"BIOFOULING IN TUBES - SOME TRENDS AND PERSPECTIVES"

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ABSTRACT

A significant increase in the literature concerning the formation of biological deposits in tubes has been noticed in the last few years. Yet, the scope of the majority of the reports is limited to the study of a single operating parameter. Besides, the operating conditions differ significantly from case to case, rendering difficult the absortion of the available information.

In this work, a survey of the most recent publications on the subject of tube biofouling is undertaken, as a means of clarifying further research programs. Emphasis is placed on the systems used, experimental equipments adopted and, essentially on the parameters studied. Of these, specially attention is given to the influence of tube material and roughness, foulant type and concentration, fluid velocity and temperature field.

1. INTRODUCTION

Fouling is a serious problem in all circulating systems and specially in what concerns heat exchangers. In this case the fouling deposits create and additional thermal resistance to heat transfer and also an increase in pressure drop resulting in a higher power consumption.

If the thickness and thermal conductivity of the fouling agent were known in advance it would be possible to predict the actual thermal performance of the equipment. However, not only these values are seldom known but also the process of fouling is dynamic in the sense that fouling builds up with time. In what concerns biological fouling, one has to consider not only the usual physical parameters (fluid velocity, initial solid surface condition, etc.) but also those associated with the growth of microorganisms such as temperature, pH, dissolved nutrients and oxygen concentration and limiting substrate concentration. Thus it is of crucial importance to examine in detail the biological factors together with the design parameters in order to implement the methods of combating the formation of this type of deposits.

In this paper it is intended to make a survey of the recent experimental procedures and equipment used in biofouling studies, as well as the reported data, in order to gather pertinent information about the phenomena and therefore infere some research guide-lines to be followed in the future.

2. EQUIPMENT

Several types of apparatus have been used to study the deposition of biological material on heated and non-heated surfaces. The equipment geometry and the type of assembly depended on the parameters that were considered as influencing the biofouling process.

Table 1 summarizes the main equipment and monitoring techniques employed in biofouling studies. As it can be seen, no heat is exchanged in the majority of the test sections and, thus, heat transfer resistances are not measured. Actually, one of the problems of heating the biological fluid in the test section is the fact that the microorganisms attached to the surface may become subjected to temperatures higher than the advisable ones.

This table also shows that in almost all cases recycling of fluid was utilized. This type of flow circuit tends to minimize changes in concentration, thus leading to the formation of more uniform films.

The microorganisms used are predominantly those found in cooling water systems. This is a consequence

TABLE 1. EQUIPMENT AND TECHNIQUES USED IN EXPERIMENTAL BIOFOULING STUDIES

	BOTT AND PINHEIRO [1]	MILLER [2]	HARTY [3]	MILLER [2]	DUDDRIDGE [4]	CHARACKLIS [5]	CHARACKLIS [5]	CHARACKLIS [6]
MAIN COMPONENTS OF THE TEST ASSEMBLY (OTHER THAN THE TEST SECTION)	Open vessel containing water and microorganism	Open vessel for growing and holding the biological solution with control of temperature, pH and dissolved oxygen	Stream of water infected with the microbial solution growing in a fermenter	Large residence time vessel inoculated continuously by the micro-organism growing in a separate fermenter. Tap water added continuously to the vessel	Large residence time vessel inoculated continuously by the micro-organism growing in a separate fermenter. Tap water added continuously to the vessel	Mixing vessel feed with dilution water, nutrient solution and microbial inoculum	Mixing vessel feed with dilution water, nutrient solution and microbial inoculum	Mixing vessel feed with dilution water nutrient solution and microbial inoculum
TEST SECTION	Rectangular duct (with water and biological fluid in counter-current) Fig 1	Circular and rectangular ducts Fig 2	Rectangular duct	Aluminium tube 1/2 " diameter	Radial flow growth chamber Fig 3	Concentric cylinders with the inner one rotating Fig 4	12-16 removable cylinders 5 cm long inserted in a sleeve	Tubular section (alum.) with a block of aluminium clamped around it and electrically heated (Fig.5)
Heat Exchange in the Test Section	Yes - Heat provided by warm water	No	No	No	No	No	No	Yes - Heat provided by an electrical system
Deposition Surface	Removable copper plate	Brass and mild steel plates	Brass plate	Inside of aluminium tubes	Removable disc plate	Removable slide on the outer cylinder	Inside of test tubes	Inside of tube
MICROORGANISM	E. Coli	Pseudomonas fluorecens	Mixture of E.Coli and Klebsiella aerogenes	Pseudomonas fluorecens	Pseudomonas fluorecens	Mixed liquor from domestic waste-water treatment plant	Mixed liquor from domestic waste-water treatment plant	Variety of microbial species

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	BOTT AND PINHEIRO [1]	MILLER [2]	HARTY [3]	MILLER [2]	DUDDRIDGE [4]	CHARACKLIS [5]	CHARACKLIS [5]	CHARACKLIS [5]
INTRODUCTION OF NUTRIENT	Discontinuously	Continuous flow into the biological fluid vessel	Without introduction in the main stream	Continuously	Continuosly	Continuously	Continuously	Continuously
TYPE OF CIRCULATION OF BIOLOGICAL FLUID	Closed circulation (Recycling)	Closed circulation (Recycling)	Open circulation	Recycle with over flow (Feed and bleed)	Recycle with over flow (Feed and bleed)	Recycle with over flow (Feed and bleed)	Recycle with over flow (Feed and bleed)	Recycle with over flow (Feed and bleed)
TECHNIQUE USED FOR MONITORING BIOFILM GROWTH	Thickness measurements	Thickness measurements	Thickness measurements	Measurement of the aluminium tube weight	Counting the number of cells attached	Biofilm thickness, mass and chemical composition	Biofilm volume determination	Change in heat transfer resistance
PARAMETERS STUDIED	Fluid velocity Fluid temperature	Fluid velocity Fluid temperat Nutrient concentration	Fluid velocity and temperature	Cell conc. Nutrient conc. Fluid temp.	Shear stress (Adhesion of cells)	Shear stress	Fluid veloc.	Glucose loading

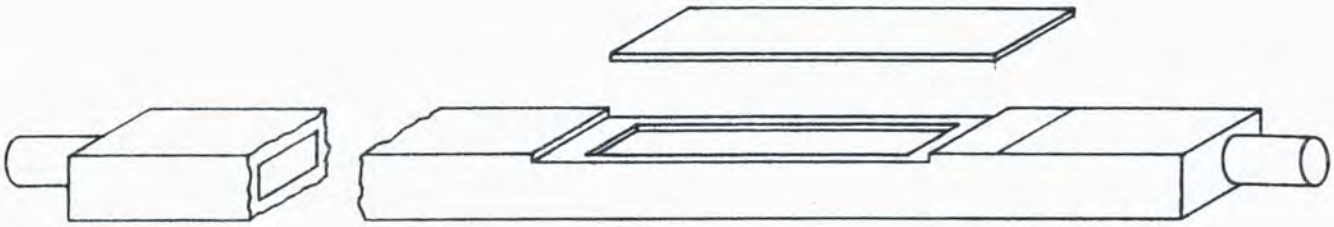

FIG. 1 - Rectangular duct with removable deposition plate[1]

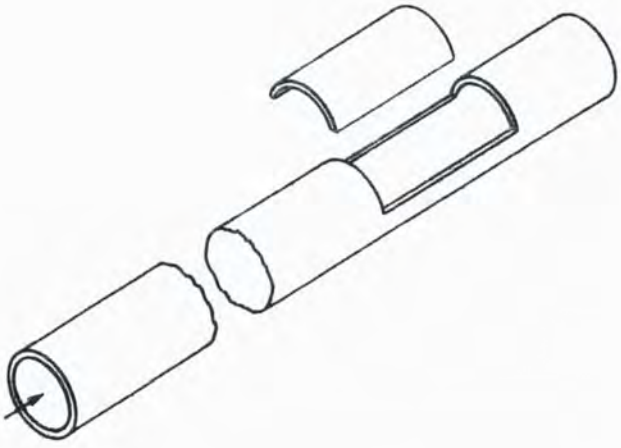

FIG. 2 - Circular duct with removable deposition plate[2]

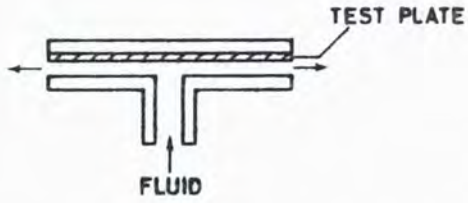

FIG. 3 - Radial flow growth chamber[4]

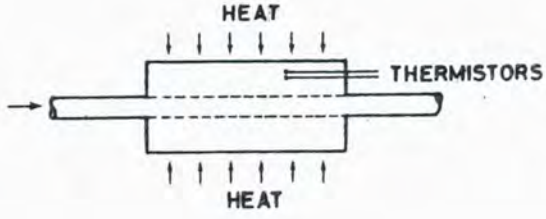

FIG. 5 - Thick walled heat exchanger[6]

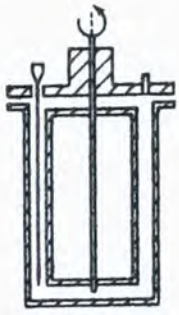

FIG. 4 - Annular reactor[5]

of the great problems that biofouling causes in these systems.

3. MEASUREMENT OF BIOFILM QUANTITY

For measuring biofilm deposits in heat exchange tube surfaces many techniques have been applied in order to relate the deposition with the variables under control. These techniques differ from case to case and, essentially, with the test duct geometry and characteristics. In that sense they can go from microscopic examination to physical and chemical examination (see Table 1).

During the first step of colonization it is quite difficult to measure the actual thickness of deposits since only small "colonies" of cells are distributed randomly on the surface. In that case, weighing procedures or volumetric measurements[7] can be the appropriate techniques, although they don't seem to be very sensitive and again they only apply to particular test sections, namely, those with a light test surface.

Viable cell count or total cell count per unit area was used by Corpe[8] to measure the early development of biofilm on glass slides immersed in seawater. Nevertheless, the total biofilm mass or thickness were not determined.

When surfaces become uniformly covered, the film thickness measurements can be made either by a travelling microscope, which reads the distance from the upper part of the film to the metal surface, or by adopting an electrical conductivity device based essentially on the different electrical conductivities between the deposits and the metallic surface, described by Harty[3].

The main disadvantage of monitoring biofilm growth through thickness measurements or cell count is that the run has to be interrupted, with the risk of causing an excessive deposit removal when it is restarted. This may explain the highly irregular curves of thickness versus time obtained in a few works (Fig. 6, 7).

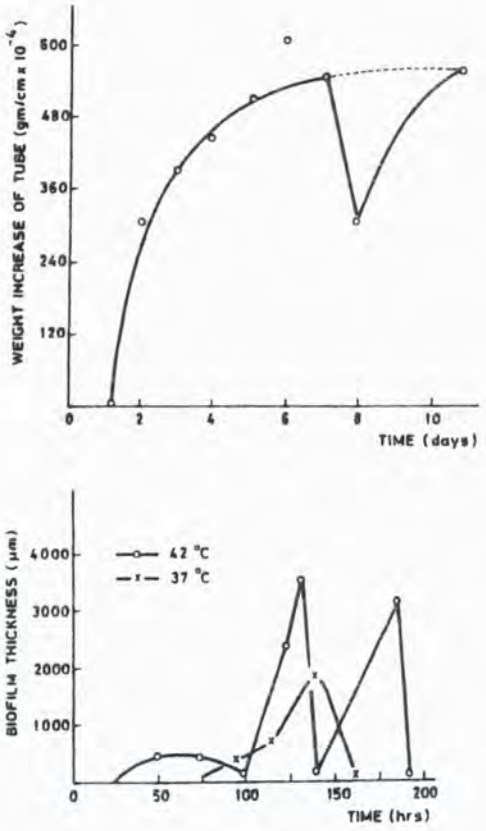

FIG. 6., 7. - Fouling curves with irregular shapes [3,2]

Pressure drop in test sections is used as an indirect measure of biofilm quantity. In fact, biofilm accumulation affects the frictional resistance in tubular sections and the pressure drop through the length of test ducts may be taken as a reasonably conclusive technique[9] as long as there are no blockage effects. In most situations, this type of measurement is more useful as a supplementary information when using other monitoring techniques, especially heat transfer.

Characklis[6] conducted some experiments to determine the influence of biofilm formation on heat transfer resistance using an heated tube. The overall heat transfer resistance was calculated from measurements of bulk water temperature flowing inside the tube and of temperatures in the electrically heated block of aluminium clamped around the tube, and was related with the biofilm thickness.

4. FACTORS AFFECTING BIOFILM FORMATION

The build-up of biological deposits involves several processes, the main ones being[10]:

- Initial surface conditioning with formation of a thin layer of organic polymer substances on the surface;
- Transport of cells and nutrient;
- Microbial cell attachment to the surface;
- Microbial growth within the film;
- Removal of portions of the deposit.

Operating and design factors such as temperature, surface characteristics, fluid velocity and composition may affect one or more of those processes leading, sometimes, to unexpected or contradictory results as discussed below.

4.1 - Temperature

The temperature that insures optimum growth for many biofouling deposits is in the range of 25 - - 40°C, but the effect of temperature on bacteria development depends largely on the actual species under consideration.

Experiments with the bacteria E. Coli in a simulated heat exchange showed that by keeping all the other variables constant, the change from 30°C to 35°c promoted an increase in film thickness of about 70%. A similar result was obtained by Miller[11] utilizing Pseudomonas fluorecens. In fact, a variation of 5°C in temperature away from the optimum growth temperature, resulted in a drastic decrease in biofilm thickness.

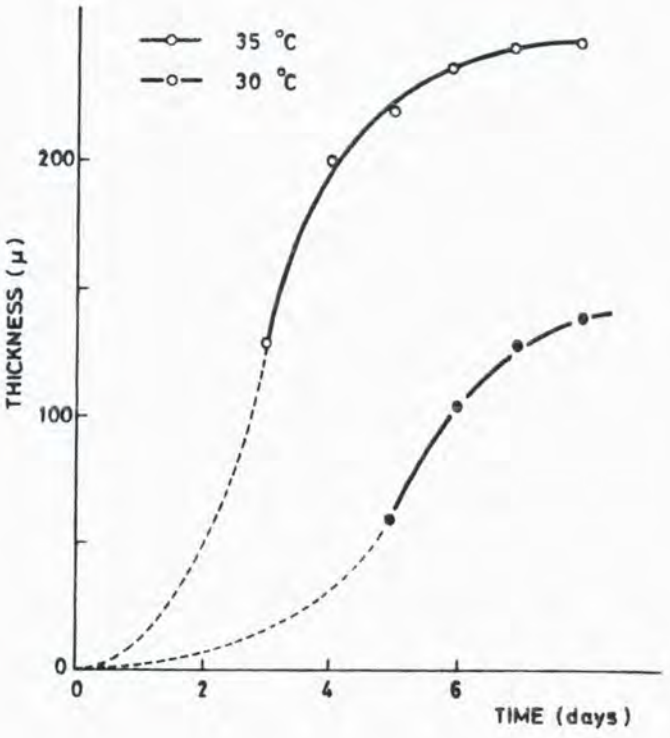

FIG. 8 - Biofilm thickness vs time

Other studies carried out in industrial cooling water systems[12] showed that the biofilm deposits increased during the summer months to which corresponds an higher mean temperature compared with temperatures in winter. It must be said that the bacterial content of these biofilms clearly showed that the most dominant genus present was Pseudomonas fluorecens whose growth temperature is around 25°C.

However, on the other hand, Novak[13] utilizing river water passing through a plate heat exchanger, observed that varying the temperature in the range of 10 - 45°C had only a negligible effect on the fouling rate. In this case the fouling deposit formed was typically gray-brown microbiological slime, but a microbiological and chemical examination was not carried out, which rises some doubts concerning the existence of more than one type of fouling substance (for instance, particulate deposition could play a relevant role in the process).

It seems that temperature, as a factor which

influences the biofilm formation in heat exchanger tubes, must be experimentally studied in a deeper way and specially in what regards the influence of the metal surface temperature. Yet, the studies that have been made, were concerned with changes in temperatures within the vessels where micro-organisms were growing, but not with the actual temperature they find when they anchor on the surfaces. If these temperatures are well above or below the optimum temperature for growth of the organism present, fouling could be prevented.

4.2 - Fluid Velocity

As biofilm formation depends on the transport of microbial cells and nutrients to the surface, microbial adhesion, uptake of nutrients and oxygen by microorganisms and detachment of deposits, it can be concluded that fluid velocity plays an important task in the overall process.

All these mechanisms take place between the fluid and the surface and, thereby, it is of primary importance to investigate the interfacial processes present at that local. However, it is difficult to measure these conditions and the easiest solution is to relate them with the bulk environment.

It is evident that some of the aspects contributing to slime formation are favoured by high velocities, but on the other hand these velocities tend, for instance, to decrease the facility of anchorage of microorganisms to the surface or to promote the dislodgement of slime masses already formed.

When slime is already deposited, high velocities promote a frequent renewal of nutrient and oxygen maintaining the growth of microorganisms. This was concluded by Heukelekian and Crosby[14] when observing fouling formation over long periods, and also by Miller[2] when he increased the fluid velocity during the same experiment after a reasonable amount of deposit had been formed. However, Purkiss[15] concludes from his work that turbulent flow tends to disrupt slime deposits and promote sloughing.

The disruption of deposits depends on the structure of the slime formed. High velocities generally promote the development of more compact films and less destructible than those formed under low velocities. Low velocities are favourable to the initial deposition of films (Fig. 9) but it seems that the structure of these films is not uniform, rather showing a fluffy aspect and vulnerability to sloughing effects.

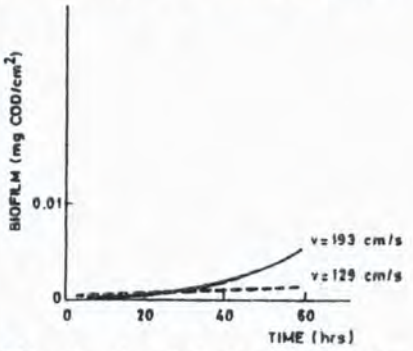

FIG. 9 - Initial deposition formed by low velocities

There are, however, many other factors that may affect the resistance of the deposits to the hydrodynamic forces; as an example, if temperature near the surface of heat exchangers becomes higher, with the development of biofilm, the growth of micro-organisms may be slowed and a different layer will be formed, which can facilitate the mechanism of disruption and sloughing.

Table 2 shows the relative influence of velocity on the different aspects of slime formation.

TABLE 2 - EFFECT OF VELOCITY ON BIOFOULING PROCESSES

	Favourable Values	
	Low Velocities	High Velocities
Deposition during induction period (anchorage of microorganisms)	X	
Renewal of nutrient and oxygen and transport of micro-organisms to the surface		X
compactness of biofilm (structure)		X
sloughing		X

4.3 - Surface Characteristics

Some authors have dedicated their work to the study of the influence of solid surface characteristics on the attachment of microorganisms.

The factors discussed in the literature regarding the effects of the solid surface are essentially the roughness, the toxicity aspects and the surface tension. All these factors seem to influence the initial adhesion process, although the bacteria properties can also play an important task in the events. In fact, Fletcher[16] points out that the most important factor regulating the ability of microorganisms to attach to different surfaces is the composition of the cell surface polymer. It is also said that these polymers, produced by cells, are genetically controlled and therefore changes in environment conditions may cause different bacterial surface properties. This must be the reason why the attachment of bacteria to different surfaces cannot be dissociated from the controlling factors (cell concentration, culture age, culture growth substrate, temperature of attachment, pH and ionic composition of medium) in each particular process.

Surface tension of materials has been related with the bioadhesiveness of bacteria. It is claimed[17] that, generally, low energy solid surfaces such as fluorcarbons are more resistant to fouling than for instance metallic surfaces (higher surface tension). Nevertheless, Fletcher[18] found that the surface charge of some of these surfaces (teflon, polyethylene, polystyrene, poly (ethylene terephthalate) controlled the adhesion of a marine Pseudomonas sp., leading to a high attachment due to opposing charges (negative for bacteria and positive for the surface).

Between metallic surfaces one can find different behaviours concerning the accumulation of biofilms. Results obtained by Duddridge[4] showed brass as the metal surface with lower levels of attachment as compared with stainless steel, mild steel or aluminium. Other studies[19] indicated that when using aluminium surfaces the induction period of biofouling was much longer than when using mild steel. The explanation is related with the toxicity aspects, since it is thought that Al^{3+} ions interact with the adhesive polysaccharide that would spontaneously cover the surface. This same aspect can be the reason for the low film thickness obtained with brass surface (the toxicity is attributed to aluminium and copper ions effective in reducing attachment).

On the other hand Birchall[20] affirms that the slime formation appears to be independent of tube metallurgy, whether this material is copper, copper alloys, mild steel, stainless steel or titanium. These studies were carried out in typical industrial open evaporative cooling systems where a wide range and varying population of microorganisms can be encountered. Yet, in these systems the operating conditions are not always constant, making it difficult to interpret the results. On the other hand, it is probably true that the metallic surface ceases to have any effect after a multilayer deposit has been formed.

In what regards the roughness of surfaces, some results[21] suggest that it does not become an important factor in the overall deposition process since the irregularities dimensions cannot be compared with the size of biological cells. However, during the induction period it is thought that the existence of microscopic irregularities on the surfaces favours the establishment of the first layers of macromolecules[1].

4.4 - Stream Composition

Two aspects related with the fluid composition have to be considered as influencing the development of biological fouling: cell concentration and concentration of nutrients (including air supply).

The necessity of having to inoculate the circulating water with bacteria, in laboratory tests, as it was done by several authors[1,2,3,4,5], to produce a measurable slime film in a reasonable time, suggests that the bacteria concentration is an important factor in biofouling process. Cell concentration of 1×10^6 cell/ml showed only little accumulation in tubes[22], as compared with concentrations of 3.6×10^6 cell/ml. In cooling

water systems, microbial population varies with the weather conditions, but measurements of biofilm thickness in these systems show increased values during those months to which correspond higher values of cell concentration in waters[23].

The analysis of the rate of attachment of marine Pseudomonas to the solid surfaces[24] showed that this process is controlled by the cell concentration in the bulk fluid.

The availability of nutrients and oxygen is essential for microbial growth. As the microorganisms become attached, growth will depend on the diffusion of those elements through the formed film, and therefore growth is related with the concentration of nutrients in the fluid.

Characklis[10] and Duddridge[25] reported an increase in the biofilm thickness resulting from an higher concentration of nutrients in the fluid. In this case the driving force of nutrient from the bulk to the biofilm is increased and growth and reproduction of microorganisms is enhanced.

Miller[2] concluded that an increase in nutrient concentration resulted in an increase in the number of viable cells per gram of biofilm. This suggests that when nutrient is available the reproduction mechanism of cells is dominant.

5. CONCLUSIONS

Although there is already a reasonable knowledge of the general features of biological fouling, it is quite difficult to predict the rates of formation of these deposits, due to the large number of factors (physical, chemical and microbiological) that affect the overall process. Experimental studies on the effects of these parameters often display contradicting conclusions, which may be due to uncontrolling errors associated with the test techniques employed and to the difficulty in identifying the process governing the build-up of deposits in each particular situation. This requires a carefully planned experimental programme involving:

* The development of suitable experimental equipment and techniques, so as to quantitatively follow biofilm formation without disturbing the phenomenon.

* The detection of the controlling processes (adhesion, bacteria growth, transport of nutrients etc.), by choosing the appropriate range of values and types of parameters to be studied in the tests.

* The individualization of some of the processes involved in biofouling, in order to study their response to changes in the operating and design variables. For instance, the influence of the initial surface on initial attachment can be assessed by running short tests with different materials and different pH, the latter affecting both the electrical charges on the deposition surface and on the bacteria, and also microbial reproduction and growth.

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