimization will increase the difficulty of these already complex problems (*e.g.* Georgiadis *et al.*, 2000; Smaïli *et al.*, 2002). The principal need there is for reliable models.

Design for cleaning

Ageing needs to be considered in order to generate deposits that can be cleaned readily – where such freedom exists! A similarly important factor is the likely distribution of deposition arising from extended fouling, as this will establish two sets of worst cases: (*a*) areas of greatest distribution, and (*b*) areas where cleaning is least effective or slowest, owing to the hydrodynamics or temperature conditions arising in subsequent cleaning operations. The two sets do not necessarily overlap, particularly where different mechanisms control the fouling and cleaning steps. Identification of the worst case scenario is important in cleaning protocol design (Figure 1), and constitutes a key principle in design for cleaning. In the food and biotech sectors, hygienic design considerations such as the EHEDG guidelines (1997) have been introduced to eliminate features which will compromise hygiene and are difficult to clean.

Multi-product or flexible manufacturing plant pose particular challenges, especially where differences in fouling behaviour and nature will require different cleaning protocols. In these cases, it may not be possible to accommodate optimal design features, and a compromise must be sought.

Design for cleaning is not always considered in heat exchanger specification, and needs to be. The aim must be to design units which operate in a mode which minimizes or eliminates fouling, and which can also be cleaned readily. Hopefully the two are not mutually exclusive. For example, the use of in-tube inserts is not practiced in the food industry owing to lack of confidence in assuring cleaning. Basic physical features need to be incorporated for off-line cleaning, such as providing access and selecting materials which will be compatible with the cleaning techniques (although the reverse is usually the case). Where CIP is used, the unit must be able to operate at the flow velocities and temperatures required, and again the materials must be compatible with the chemicals employed. The ultimate aim for fouling and cleaning modeling work must be to generate designs where the sites of worst fouling can be identified so that these can be ranked for cleaning, and sensors fitted so that these regions can be monitored closely.

Computational fluid dynamics (CFD) modeling has an important role to play in design for cleaning. CFD allows reasonable estimates of the distributions of key parameters such as surface shear stress and temperature to be mapped out for prospective designs, and has been applied to several fouling applications (*e.g.* Brahim *et al.*, 2003). It is also being applied to support assessments of cleanability of process equipment (Friis and Jensen, 2002), and there is obviously scope for using these techniques together to identify exchangers which are truly 'better by design'. The key inputs for such simulations are reliable fouling and cleaning models. Models based on physical understanding also highlight the key factors affecting cleaning, and therefore in need of accurate simulation. An example is the experimental work by Lelièvre *et al.* (2002b), who found that fluctuations in shear stress – as well as the magnitude of the average shear stress – affected the removal of bacteria from stainless steel surfaces. CFD simulations of this process must therefore quantify stress fluctuations reliably.

Finally, it is also important to note that the structures of biofouling deposits are sensitive to the nature of the surface (via adhesion) and the prevailing heat, mass and shear environment. Zhao *et al.* (2002) have shown how modified surfaces can deter biofilm attachment. The effects of 'stress' on microbial activity and biofilm structure are well documented in the literature (*e.g.* Verran, 2002) and will have implications for cleaning.

CLEANING

Knowledge of the physical and chemical nature of a fouling deposit is required, alongside process specifications, to identify appropriate cleaning methods. Once this information is available, the operator has to choose between a wide range of available technologies (*e.g.* Wilson, 1999: Müller-Steinhagen, 2000). Cleaning requires bond rupture within fouling layers or at fouling-equipment interfaces. The techniques available achieve this by direct (*e.g.* erosion) or indirect (*e.g.* thermal shock) application of shear or normal forces, or by chemical conversion of the fouling species to a less cohesive or less adhesive material, which can then be readily removed.

Factors to be considered in selecting cleaning techniques include

(*i*) effectiveness and efficiency;
(*ii*) extra equipment requirements;
(*iii*) cost;
(*iv*) verifiability;
(*v*) scope for contamination, or compatibility, and
(*vi*) cost of disposal of deposit material and cleaning chemicals.

The latter, environmental impacts of cleaning are growing in importance, both in terms of minimizing operating costs but also in terms of maintaining operability as solvents are re-categorised as health or environmental risks. Recycling of CIP solutions is widely practiced, while emphases on waste minimization (Perka *et al.*, 1993) and the use of aqueous cleaners are driving interest in alternative strategies (*e.g.* enzymes - Graβhoff, 2002, or green chemistry, *e.g.* Burns *et al.*, 2002) and optimization of cleaning cycles. Another strategy attracting attention is the search for CIP solutions which operate effectively at similar temperature conditions to the process, thereby reducing the time taken to implement a CIP cycle, simplifying operations, and likely to also reduce energy consumption.

Cleaning mechanisms

Optimisation of cleaning requires more detailed knowledge of the mechanisms involved in order to improve the rate or effectiveness of the process. Where fouling is repeated consistently, considerable progress has been made in developing semi-quantitative models for those cleaning applications, *e.g.* in the dairy sector. The underlying approach is essentially one of *materials science*, understanding how a soil responds to the cleaning action and exploiting this information to enhance that action or weaken the deposit's resistance to it.

Investigations have been greatly assisted by the developments in modern instrumentation which allow one to study surfaces and structured layers down to the nanoscale – notably the atomic force microscope (AFM, *e.g.* Verran, 2002), and the diverse branches of electron microscopy. Of particular importance for aqueous systems is the development of the environmental scanning electron microscope (ESEM), which allows investigation of microstructures of hydrated samples in close to real time: previous methods required dehydration – and problems of collapse – for biological and gel samples. Cleaning studies, however, pose challenges for these instruments as they involve dynamic phenomena arising at the micron or milli-metre scale under shear environments. This has prompted the development of micro-level devices for investigating CIP mechanisms, and particularly the role of shear stress. Direct measurement of layers undergoing removal – such as by micromanipulation (Liu *et al.*, 2002) or by fluid dynamic gauging (Tuladhar *et al.*, 2002) – will elucidate removal mechanisms and allow reliable models to be developed.

Where micro-layers are involved, spectroscopic techniques (confocal microscopy, reflective FTIR, near infra-red (NIR)) can be used to probe the molecular identity and the extent of fouling (Flemming *et al.*, 1998). Some spectroscopic techniques have potential as on-line sensors as well as laboratory tools. Magnetic resonance imaging (MRI) and other tomographic techniques have been successfully used to study materials processing since the 1990s, but application of these methods to fouling and cleaning systems has yet to be reported owing to the challenges of speed, resolution and cost.

Model development, however, requires expenditure, and there are likely to be instances where the accuracy of the model will be limited on resource grounds – so cheaper instrumentation and assessment methods are required. Where removal is considered to be affected by mass transfer, CIP processes have been successfully simulated using relatively simple devices such as the spinning disc (Grant *et al.*, 1996; Morison and Thorpe, 2002a). More complex arrangements are required to probe the mechanisms further.

Most of the above discussion applies to coherent layers, whereas the mechanisms controlling the removal of *discrete* species such as bateria or spores are unlikely to feature the same physico-chemical interactions and removal characteristics as macro-layers. It cannot be assumed that a process which removes soil layers will be effective against micro-organisms attached to the surface, and vice versa. As with fouling caused by mixtures of mechanisms, there is relatively little reported on cleaning over different length scales.

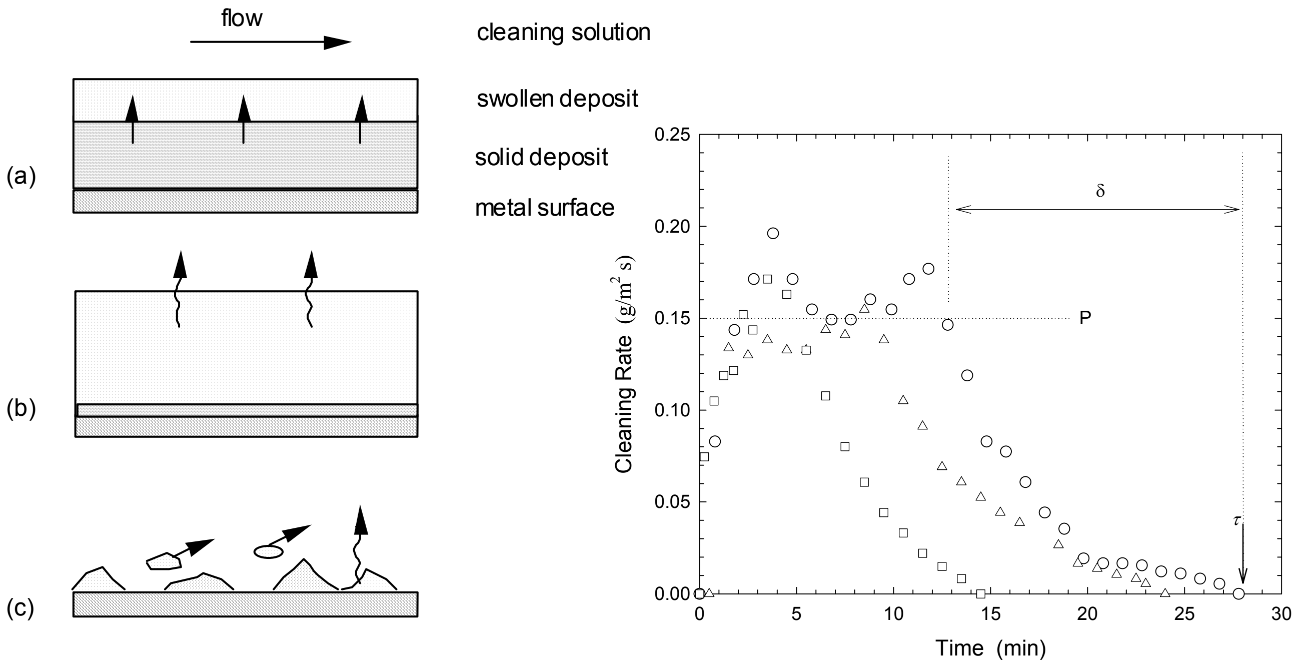

Figure 2 Schematic of whey protein cleaning mechanism (after Gillham, 1997)
(*a*) $t < 3$ min – swelling stage: (*b*) uniform removal rate stage; (*c*) decay stage of length δ, ~ 10 min.
Data on right show protein removal rates for different initial amounts of deposition.
Conditions: 6 mm i.d. tubes with 0.5 wt% NaOH at 70ºC and bulk *Re* ~ 600.

Case Study – Whey protein cleaning

An example of cleaning mechanism elucidation is for alkaline-based CIP of denatured whey proteins, which has received consistent attention owing to its importance in dairy applications. Whey protein fouling is a dominant feature in dairy exchangers used in milk pasteurization and in preheaters for UHT milk treatment (Burton, 1968), and is usually removed by CIP based on alkaline cleaners.

Timperley and Smeulders' (1988) investigations of protein cleaning rates showed that the fouling mechanism involved complex chemistry, as indicated by their observation of an optimal cleaning rate at NaOH concentrations of 0.5 wt%. Early cleaning models featured overall first- or zeroth-order kinetics, whereas Bird and Fryer (1991) showed that the cleaning mechanism featured the three distinct stages illustrated in Figure 2 –

(I) swelling of the deposit on contact with cleaning solution and reaction to form a removable gel;

(II) removal of the gel by a mixed reaction/mass transfer process, until a final decay stage,

(III) the decay state, where the strength of the deposit was reduced to a point where shear controlled its removal.

These steps were confirmed by Tuladhar *et al.* (2002) using fluid dynamic gauging, and by Xin *et al.* (2002).

Exploitation of this mechanistic model has followed different avenues. Bird and Fryer's initial work indicated the existence of an optimal concentration of NaOH, near 0.5 wt%, which is used as a standard in several cleaning agents, and NaOH levels in CIP systems are often monitored lest reaction take the value outside the desired range. Christian *et al.* (2002) have investigated the effect of switching cleaning chemicals in a programmed manner in order to maximize protein and mineral scale removal, as the most effective combination of acid or alkaline rinses is the subject of debate.

Another exploitation strategy, described by Gillham *et al.* (2000), follows the observation that the decay stage is long, and is controlled by the shear stress acting on the deposit surface. They investigated the effect of increasing the shear stress by flow pulsing at 1-5 Hz, and demonstrated a significant increase in overall cleaning rate over that obtained for steady laminar flows. Laminar conditions were studied owing to limitations in their laboratory equipment, and to explore the method as an alternative to turbulent flows when cleaning viscous liquids.

Recent numerical work (Pore and Patel, 2003) has indicated that this pulsing induced turbulence in the flow, so that this flow pattern represents a method for achieving these conditions without use of high bulk flow rates.

Flow pulsing has been demonstrated by Augustin and Bohnet (2001) to be effective in mitigating deposition crystallisation fouling: such strategies represent manipulation of flow patterns to exploit key in fouling or cleaning processes. Flow pulsing generates large fluctuations in local shear stress, which Lelièvre *et al.* (2002b) have shown to enhance the removal of spores.

Quantitative modeling of the uniform removal stage has been improved by Chen and co-workers, utilizing concepts developed for polymer swelling and dissolution (*e.g.* Hunek and Cussler, 2002) to model the removal of swollen protein fragments (Xin *et al.*, 2002). This work will allow fouling-cleaning models to be developed for process optimization and equipment design. It also indicates how materials science concepts can be incorporated into cleaning models.

For physical removal techniques, however, the heterogeneity and soft-solid nature of many fouling deposits results in complex mechanical deformation characteristics, so that modeling of force-based removal mechanisms is likely to require development of the underlying science.

One underlying challenge with all cleaning mechanism studies is that of reliable scaling up, to account for process and fouling variations. This problem also exists in development of new cleaning protocols, in transferring from laboratory and pre-qualification trials to production and trying to maintain a high degree of success. The difficulty of replicating production conditions in the laboratory is common to fouling studies, and highlights the need to identify the key mechanisms in order to devise appropriate experiments.

Cleaning techniques

Cleaning techniques can be roughly categorized into physical and chemical methods. Formulation chemistries continue to develop, either to improve efficiency, *e.g.* multiple agent formulations in order to combine cycle steps, or effectiveness against particularly resilient deposits. Environmental considerations have already been identified as important market factors. Matching a formulation to customer needs, and achieving reliable implementation without extended trails, are the vendor's aims and local expertise will be developed for this.

Few new cleaning technologies have been commercialized, although there continue to be improvements in both physical and chemical methods. Techniques such as flow pulsing and air rumbling enhance chemical cleaning via increases in shear stress, but the underlying reaction chemistry is still required to achieve removal. Physical mechanisms based on scouring and pigging are accompanied by improvements in device technology. A relatively new departure is the work on 'ice pigging' by Quarini and co-workers, employing dense suspensions of ice to purge products from process lines. These soft solids plugs can be pumped safely through a range of pipe fittings and process units, achieving very good degrees of sweeping (Quarini *et al.*, 2002). Noteworthy features of the technique include its benign chemical nature, safety, small fluid inventory and relief of blockage (by melting). Ice pigging must, however, be accompanied by CIP or other methods in order to reliably clean surfaces. It is not directly applicable to hydrocarbon systems, but fat or wax-based analogues could be considered.

An important CIP technique, though not applied to heat exchangers, is the use of spray balls and particularly the use of high pressure jets. Simulations of spray ball coverage of vessel surfaces now allow one to anticipate the jet paths and, ostensibly, cleaning performance. Recent work by Morison and Thorpe (2002b) has indicated that the effectiveness of cleaning is mainly controlled by the wetting film generated by the flow, as the jet impact zone rarely covers the whole surface for long periods. Relatively simple experiments can be used to design a cleaning protocol, using the same simulations to calculate an average wetting rate.

MONITORING AND MEASUREMENT

All cleaning stages require a designated end-point, and this may be either set by protocols based on trials, or, ideally, indicated by sensors which can monitor the progress of the cycle and determine when cleanliness is reached. Industry requires devices that measure relevant parameters: are robust and reliable; meet claimed specification in terms of sensitivity and accuracy; are simple to install, self-diagnostic, easy to maintain, and cost effective (if there are alternatives) and be compatible with other equipment on the plant (Hasting, 2002). The data generated by sensors must be readily interpretable by process operators and thus be linked to protocols such as HACCP (Hazard Analysis and Critical Control Point) analysis so that appropriate corrective actions are identified by particular combinations of indicators. Few cleaning processes in the chemicals industry are equipped to this level.

One of the primary challenges in using cleaning monitors or sensors is that, as mentioned previously, deposition is rarely uniform and evenly distributed. Sensors, which can be classified as integrated, localized or indirect, are therefore subject to issues arising from spatial scaling:

1. *Integrated* measures are taken over the complete system or part thereof – *e.g.* overall heat transfer or pressure drop. Sensitivity of these lumped parameter models to local (worst-case) variations is often poor,

and there are often sizeable measurement errors. Some integrated techniques are not applicable to cleaning, such as heat transfer measurements when the system is operated isothermally.

2. *Localised* measurements are made at specific points within the system. The use of heat flux sensors for heat transfer systems has increased noticeably in recent years (Baginski *et al.*, 2001: Truong *et al.*, 2002). Identifying representative locations for the sensors (or tests such as swabbing), or relating the information generated from remote devices to process units when access is not possible, are key issues which are shared with fouling monitors (*e.g.* on sidestreams). Recent developments include surface resistance measurement (Chen *et al.*, 2002), whereby techniques akin to corrosion testing may be used to interrogate the state or occupancy of a surface relatively cheaply and robustly.
3. *Indirect* techniques, such as measurement of key parameters such as concentration of detergent, ATP assays, temperature, monitoring of valve openings, are subject to uncertainties in measurement and interpretation, particularly where the response may indicate more than one event. An important issue with these techniques is how well they represent the cleaning process

   Chemical assays can be made more reliable by correlating different sensors, but end-point determination is still difficult owing to the relatively small change in concentration which occurs as the last fragments of soil are removed. New sensor technologies such as dynamic capacitance methods (Kaiku, 2003) offer some improvements in sensitivity and robustness.

Table 1 summarises some of the challenges involved in existing process sensor technologies. Until the 'smart surface' is developed which not only discourages attachment (*e.g.* Zhao *et al.*, 2002) but reports on its condition, monitoring will feature interpretation of incomplete sets of data.

One of the challenges is then to identify data sets which allow one to track fouling and cleaning reliably, and can be understood by the process operators.

Table 1 Sensing techniques for fouling and cleaning in CIP systems (*after* Hasting, 2002)

Technique	*Measuring*	*Timescale*	*Issues*
Overall heat transfer	Thermal performance - fouling level	Real-time	Accuracy: Interpretation: Dependent on process model
Local heat flux	Thermal performance - fouling level	Real-time	Reliability: Local - scale up: material model
Overall pressure drop, or flow rate	Hydraulic performance - foulant thickness	Real-time	Accuracy (differential pressure): interpretation for complicated units: dependant on flow pattern
Ultrasonics	Foulant thickness	Real-time	Local - scale up: intrusion into flow: calibration for foulants
ATP/DNA techniques	Microbiological activity	Retrospective	Time lag: specificity of detection (at cost): bulk (liquid) measurement: dormant cells
Microbiological (e.g. swabbing)	Chemical and microbiological activity	Retrospective	Soluble and soluble materials on surfaces: Time lag and time consuming: skilled operators: access and is invasive: is local sampling representative of key sites
Optical (eye)	Foulant or biofilms	Real-time	Easy to do, minimal equipment, rapid. Access: subjective assessment: accuracy and resolution: training and cost: non-quantitative
Optical (instrument, e.g. FTIR, NR)	Foulant or biofilms	Real-time	Access to process surfaces: local measurement: calibration (threshold sensor?)
Liquid electrical properties (capacitance, conductivity, amperometric)	Foulants	Real-time	Detects material in liquid, not on surface, so uncertainty over source: sensitivity varies for different contaminants: resolution changes over range of concentrations: specificity:
Surface electrical properties	Foulants, biofilms, corrosion	Real-time	Local - scale up: implementation in process areas: calibration

Hasting (2002) summarises the need for sensors by contrasting the different responses of process monitoring by reconciliation of readily available pressure drop and thermal performance data. Apart from the issues of measurement error, the two techniques show markedly different sensitivity to foulant thickness (Visser *et al*., 1997). Pressure drop measurements are more sensitive when duct dimension reduction is large, whereas thermal fouling resistance measurements are most sensitive when the fouling layer is small.

Correlating the two sets of data is further complicated by the uncertainty caused by deposit roughness and non-uniform fouling. Other data are therefore required in order to reliably track cleaning performance. Such an integrated monitoring system is most likely to fit the basic industrial requirement of being robust, reliable and cost effective. Van Asselt *et al.* (2002) describe how process performance and chemical assay information can be combined to track cleaning systematically. A secondary benefit is that this level of monitoring can also provide information about process integrity and disturbances. Thirdly, combinations of sensors provide some flexibility when different products are processed.

The challenges here are therefore:

(i) Identification of appropriate sensors and monitoring techniques.
(ii) Verification of cleaning end-point detection, particularly for different products in flexible manufacturing plants.
(iii) Validation and education of operators as part of a quality assurance mechanism.

The importance of validation will vary between applications, reflecting the aims, culture and importance attached to cleaning. Setting appropriate aims – and always erring on the side of caution – therefore comes full circle.

CONCLUSIONS

Cleaning poses several challenges, starting from the need to define the desired state of cleanliness and finishing by defining suitable assurance mechanisms that cleaning has been performed satisfactorily.

The key factor in developing cleaning protocols is the nature of the fouling deposit as this will determine the most appropriate cleaning technique. The links between fouling and cleaning should be appreciated, particularly where ageing processes can significantly affect the deposit nature. Such links indicate that fouling and cleaning should both be considered during equipment design.

Optimisation of cleaning requires mechanistic understanding of the removal processes, which can be probed quite successfully using the wide range of instruments available. Quantitative models are being developed for cases of repeatedly consistent fouling, which can be used to improve removal rates or designs. The range of cleaning techniques is increasing slowly.

Cleaning must be accompanied by verification protocols, which will ideally be linked to data from process sensors. The need for reliable sensors is increasing as the need for validation becomes more common. The problems with monitoring cleaning using integrated and localised sensors mean that several sets of data need to be collected simultaneously and interpreted wisely. The intellectual tools required - featuring chemistry, materials science, engineering and data reconciliation - constitute an interdisciplinary set of skills that are not imparted in a standard technology course. Training operators and engineers to interpret such data represents a final, human, challenge.

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