Compo[illegible] of biofilms in conduits. 73-003

Water Research Pergamon Press 1973. Vol. 7, pp. 1249–1258. Printed in Great Britain

REVIEW PAPER

ATTACHED MICROBIAL GROWTHS—II. FRICTIONAL RESISTANCE DUE TO MICROBIAL SLIMES

WILLIAM G. CHARACKLIS

Department of Environmental Science and Engineering, Rice University, Houston, Texas, U.S.A.

(*Received* 1 *January* 1973)

FRICTIONAL RESISTANCE DUE TO MICROBIAL SLIMES

A NUMBER of cases have been reported in which water-carrying conduits have suffered from remarkable losses in delivery capacity within relatively short operation periods. In one instance (SEIFERT *et al.*, 1950), the maximum capacity of a 24-in. (nominal diameter), 50 mile long water supply line was reduced to about 55 per cent of its original value within a few years. The loss was due to a thin, slimy layer that consisted largely of organic material imbedded with fine clay particles and was not caused by a substantial decrease in effective internal diameter. The layer was characterized by a "ripple-like" surface having an average height of 0.025 in. The results indicate that this type of roughness could not be explained in terms of equivalent sand roughness common to friction factor relationships.

The rippled surface structure seems to be an essential, but not the only, factor involved in the unusual frictional behavior caused by microbial slimes. Experiments using solid surfaces of similar pattern have shown a high frictional resistance, but not nearly as high as those occurring in water mains.

BRAUER (1956) performed experiments on form stability of the interior of asphalt-lined pipes as a function of temperature of the flowing water. At higher temperatures the asphalt coating assumed a rippled surface structure which was accompanied by an unusual increase in frictional resistance. Brauer explained the phenomenon as an actual flow of the coating under the action of shear stresses resulting in a true two-phase fluid flow. Additional energy expended by the bulk liquid in dragging along the asphalt lining accounts for much of the increased flow resistance.

In water and wastewater, wetted surfaces are subject to an extensive biological growth. Furthermore, small quantities of particulate matter may be deposited at the conduit wall. The slime layer has quite different physical properties compared to the original conduit material, including a much lower modulus of elasticity, and is more likely to be deformed by external forces.

The complicated nature of turbulent motion can be visualized by assuming that fluid particles moving near the wall coalesce into lumps and travel bodily together for a certain distance (SCHLICTING, 1960). If such a lump of fluid collides with the leading part of a roughness element, the fluid changes its direction and a momentum exchange takes place. Any forced motion of the fluid particles in a direction transverse to the flow corresponds to an increase in general turbulence. This phenomena causes energy losses in flow past rigid rough surfaces.

If the material constituting the roughness element has a low modulus of elasticity, the force exerted on the roughness element by the fluid may be sufficient to cause a

TABLE 1. CHEMICAL PROPERTIES OF ATTACHED MATERIAL OBTAINED FROM CLOSED CONDUITS EXPERIENCING EXCESSIVE SLIME FRICTIONAL LOSSES

	POLLARD (1959)	HEUKELEKIAN (1959b)	MINKUS (1954)	MINKUS (1954)	ARNOLD (1956)
Water	87	95.4	85.6	90	95
Organics	2.5	3.25	2.7	1.9	2.4
Minerals	10.5	1.35	11.7	8.1	2.6
Ammonia N (as per cent minerals)		0.23			
Si (as per cent minerals)			7.0	11.8	12.5
Fe (as per cent minerals)			18.5	7.9	1.4
Al (as per cent minerals)			7.5		3.9
Ca (as per cent minerals)			1.0	5.6	
Mg (as per cent minerals)			2.5		3.2
Mn (as per cent minerals)			59.5	56.3	4.9
SO_4 (as per cent minerals)					
pH		6.8			
Specific gravity at 20°C		1.01			

The 42-in. line was dosed with 50 mg l^{-1} chlorine for 11 days and then flushed for $\frac{1}{2}$ h at a flow velocity of 6 ft s^{-1}. The treatment proved effective as exhibited by highly colored and turbid water and capacity measurements shown below:

	Before chlorination	After chlorination
Hazen–Williams coefficient	111	133

Similar flushing without chlorination had produced a clear effluent. Inspection of the line after chlorination showed that treatment had not removed the film entirely. Two years later, without further chlorination, the Hazen–Williams coefficient equalled 102.

POLLARD (1959) described a deposit in a hydraulic tunnel that had caused increases in power loss of 5 million kWh due to excessive hydraulic head losses in a power conduit. The Santeetlah Hydroelectric Plant (North Carolina) is supplied by a closed pressure conduit of 11 ft dia. and approximately 4.5 miles long, consisting of 3 miles of concrete-lined tunnels and 1.5 miles of riveted steel pipe.

When the plant was first placed in operation (1928), tests showed conduit friction head losses to be 40.6 ft at 900 ft^3 s^{-1} flow. Inspection of the conduit 17 yr later showed no structural damage to the concrete lining or the bituminous paint on the steel pipe, however a rough, black deposit approximately $\frac{1}{2}$ in. thick was found on the concrete tunnel linings. The head loss at this time was 55 ft at 900 ft^3 s^{-1}. The deposit was described as looking like a "dense layer of soot". Chemical analysis of the material is shown in TABLE 1.

The residual organic matter in the slime was predominantly polysaccharide in nature. The nitrogenous material had been almost completely utilized by saprophytic microorganisms. The mineral matter consisted of entrapped rock fragments (silica and aluminium) along with iron and manganese oxides adsorbed in the polysaccharide material.

TABLE 2. DATA SUMMARY FROM CASE HISTORIES OF CLOSED CONDUITS EXPERIENCING EXCESSIVE FRICTIONAL LOSSES DUE TO SLIMES

Reference	MINKUS (1954)	MINKUS (1954)	POLLARD (1959)	ARNOLD (1963)	WIEDERHOLD (1949)	DERBY (1947)
Diameter (in.)	42	36	132	36	24	14
Length (miles)	7	7	4.5	22	50	1.25
Surface	Cement	Concrete	Concrete–steel	Steel	Steel	Steel
Slime thickness (in.)	$\frac{1}{32}$–$\frac{1}{16}$		$\frac{1}{2}$	$\frac{1}{8}$–$\frac{1}{4}$	$\frac{1}{40}$	
Frictional head (ft)			15 ft–900 ft^3 s^{-1}			
Loss in capacity (as % of design capacity)	12 (2 yr)	23		16 (3 wk)	55 (3 yr)	35 (3 yr)
Chemical added	Chlorine*		Lime	Chlorine–ammonia		Chlorine
Chemical concentration (mg l^{-1})	50		20	0.7–0.2		9–12

* Accompanied by flushing at 6 ft s^{-1}.

CHEMICAL CONTROL OF SLIMES

The effectiveness of a slimicide is usually determined by observing the reduction in cell number with different concentrations of additive and different reaction times (MUELLER, 1968; STUNDL, 1963). Determinations of this type are frequently carried out in well-mixed, batch reactors and frequently omit adsorption of the chemical on solids and reaction with other chemicals in the system. Consequently, estimates pertaining to the amount of chemical required are frequently low (CURTIS, 1969; FREEDMAN, 1967; STUNDL, 1963). Cell counts are usually made on non-specific culture medium and all cells growing on the media are studied. This procedure is based on three questionable assumptions: (1) all cells growing on the medium are slime-forming organisms, (2) slime producing organisms react to the chemical additive in the same was as other organisms, and (3) organisms react to the additive in the same way in attached or suspended form.

Neutralization of bacterial poisons by other substances may not be a function of their concentration in the bulk fluid, but rather on their concentration at the bacterial surfaces. Diffusion rates of bacterial inhibitors are decreased by increases in the viscosity of the suspending fluid, a factor to which the capacity of bacteria to produce and accumulate slime material makes an important contribution. The production of slime layer material capable of reacting with a disinfectant, further reduces the effective concentration of the disinfectant (LAMANNA, 1965).

LAMANNA (1965) notes that increased resistance against chemical disinfection in the presence of organic matter might on occasion be due to a process of dehydration. Extensive hydration of organic matter could reduce the thermodynamic activity of water (polysaccharides are highly hydrated organic molecules). Presumably such a mechanism would be effective when a disinfectant functions by means of either harmful hydrolysis or denaturation of proteins (e.g. hypochlorite). It is possible that this type of mechanism could be at work in the attack of attached bacterial growth by chlorine.

Slimicides

Chlorine, in various forms is the most feasible substance for large scale use as a slime control compound (CURTIS, 1969; MUELLER, 1968; SANBORN, 1944). Sodium hypochlorite and chlorine gas are equally effective below breakpoint concentrations with equal amounts of available chlorine (SPRINGS, 1957). Because of its reactivity, however, chlorine frequently is dissipated in side reactions reducing its disinfectant power. Under such conditions, other bactericides become economically more attractive.

Chlorine dioxide possesses 2.6 times the oxidizing power of chlorine. It oxidizes without chlorination and destroys microorganisms by reaction with the cell structure and by accelerating metabolism to the detriment of cell growth (LOVELY, 1966) or by inhibiting protein synthesis (BENARDE *et al.*, 1967). CRAVENS (1966) claims that ClO_2 cleans away slime particles to which inorganic residues attach on surfaces of pipes and vats. In this way it removes the primary means of slime adhesion. CHARACKLIS (1970) suggests a similar mechanism with regard to the effect of hypochlorite on microbial slimes. ClO_2 has also been effective in control of iron bacteria (PIATEK, 1969).

Acrolein is effective as a broad spectrum bactericide and slimicide. Its effectiveness is attributed to its reaction with protein sulfhydryl groups (HERBLE, 1968). It is advantageous in waters with high chlorine demand because it does not react with most oxidizable materials. In steel lines, it has a tendency to adsorb to the pipe wall thereby decreasing its activity.

Other substances such as silver, copper, chlorinated phenols and quaternary ammonium compounds have been used with limited success as slimicides (CHAMBERS, 1966; MAGUIRE, 1956; MUELLER, 1968; NASON, 1938). Frequently more than one compound is needed and methods and frequency of feeding must be varied for each situation (CHAMBERS, 1966).

MUELLER and LITSKY (1968) conducted experiments on a specific slime organism, *Sphaerotilus natans*, in order to determine the amount of chemical required for control. The following chemicals were tested:

	Active ingredient
Clorox (Clorox Co., Oakland, California)	Sodium hypochlorite
Chlorine Dioxide (prepared in lab.)	Chlorine dioxide
Busan 90 (Beckman Lab., Memphis, Tenn.)	2-Bromo-4-hydroxy-acetophenone
Slimacide V-10 (Vineland Chemical Sales Co., Vineland, N.J.)	Bis-1, 4-bromoacetoxy-2-butene

The tests were conducted at 80°F. in distilled water and also in paper mill process water using three different contact times. The results show the concentration of the chemical needed for 100 per cent kill.

	Distilled water			Paper mill		Process water
Time (min)	30	60	120	30	60	120
Clorox (ppm)	9	6	5	5	4	4
Chlorine dioxide (ppm)	9	6	5	12	11	11
Busan 90 (ppm)	10	10	9	16	15	14

At high levels of hypochlorite, formation of soluble products is evident (HULLINGER, 1963). Oxidation of starch granules seems localized to some extent and once it has begun on a certain portion of the carbohydrate molecule, it continues on that same portion to produce a highly degraded acidic fragment.

DYDEK (1972) presents incomplete data suggesting a shift in molecular weight of microbial polysaccharides following hypochlorite addition. Conclusive data does indicate a greater decrease in suspended solids (measured by filtration) for bacteria with large amounts of capsular material indicating that hypochlorite solubilizes portions of the microbial polysaccharide envelope.

The effect of hypochlorite on attached microbial growths in an experimental apparatus has been attributed to oxidation of biologically produced polymers in slime which are subsequently released from the surface (CHARACKLIS, 1970). The bactericidal nature of hypochlorite did not significantly influence the removal of slime as evidenced by parallel studies using mercuric ion as a microbial poison.

Role of microbial polymers

Chemical additives, slimicides, have been conceptually presumed to "disinfect" the pipeline, i.e. the slime is "killed" by the chemical, resulting in a decrease in frictional resistance in the pipeline. Previous investigators suggested, however, that the hypothesis of a dead slime may not be tenable (CURTIS, 1969; MINKUS, 1954; SANBORN, 1944; STUNDL, 1963). The data from recent research suggest that hypochlorite reacts with polysaccharide material in the slime causing direct release of organic matter into solution or indirect removal by fluid shear forces at surface irregularities formed by the chemical reaction (CHARACKLIS, 1970).

Investigations by CHARACKLIS (1971) suggest that released polymers play a role in the observed drag reduction following hypochlorite additions. PATTERSON *et al.* (1969) and many others describe the high drag reductions obtained through the addition of small amounts (10–10,000 mg l^{-1}) of certain soluble polymers to the fluid. KENIS (1968a, 1971) reports similar results for bacterial polysaccharide.

Polymer material injected into the boundary layer of turbulent pipe flow has a tendency to decrease frictional resistance (PATTERSON *et al.*, 1969; SEYER, 1966; NICODEMO *et al.*, 1969). The slime material is certainly at or near the boundary layer in flow of this nature, consequently the polymer being released by the slime could be causing a drag reduction in the pipeline.

Patterson describes a different approach to drag reduction involving the use of a thin visco-elastic liquid layer injected near the wall to form an annular film around a viscous flowing fluid. This technique has caused spectacular drag reduction in certain applications. A similar process may be the continued release of polymers from slime layers in pipelines which occurs under conditions of high shear forces and low organic carbon concentration (RENN, 1969).

ASTARITA (1965) has suggested that drag reduction by polymer solutions is caused by visco-elasticity. The results lend support to interpretations based on the idea of reduced energy dissipation rate in turbulent flow of visco-elastic liquids. SCHUSTER (1971) has conducted rheological tests on actual biological slime and results indicate an elastomertype material.

KENIS (1968) also presented results clearly demonstrating that some suspended bacteria can enhance the drag-reducing properties of the growth medium. Bacteria from

Horbund H. M. and Freiberger A. (1970) Slime films and their role in marine fouling: a review. *Ocean Engng* 1, 631–634.

Hullinger C. H. (1963) Hypochlorite-oxidized starch. *Methods Carbohyd. Chem.* Vol. II, 313–315.

Jennings D. M., Littauer E. L. and Woodhouse J. R. (1967) *Marine Fouling and Anti-fouling Techniques.* Lockheed Aircraft Service Co., Marine Research Laboratories.

Kenis P. R. (1968a) Drag reduction by bacterial metabolites. *Nature* 217, 940–942.

Kenis P. R. (1968b) Effects of pH on the production of bacterial extracellular drag-reducing polymers. *Appl. Microbiol.* 16, 1253–1254.

Kenis P. R. (1971) Turbulent flow friction reduction effectiveness and hydrodynamic degradation of polysaccharides and synthetic polymers. *J. appl. Polym. Sci.* 15, 607–618.

Lamanna C. and Mallette M. F. (1965) *Basic Bacteriology.* Williams & Wilkins, Baltimore.

Lee R. W. H. (1962) Marine fungi and algae—their fouling problems and control, prevention of deterioration center. National Academy of Science, PDL 44131.

Lovely C. F. (1966) The use of stable chlorine dioxide complex in water treatment. Presented to New Jersey Section, AWWA, Atlantic City, N.J.

Maguire J. J. (1956) Biological fouling in recirculating cooling water systems. *Presented at 129th ACS Meeting* (April).

Minkus A. J. (1954) Determination of the hydraulic capacity of pipelines. *J. New Engl. Wat. Wks Ass.* 68, 1–10.

Mueller W. S. and Litsky W. (1968) Effect of various chemical agents for the inhibition of *Sphaerotilus natans* in paper mill process water. *Water Research* 2, 289–296.

Nason H. K. (1938) Chemical Methods in slime and algae control. *J. Am. Wat. Wks Ass.* 30, 437–452.

Nicodemo L., Acierno D. and Astarita G. (1969) Velocity profiles in turbulent pipe flow of drag-reducing liquids. *Chem. engng Sci.* 24, 1241–1246.

Patterson G. K., Zakin J. L. and Rodriquez J. M. (1969) Drag reduction. *Ind. engng Chem.* 61, 22–30.

Piatek A. (1967) Preventing filamentous scale in well water. *Wat. Wastes Engng* 4, 54–55.

Pollard A. L. and House H. E. (1959) An unusual deposit in a hydraulic tunnel. *J. Pwr Div. Am. Soc. civ. Engrs* 85, PO6, 163–171.

Sanborn J. R. (1944) Slime-producing coliform and coliform-like bacteria. *J. Bact.* 48, 211–217.

Schlicting H. (1960) *Boundary Layer Theory*, 4th edn. McGraw-Hill, New York.

Schuster H. (1971) Fluid friction in the presence of non-rigid boundaries. Ph.D. Thesis, Johns Hopkins University.

Seifert L. and Kruger W. (1950) Unusually high friction factor in a long, water supply line. *VDI Z* 92, 189–191.

Seyer F. A. and Metzner A. B. (1969) Turbulence phenomena in drag-reducing systems. *Am. Inst. Chem. engng J.* 15, 420–434.

Springs J. D. (1957) Hypochlorination for slime control. *Power* 101, 102–104.

Stundl K. (1963) Testing the effect of inhibiting substances on slime-producing bacteria in recirculating water in paper factories using stirred cultures. *Zentbl. Bakt.* 91, 203–208.

Whistler R. L., Linke E. G. and Kazeniac S. (1956) Action of alkaline hypochlorite on corn starch amylose and methyl 4-o-Methyl-D-Glucopyranosides. *J. Am. chem. Soc.* 78, 4704–4709.

Whistler R. L. and Schweiger R. (1957) Oxidation of amylopectin with hypochlorite at different hydrogen ion concentrations. *J. Am. chem. Soc.* 79, 6460–6464.

White A., Handler P. and Smith E. L. (1968) *Principles of Biochemistry*, 4th edn. McGraw-Hill, New York.

Wiederhold W. (1949) Effect of wall deposits on hydraulic loss in pipelines. *Gas WassFach.* 90, 634–641.