



## LIQUID-SIDE FOULING OF HEAT EXCHANGERS. AN INTEGRATED R & D APPROACH FOR CONVENTIONAL AND NOVEL DESIGNS

A. J. Karabelas,\* S. G. Yiantsios,\* B. Thonon† and J. M. Grillot†

\*Chemical Process Engineering Research Institute and Department of Chemical Engineering,  
Aristotle University of Thessaloniki, P.O. Box 1517, GR 540 06, Thessaloniki, Greece and

†Groupment pour la Recherche sur les Echangeurs Thermiques, 17 av des Martyrs, 38054, Grenoble,  
Cedex 9, France

**Abstract**—Particulate fouling of heat exchangers is a major fouling category with very significant technical and economic implications. It is studied here as part of a study aimed at improving design standards for novel and conventional heat exchangers. New fouling data are reported for plate heat exchangers (of two angles of corrugation, 30 and 60°) and particles of mean size  $\sim 5 \mu\text{m}$ . The flow passage geometry and the fluid velocity have a strong effect on the fouling resistance  $R_f$ . These results show that fouling (under the test conditions) is adhesion controlled and that the maximum measured resistance  $R_f$  is almost an order of magnitude smaller than the TEMA recommendations. Particle adhesion and removal from flat surfaces leads to improved understanding of particulate fouling mechanisms and facilitates interpretation of the above data. Tangential hydrodynamic forces appear to be responsible for particle detachment. For a specific particle size, a distribution of adhesive strengths is obtained (and not a single value), which is strongly influenced by pH and may be time-dependent for very small sizes. Various applications of the new results are outlined, including the interpretation of the measured adhesive force distributions in terms of the well-known particle sticking probability. © European Communities 1997. Published by Elsevier Science Ltd.

**Keywords**—Heat exchangers, compact types, particulate fouling, liquids, sticking probabilities.

### NOTATION

$C_0$	initial particle concentration, $\text{kg}/\text{m}^3$
$C^*$	final particle concentration, $\text{kg}/\text{m}^3$
$d$	particle diameter, m
$F$	hydrodynamic force, N
$k$	thermal conductivity, $\text{W}/\text{mK}$
$M^*$	final deposit mass per plate, kg
$m$	deposit mass per unit area, $\text{kg}/\text{m}^2$
$R_f$	fouling resistance, $\text{m}^2\text{K}/\text{W}$
$R_f^*$	asymptotic fouling resistance, $\text{m}^2\text{K}/\text{W}$
$t$	time, s
$t_c$	time constant, s
$U$	heat transfer coefficient, $\text{W}/\text{m}^2\text{K}$
$u^*$	shear velocity, $\text{m}/\text{s}$

#### Greek letters

$\nu$	kinematic viscosity, $\text{m}^2/\text{s}$
$\rho$	deposit density, $\text{kg}/\text{m}^3$
$\tau_w$	hydrodynamic wall shear stress, $\text{N}/\text{m}^2$
$\Phi_d$	mass deposition rate, $\text{kg}/\text{m}^2 \text{ s}$
$\Phi_r$	mass removal rate, $\text{kg}/\text{m}^2 \text{ s}$

### INTRODUCTION

Progress has been made over the past 10 years in almost every aspect of designing and operating heat exchangers, with one possible exception, i.e. procedures for reliably taking into account fouling. Although the fouling resistance  $R_f$  is established as a convenient and representative quantity for design, its temporal variation as a function of the many problem variables (mainly those representing water properties, flow characteristics and temperatures) cannot be predicted at present with any degree of confidence. The thermal resistance  $R_f$  vs time curve [1], which is typical of most cases of cooling water fouling, is characterised by an asymptotic value ( $R_f^*$ ) prevailing at

long times and by a time constant  $t_c$ . A frequently used expression, relating the above quantities, is as follows:

$$R_f = R_f^*[1 - \exp(-t/t_c)]. \quad (1)$$

The open literature does not provide clear guidance on how to account for fouling in heat exchanger design, despite some commendable efforts, e.g. ref. [2]. Indeed, the designer is instructed [1, 2] either to use 'experience' or to consult the TEMA standards, i.e. a simple list of  $R_f$  values for various categories of water. The inadequacy of the TEMA recommendations is evident, since all the major process variables are essentially ignored. This poor state of technology has serious consequences. For instance, the present design practices usually result in oversizing heat exchangers, thus substantially raising plant capital investment. Water treatment to cope with fouling may be also responsible in certain cases for the use of environmentally undesirable additives. Therefore, the main objective of this project is to investigate the fouling behaviour of conventional and novel heat exchangers in order to develop improved design and operating procedures.

In this paper, reference is made only to the two main types of fouling, i.e. particulate and precipitation. Biofouling is not considered, assuming that biocides are effective. Generally, two processes compete to determine deposit characteristics; i.e. deposition and removal, so that the net deposition flux is given as

$$\frac{dm}{dt} = \Phi_d - \Phi_r, \quad (2)$$

where  $\Phi_d$ ,  $\Phi_r$  are the intrinsic deposition and removal fluxes, respectively. Adequate understanding of both processes appears to be a prerequisite to successfully correlating the composite  $R_f$  vs time curve. Deposition has been studied extensively in conventional configurations but not in novel heat exchanger designs. Nevertheless, significant aspects of this process remain unclear. Deposit removal, in contrast, has been very inadequately researched and poorly understood, despite its great significance in determining asymptotic fouling rates [3].

The following were main activities to achieve the study objectives:

1. Experiments with novel (i.e. compact) heat exchanger designs as well as with a conventional configuration to investigate their fouling behaviour. Particular attention was paid to particle detachment as it affects overall fouling rates.
2. On the basis of data from this project and from other sources, an assessment of presently used standards was made, to narrow the margin of uncertainty and to improve design recommendations.
3. Experimental procedures were evaluated in order to develop guidelines for standardizing fouling measurement methods.
4. A typical cooling water circuit was computer-simulated to identify the influence of overall process parameters on fouling. Partners in the study were the Chemical Process Engineering Research Institute (CPERI), Thessaloniki; Groupment pour la Recherche sur les Echangeurs Thermiques (GRETh), Grenoble; AEA Technology, Harwell; National Engineering Laboratory (NEL), Glasgow; and Vicarb S.A., Grenoble.

This paper is focused on one major area of the project, which is particulate fouling, with emphasis on compact heat exchangers. New data obtained at GRETh with plate heat exchangers are reported first. Results obtained, on particle adhesion and detachment, in well-controlled experiments are presented next. These results are of general applicability; but they are also employed here to interpret the data from plate heat exchangers.

#### PARTICULATE FOULING OF COMPACT HEAT EXCHANGERS

Fouling studies of new configurations of compact heat exchangers were carried out by GRETh. The tests were carried out in an experimental liquid/liquid heat transfer facility (OSCAR loop), where two full-scale plate heat exchangers with different corrugation angles have been installed. The corrugation angle is a major parameter influencing hydraulic and thermal performance.

Table 1. Experimental conditions of tests at GRETh with a corrugated plate heat exchanger

Velocity, m/s	Time, h	$C_o$ , g/l	$C^*$ , g/l	$U$ (30), W/m <sup>2</sup> K	$U$ (60), W/m <sup>2</sup> K	$R_f^*$ (30), m <sup>2</sup> K/W	$R_f^*$ (60), m <sup>2</sup> K/W	$M^*$ (30), g	$M^*$ (60), g
0.35	227	4.50	1.66	3380	7380	$13.5 \times 10^{-5}$	$4.20 \times 10^{-5}$	117.3	37.4
0.5	90	4.47	4.27	4010	9970	$10.1 \times 10^{-5}$	$0.96 \times 10^{-5}$	103.4	
0.5	216	4.24	3.90	3820	8660	$9.6 \times 10^{-5}$	$2.5 \times 10^{-5}$	167.3	46
0.75	70	4.40		4160	9220	$3.25 \times 10^{-5}$	$0.2 \times 10^{-5}$		
1.0	210	4.45	4.40	4900	10480	$3.0 \times 10^{-5}$	$0.0 \times 10^{-5}$	42.9	
1.35	330	4.40		5560	11600	$1.7 \times 10^{-5}$	$0.3 \times 10^{-5}$	26.3	

Experiments have focused on particulate fouling at conditions representative of those in industrial plants.

The two heat exchangers had 10 channels per fluid pass and were identical in their geometrical characteristics, except for the corrugation angle which was 30 and 60°, respectively. The exchangers were connected in series and supplied by the fouling fluid, which was prepared by adding CaCO<sub>3</sub> particles (Solvay 90A) to demineralised water and was kept in a stirred tank. Heating and cooling of the exchangers was accomplished by supplying particle-free fluid at controlled temperatures and flow rates. Measurements included independent flow rates for each branch of the fouling-side circuit, temperatures at the entrance and exit of each exchanger, particle concentration and granulometry during the course of experimental runs, using a MALVERN Mastersizer X, and deposit mass in all channels at the end of tests by weighing. The mean particle size was 5 mm and granulometry was not altered during the 100–300 h of experiment duration. Based on these measurements the initial thermal performance, as well as the evolution of fouling resistance was determined.

Six different tests were performed with the same particles. The initial concentration was approximately 4.4 g/l, which remained constant during the course of the experiments, except for the test at low velocities (0.35 m/s). The operating parameters and the main results are summarised in Table 1.

For the 60° corrugation angle heat exchanger at high velocities the fouling resistance remains negligible and mass measurements are not possible. At low velocities ( $u < 0.75$  m/s) the deposit is scarce and mainly located downstream of the contact points, in contrast to the 30° exchanger where the deposit is quite uniform. Comparison between deposit mass and fouling resistance suggests that

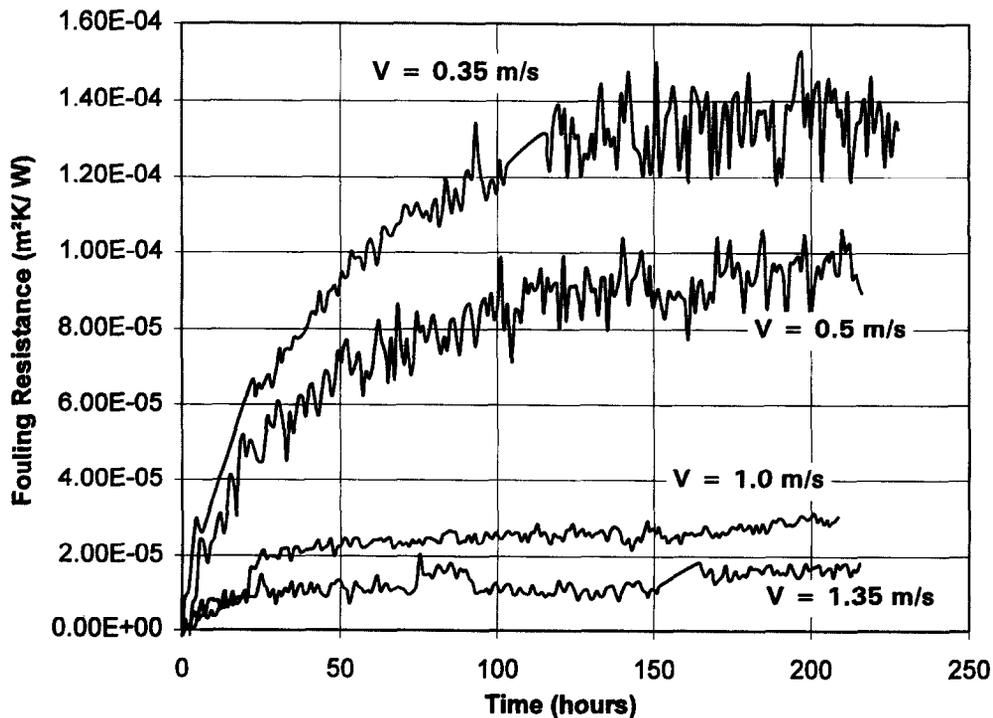


Fig. 1. Effect of flow velocity on the fouling resistance evolution of a 30° corrugation angle plate heat exchanger fabricated by Vicarb.

the two quantities are not proportional, as is also evident from the non-uniform deposit distribution.

Figure 1 shows the evolution of fouling resistance for the 30° heat exchanger at different velocities. It appears that the initial slope of these curves tends to decrease with increasing velocity, which is contrary to a convective transport-controlled mechanism. Furthermore, on the assumption that the product  $\rho k$  of scale density and thermal conductivity remains constant, the above behaviour may be indicative of an adhesion-controlled process. In all cases an asymptotic fouling behaviour is exhibited. A strong velocity effect exists and this is also observed with the 60° exchanger. The effect of velocity on the asymptotic fouling resistance for the two exchanger configurations is further shown in Fig. 2. This behaviour suggests that particle detachment plays a dominant role and that the fouling process is, indeed, adhesion controlled [4]. These results are supported by independent detachment measurements with similar particle sizes carried out at CPERI, as outlined in the following section.

It will be noted that in the velocity range of practical interest (e.g. for  $u > 0.5$  m/s), the measured asymptotic fouling resistance is much smaller (by almost an order of magnitude) than the recommended TEMA values ( $R_f \cong 3.5 \times 10^{-4}$  m<sup>2</sup>/WK). However, this is not the first time such a discrepancy has been observed in plate heat exchangers; see, for example, Cooper *et al.* [5].

Comparison of the performance of the two types of heat exchanger suggests that the zigzag flow pattern associated with high corrugation angles leads to better heat transfer performance and induces significantly lower fouling than the furrow flow structure at small corrugation angles. However, the former is associated with a greater pressure drop than the latter. Therefore, an overall performance assessment for constant heat duty must take into account the capital cost of the extra surface required to counterbalance the fouling resistance, as well as the operating (pumping) expenses. Obviously, flow velocity and heat exchanger (flow passage) geometry affecting, in opposite directions, fouling resistance and operating expenses (pressure drop) are the main design variables in such an optimisation procedure.

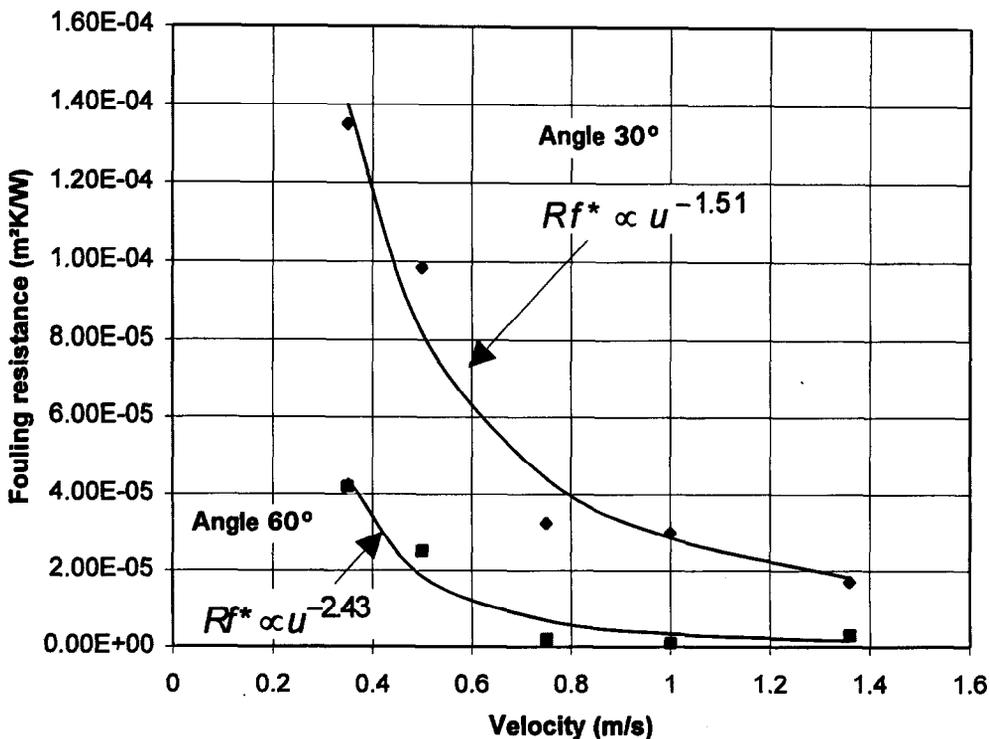


Fig. 2. Asymptotic fouling resistance as a function of velocity for two plate heat exchangers of 30 and 60° corrugation angles.

## PARTICLE DETACHMENT FROM FLAT SURFACES

The problem of removal is very complicated since it involves stresses due to fluid flow exerted on generally irregular particle assemblies (or 'layers') deposited on a surface. In a recent theoretical effort [3] this physical situation was modelled by linking removal to the morphological and mechanical characteristics of deposit microstructure. A central issue in all these efforts was the nature and strength of adhesive bonds holding microscopic particles attached to each other or to flat surfaces. The study of particle detachment from flat surfaces, summarised here, provides valuable information in that respect.

*Forces involved*

At the fundamental level, one can recognise two key issues that must be addressed in order to understand the behaviour of an isolated particle in contact with a flat surface; first, the physicochemical interactions that keep a particle attached on the surface and determine the nature and strength of the respective adhesive bond; and, second, the hydrodynamic interactions due to the flowing fluid which tend to break the adhesive bond between the two surfaces and dislodge the particle.

Regarding the first aspect, considerable research efforts have been conducted over the years to establish the nature of physicochemical interactions [6–8] and explain them in terms of London–van der Waals electrostatic interactions and the so-called 'structural' forces. However, when a particle overcomes any possible electrostatic potential barriers the two adhering surfaces approach each other to within not more than a few molecular diameters. Thus, any treatment using the macroscopic DLVO theory [9] or any possible extensions thereof may be inadequate. The whole picture is further complicated by the magnitude of surface roughness, which may very well exceed the contact area estimated for hypothetically smooth particles. Finally, it is pointed out that the macroscopic DLVO theory predicts only central interactions, while the resistance of adhering surfaces to tangential loads and couples is an issue not clearly elucidated. Surface inhomogeneity or roughness has to be invoked to predict such effects [10].

Regarding the aspect of hydrodynamic forces, the issues are much more clear, although misunderstandings still exist in the literature. Thus, for particles in the micron-size range which are usually deeply immersed in the viscous sub-layer of a turbulent flow, the major hydrodynamic forces can be found from the analysis of O'Neill [11]. This predicts forces parallel to the flowing

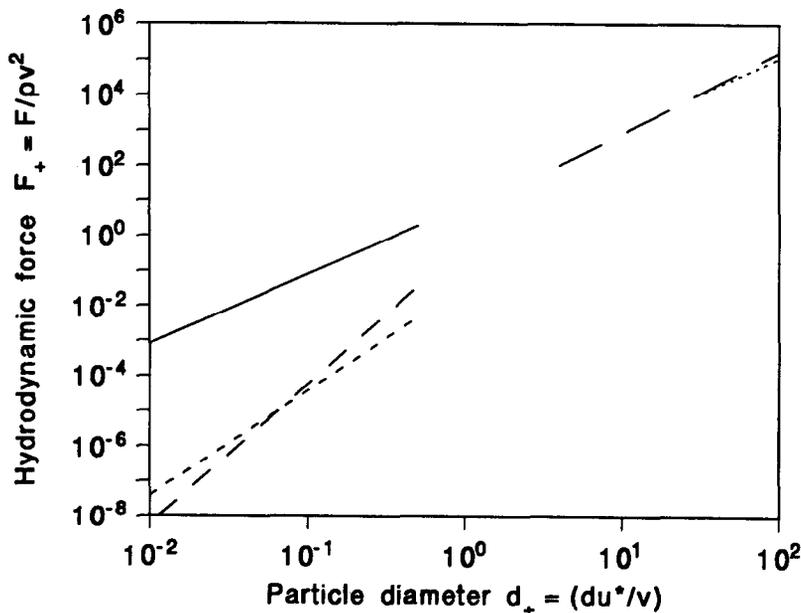


Fig. 3. Hydrodynamic forces on spherical particles resting on a flat substrate. — Tangential force [11]; - - - lift force [12], - . - lift force [14]; — — — experimental lift forces [15]; · · · experimental lift and drag forces [16].

fluid and the flat substrate. Lift forces, which can be found from the analysis of Leighton and Acrivos [12], due to inertial effects, and of Goren and O'Neill [13], due to the fluctuating normal velocity components, are much less significant. These observations cast doubt on the relevance of the only existing theory of particle detachment by Cleaver and Yates [14], which is based on the action of random lift forces.

The above theoretical results for microscopic particles are summarised in Fig. 3, together with some experimental data for larger particles [15, 16], which are included here for completeness. Forces and particle diameters are non-dimensionalised in the Figure using turbulent flow wall parameters. An inspection of Fig. 3 suggests that, indeed, tangential forces dominate for particles in the colloidal size range. Therefore, understanding the response of an adhesive contact to tangential forces should be of primary importance in any effort to describe detachment phenomena.

#### *Experimental set-up and procedure*

Two glass plates 10 cm long by 4.5 cm wide and 3 mm thick were separated by Teflon strips 0.5 mm thick, thus creating a narrow channel of 1 cm width and 0.5 mm clearance. A special test-section has been constructed of SS 316, which included entrance and exit sections providing smooth transition to channel flow. Wall shear stresses from 1 up to 1000 dynes/cm<sup>2</sup> could be achieved while maintaining laminar, steady, fluctuation-free and fully developed flow.

The test-section was placed under a microscope equipped with a vidicon camera which was connected to a monitor and a video recorder. The latter was also connected to a mini-computer through a frame grabber board so that selected images could be digitised and stored for processing with image-analysis software.

Spherical Ballotini glass particles were used in the test. Samples of mean diameter 2, 5, 10 and 15  $\mu\text{m}$  have been fractionated to obtain nearly monodispersed size distributions with a standard deviation of  $\sim 12\%$ . A dilute suspension of particles (after being ultrasonicated) was injected into the narrow channel and the particles were allowed to settle by gravity. In this way a sparse deposit was created, yet containing a significant number of particles (150–300) within the field of view. Distilled water (filtered through a Millipore membrane with a nominal pore size of 0.22  $\mu\text{m}$ ) was used, with a conductivity of 1.5  $\mu\text{S}/\text{cm}$ . Solution pH was adjusted using HNO<sub>3</sub> or NaOH.  $\zeta$ -Potentials of the particles in the same test solutions were measured using the flat cell of a Rank Brothers Mark II microelectrophoresis apparatus. The  $\zeta$ -potentials of the glass plates were

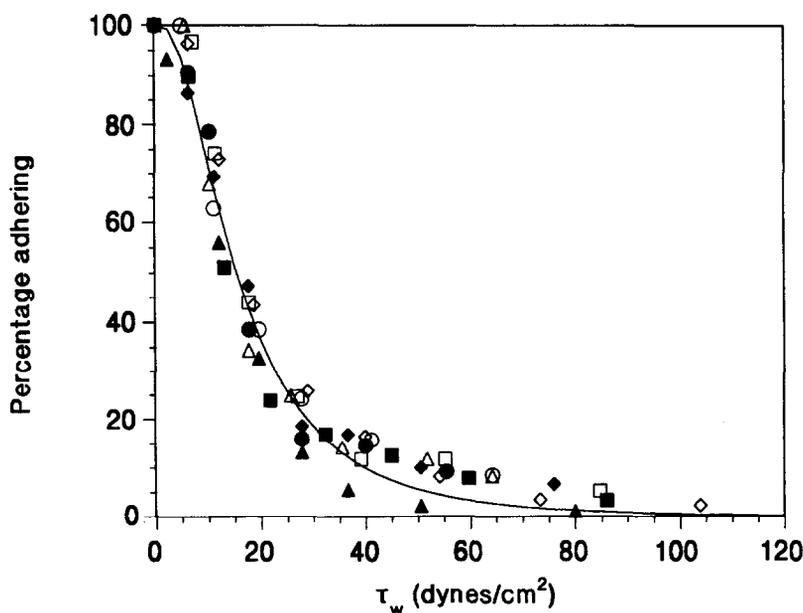


Fig. 4. Adhesive strength distribution of 5  $\mu\text{m}$  particles for pH 2. Settling time:  $\circ$ ,  $\bullet$  1 h;  $\triangle$ ,  $\blacktriangle$  2 h;  $\diamond$ ,  $\blacklozenge$  4 h;  $\square$ ,  $\blacksquare$  8 h. — Data fitting by a log-normal distribution.

measured using the streaming potential technique. As expected for  $\text{SiO}_2$ , the  $\zeta$ -potential was close to zero at pH 2, becoming progressively more negative as the pH was raised.

During an experiment the flow rate was kept at a certain level until all particles amenable to detachment were removed, then it was gradually increased to a higher level, and the procedure was repeated until all the particles were removed from the surface. Images of the particles at each level of flow rate were analysed to obtain the number and coordinates of each particle, which were then compared (using a computer program) to determine the fraction of particles adhering at each level of flow rate. Flow rates were converted to wall shear stresses through well-known hydrodynamic relations for channel flow, which included a correction for the finite channel aspect ratio.

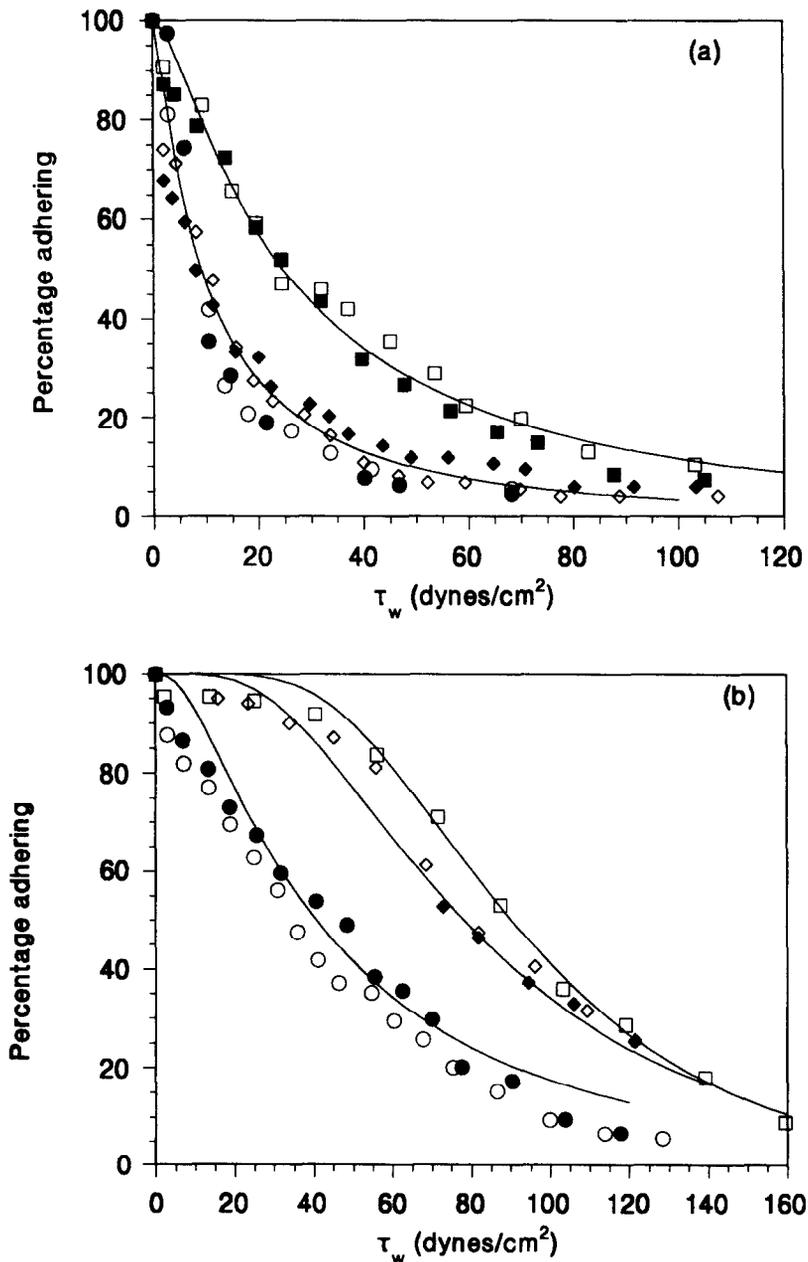


Fig. 5. Adhesive strength distribution of  $5 \mu\text{m}$  particles for pH 3. Settling time: (a)  $\circ$ ,  $\bullet$ ,  $\diamond$ ,  $\blacklozenge$  1 h;  $\square$ ,  $\blacksquare$  4 h; (b)  $\circ$ ,  $\bullet$  8 h;  $\diamond$ ,  $\blacklozenge$  24 h;  $\square$  44 h.

### Results

In Fig. 4, the adhesive strength distribution of  $5\ \mu\text{m}$  particles for pH 2 is shown as the percentage of adhering particles versus the applied wall shear stress. This can be converted to hydrodynamic force applied on the particle through the well-known relation  $F_H = 8\tau_w d_p^2$ . As expected from similar experiments in the literature, it is not a single-valued force that removes all the particles but rather a continuous distribution of forces. As shown in the Figure caption, the particles were allowed to settle on the substrate between 1 and 8 h. Yet, no strengthening of the adhesive bonds is evident and it can be concluded that no time effects exist at these particular conditions.

In Fig. 5, similar adhesive strength distributions are shown for pH 3. Different symbols on the same graph refer to different experiments under identical conditions, indicating that the reproducibility of the results is satisfactory. It is now apparent that at pH 3 time effects exist and the adhesive strength is increased as the time before commencement of detachment is increased.

In Fig. 6 the shear stress at which 50% of the particles are removed is plotted versus the 'settling' time. It can be seen that an asymptote is approached, suggesting that no chemical bonds are involved (which would cause irreversible binding of the particles on the substrate) but only forces of physicochemical nature. Another observation is that the adhesive forces become much higher than in the pH 2 case. This may be considered counter-intuitive, since one would expect the opposite, given the absence of any electrostatic force barriers at pH 2, as the  $\zeta$ -potential measurements suggest. However, as already mentioned, adhesive contacts are not necessarily explained in terms of the macroscopic DLVO theory. The reduced tendency of silica surfaces for coagulation for pH 2 may be attributed to the presence of hydration layers hydrogen-bonded to the surface SiOH groups [17].

Observations with particles of different sizes indicate that similar time effects exist for smaller particles ( $2\ \mu\text{m}$ ) but not for larger ones ( $10$  and  $15\ \mu\text{m}$ ). This suggests that gravity, which is the sole force driving the particles toward the surface, is sufficient to overcome any possible electrostatic barriers and bring the particles quickly to adhesive contact, while for smaller particles the two opposing forces are closer to each other and thus a longer time period is necessary.

Another important issue is the dependence of the force at 50% removal on particle size, shown in Fig. 7. Long time values are used for the  $2$  and  $5\ \mu\text{m}$  particles where time effects are observed. The data are fitted with the expression  $\tau_w = 300 R^{-1.8}$ , where  $R$  is the particle radius. Theoretical arguments [18] concerning adhesive contacts, subject to tangential loads and couples, in connection with the experimentally determined dependence of  $\tau_w$  on particle size, suggest that a rolling mechanism prevails. This is in agreement with results from recent similar investigations in the

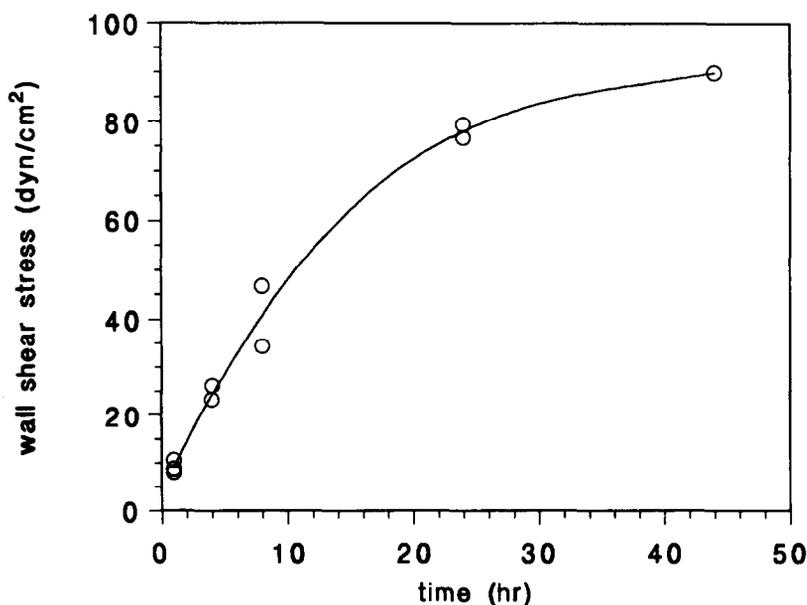


Fig. 6. Wall shear stress for 50% removal of  $5\ \mu\text{m}$  particles as a function of time; pH 3.

literature [19]. Furthermore, the resistance to rolling appears to be determined by surface microroughness.

### *Practical application of results*

Studies such as the one outlined here can provide valuable information concerning minimum flow rates and shear stresses required (under given particulate fouling conditions) for hydrodynamic detachment to prevail, and for eliminating any deposit layer and thermal resistance  $R_f$ . Adhesive force distributions were obtained under all conditions studied rather than sharply defined adhesive forces. It is proposed that these distributions are closely related to the concept of sticking probability, frequently employed to correlate particulate deposition data. Indeed, by definition, sticking probability is the measure of a particle's ability to overcome electrostatic barriers and hydrodynamic forces and adhere on the substrate. It is evident, therefore, that simple correlations accounting for the effect of the hydrodynamic shear stress are not sufficient. Physicochemical conditions and the nature of the adherents (particles and substrate) are equally important factors. The significance of this observation for practical applications is fairly obvious, i.e. using the techniques developed in this study one may be able to determine sticking probabilities for various particles, fluids and substrates.

It may be further suggested that the measured shear stresses are representative of the shear stresses required for detachment of a class of particles such as sand, silt, various oxides, etc. For particle sizes larger than  $\sim 5 \mu\text{m}$  the measured shear stresses for detachment were comparable to or lower than those usually encountered in heat transfer equipment. Therefore, the deposition of such particles will, in general, be adhesion controlled and the increase of deposition rates with velocity, as predicted by transport theories, may not be observed. Instead, a decrease of deposition rate with velocity may be the rule. For particles in the micron and colloidal-size range, in contrast, rather severe hydrodynamic conditions appear to be required for detachment. However, for such particles time effects exist in the process of deposition so that the measured adhesive forces may represent an overestimate of their sticking probability. Additionally, physicochemical interactions become increasingly important and it is well known that stable colloidal suspensions produce only particle monolayers on the substrate. Further deposition is inhibited by unfavourable physicochemical interactions between deposited and suspended particles [20, 21]. Colloidal suspensions produce significant deposits only when they are unstable, in which case bulk aggregation also takes place, leading to an effective particle size which is different from that of the primary units [22]. Several datasets from the particulate fouling literature appear to agree with these

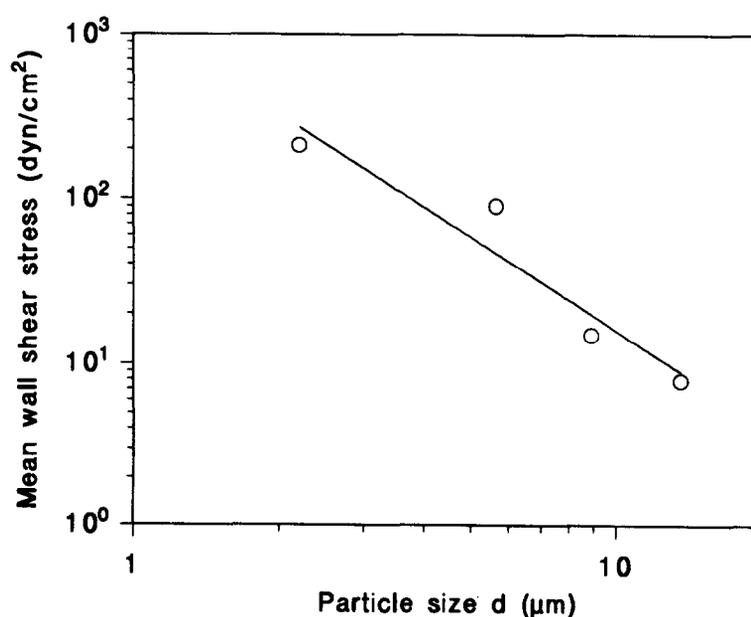


Fig. 7. Mean hydrodynamic shear stress for 50% detachment as a function of particle size; pH 3.

observations [23], including those outlined here from the fouling experiments at GRETh, as is evident from the dependence of the initial fouling rates and the asymptotic fouling resistances on flow velocity.

Another aspect of the new results of possible practical significance is the measured time effect. The latter may essentially account for observed ageing phenomena of deposits, as yet unexplained. Furthermore, the rather accurately measured adhesion forces at single point contact provide the necessary basic information for modelling and/or computing adhesive strength due to multiple point contacts.

## CONCLUSIONS

Improvement of design standards, to cope with fouling, depends on understanding both the deposition and removal processes taking place at heat exchanger surfaces. Removal appears to be responsible for the level of asymptotic thermal fouling resistance  $R_f^*$ . Data from novel (corrugated plate) heat exchangers tend to confirm this observation. Experimental results on particulate fouling of compact heat exchangers suggest a strong effect of flow velocity, as well as a performance which is significantly better than TEMA standards recommendations. Fouling under the specific experimental conditions appears to be adhesion controlled, which is consistent with the independent observations on particle detachment. It should be pointed out, however, that this conclusion is on tenuous grounds and that more work is clearly required. In particular, better knowledge of the flow structure inside the complicated passages of a compact heat exchanger and of fluid-particle interactions seems to be essential for clarifying the respective fouling mechanisms.

Experimental results are presented on adhesion and detachment of spherical glass particles from a glass surface. They show that tangential hydrodynamic forces cause particle removal (rolling) and not lift forces occasionally referred to in the literature. For a certain particle size a distribution of adhesive forces is measured (rather than a single valued adhesion force), which is strongly influenced by pH. The force distribution may be linked with the concept of sticking probability—a parameter usually employed in correlations. A time variation of adhesive force, for very small particles, is attributed to the interplay between gravitational and electrostatic repulsive forces.

The above results (and their possible applications indicated here) suggest that careful experimentation, combined with realistic modelling, is essential for making progress in a long-standing problem such as fouling.

*Acknowledgements*—The financial support of the European Commission is gratefully acknowledged. In addition to the authors, other participants in this project were Dr N. Andritsos and Mr M. Perrakis (CPERI), Dr A. Pritchard (AEA Harwell), Dr J. H. Howarth (NEL) and Mr C. Roussel (VICARB S.A.).

## REFERENCES

1. J. G. Knudsen, Conquer cooling-water fouling. *Chem. Eng. Progress*, April, 42–48 (1991).
2. J. M. Chenoweth, General design of heat exchangers for fouling conditions. In *Fouling Science and Technology*, Edited by L. F. Melo *et al.*, pp. 477–494. Kluwer Academic, The Netherlands (1988).
3. S. G. Yiantsios and A. J. Karabelas. Fouling of tube surfaces: modeling of removal kinetics. *AIChE J.* **40**, 1804–1813 (1994).
4. N. Epstein, General thermal fouling models. In *Fouling Science and Technology*, Edited by L. F. Melo *et al.*, pp. 15–30. Kluwer Academic, The Netherlands (1988).
5. A. Cooper, J. W. Suito and J. D. Usher. Cooling water fouling of plate heat exchangers. *Heat Transfer Engng* **10**, 4, 30–36 (1980).
6. A. D. Zimon, *Adhesion of Dust and Powder*. Plenum Press, New York (1969).
7. H. Krupp. Particle adhesion. Theory and experiment. *Adv. Colloid Interface Sci.* **1**, 111–239 (1967).
8. J. Visser, Adhesion of colloidal particles. In *Surface and Colloid Science*, Edited by E. Matijevic, Vol. 8, pp. 3–84. John Wiley & Sons, New York (1976).
9. J. N. Israelachvili, *Intermolecular and Surface Forces*. Academic Press, London (1985).
10. M. Kostoglou and A. J. Karabelas. Effect of roughness on energy of repulsion between colloidal surfaces. *J. Colloid Interface Sci.* **171**, 187–199 (1995).
11. M. N. O'Neill. A sphere in contact with a plane wall in a slow linear shear flow. *Chem. Engng Sci.* **23**, 1293–1298 (1968).
12. D. Leighton and A. Acrivos. The lift on a small sphere touching a plane in the presence of a simple shear flow. *ZAMP* **36**, 174–178 (1985).
13. S. L. Goren and M. N. O'Neill. On the hydrodynamic resistance to a particle of a dilute suspension when in the neighborhood of a large particle. *Chem. Engng Sci.* **26**, 325–338 (1971).

14. J. W. Cleaver and B. Yates. Mechanism of detachment of colloidal particles from a flat substrate in turbulent flow. *J. Colloid Interface Sci.* **44**, 464–474 (1973).
15. D. Hall. Measurements of the mean force on a particle near a boundary in turbulent flow. *J. Fluid Mech.* **187**, 451–466 (1988).
16. J. D. Fenton and J. E. Abbott. Initial movement of grains on a stream bed: the effect of relative protrusion. *Proc. R. Soc. Lond., A.* **352**, 523–537 (1977).
17. R. K. Iler, *The Chemistry of Silica*, p. 373. John Wiley & Sons, New York (1979).
18. S. G. Yiantsios and A. J. Karabelas. Detachment of spherical microparticles adhering on flat surfaces by hydrodynamic forces. *J. Colloid Interface Sci.* **176**, 74–85 (1995).
19. S. K. Das, R. S. Schechter and M. M. Sharma. The role of surface roughness and contact deformation on the hydrodynamic detachment of particles from surfaces. *J. Colloid Interface Sci.* **164**, 63–77 (1994).
20. R. J. Kuo and E. Matijevic. Particle adhesion and removal in model systems. 2— Monodispersed chromium hydroxide on steel. *JCS Faraday I* **75**, 2014–2026 (1979).
21. B. D. Bowen and N. Epstein. Fine particle deposition in smooth parallel-plate channels. *J. Colloid Interface Sci.* **72**, 81–97 (1979).
22. R. Blochl and H. Muller-Steinhagen. Influence of particle size and particle/fluid combination on particulate fouling in heat exchangers. *Can. J. Chem. Engng* **68**, 585–591 (1990).
23. A. J. Karabelas. Cooling water fouling of heat exchangers. An integrated R and D approach for conventional and novel designs, EC Contract JOU2-CT93-0371, Fourth periodic report 1.7.95-31.12.95 (1996).