We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists



186,000

200M



Our authors are among the

TOP 1% most cited scientists





WEB OF SCIENCE

Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us? Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected. For more information visit www.intechopen.com



Particle Deposition in Microfluidic Devices at Elevated Temperatures

Zhibin Yan, Xiaoyang Huang, Chun Yang, Mingliang Jin and Lingling Shui

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.78240

Abstract

In microchannels, interaction and transport of micro-/nanoparticles and biomolecules are crucial phenomena for many microfluidic applications, such as nanomedicine, portable food processing devices, microchannel heat exchangers, etc. The phenomenon that particles suspended in liquid are captured by a solid surface (e.g., microchannel wall) is referred to as *particle deposition*. Particle deposition is of importance in numerous practical applications and is also of fundamental interest to the field of colloid science. This chapter presents researches on fouling and particle deposition in microchannels, especially the effects of temperature and temperature gradient, which have been frequently 'ignored' but are important factors for thermal-driven particle deposition and fouling processes at elevated temperatures.

Keywords: particle deposition, microchannel, temperature, temperature gradient

1. Fouling

In the oil and gas industry, people first studied fouling and then it begun to be often adopted to describe any undesirable deposit that led to an increase of flow resistance in fluid pipes or thermal resistance in heat exchanger [1]. Most of the published researches on fouling are focused on macro-scale phenomena and parameters, such as changes of hydraulic performances and thermal resistances. According to the causes of formation, fouling can be categorised into different types, which include crystallisation fouling, or particulate fouling, scale formation, chemical reaction fouling, corrosion fouling, biological fouling, solidification fouling and mixed fouling [2]. In this chapter, the authors will concentrate on the studies on

IntechOpen

© 2018 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

particulate fouling in microfluidic applications. Particulate fouling refers to that finely suspended solid particles accumulate onto solid surfaces. The diameters of particles are usually less than microns. Without other mechanisms having particles firmly attached onto solid surface, the deposit formed by particulate fouling is normally thin and easily removed.

2. Particle deposition

Particulate fouling is caused by particle deposition onto the solid surfaces of collectors. This is a complex process affected by diffusion, convection, colloidal, and external interaction forces. To better understand the physical process of particle deposition, it can be conceptually divided into three steps [3]:

1. Particle transport/diffusion

When particles are at large distances from the collector surface, the particles are transported from the bulk fluid to the collector by diffusion, flow convection, and migration due to external forces. Particle concentration gradients usually exist between the bulk fluids to the collector surfaces and drive the suspended particles approaching the collector surfaces. Flow convection, especially in turbulent flow, could give particles momentum to move across the bulk fluid toward the collector surface. Besides, particles would migrate to the collector when they are affected by external fields, such as gravity filed and electric field.

2. Particle-wall hydrodynamic interaction

When particles get close to the collector within a distance comparable to the particle radius, the motion of the fluid between the particle surface and the collector surface becomes much more difficult compared to the scenario at large distances. It is because that the particles need to experience additional hydrodynamic drag caused by the presence of the collector surface. Thus, the reduction of particle mobility is commonly attributed to the particle-wall hydrodynamic interaction.

3. Particle adhesion

As particles approach the collector at even closer distances, typically less than 100 nm, the motion of the particles is influenced by colloidal forces besides the hydrodynamic interaction. Within such extremely short distance, the influences of the colloidal forces are overwhelmingly stronger than those of external forces. Thus, the particle adhesion onto the collector is mainly determined by the competition of the attractive and repulsive colloidal forces. The colloidal forces consist of the universal van der Waals (VDW) force and the electric double layer (EDL) force. These two interaction forces form the basis of the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory of colloidal chemistry. The van der Waals force originates from spontaneous electrical and magnetic polarizations, which generate a fluctuating electromagnetic field within the particle and the collector as well as in the gap between them. Solid surfaces in aqueous media (electrolyte solution) are always charged because of the dissociation of ionisable surface sites or the adsorption of ionic surface active sites. As a result, electric double layers are formed in the vicinity of both the particle and the collector surfaces. When these two charged surfaces approach each other in the electrolyte solution, two electric double layers overlap and a repulsive interaction is developed in this region if the particle and the collector carry the same sign of charge. This repulsive interaction is known as the electric double layer force. In addition, other non-DLVO colloidal interactions might affect the particle deposition in short ranges (0.5–5 nm) under certain physicochemical conditions.

3. Theory of surface forces

The behaviours of particles in aqueous media are significantly influenced by the physicochemical characteristics of the interaction forces between particles and solid surfaces [4]. Thus, the interaction forces exerted on colloidal particles determine particulate fouling or particle deposition. In this section, the colloidal forces between particles and surfaces are briefly reviewed, including colloidal interaction forces, van der Waals attraction force and electrical double layer repulsion force. These two forces form the basis of the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory, which were independently developed by Derjaguin and Landau [5] from Soviet/Russian and Verwey and Overbeek [6] from Netherlands. Besides the DLVO forces, non-DLVO forces are also involved in particle deposition and aggregation, such as polymer bridging, solvation forces, steric forces or hydrophobic forces.

3.1. Derjaguin-Landau-Verwey-Overbeek (DLVO) theory

In the DLVO theory, van der Waals attraction force and electrostatic repulsion force are suggested as the dominant interactions between two charged hydrophobic or lyophobic particles/surfaces in electrolyte solution. Moreover, the total interaction between particles and solid surfaces in a liquid is assumed as the sum of the two interactions. This is the first theory enabling to explain and predict the experimental observations of particle deposition and aggregation in a quantitative way. The van der Waals interaction arises from the electromagnetic effects of the molecules composing the particles while the electric double layer interaction is caused by the overlapping of the electric double layers of two particles/surfaces in an aqueous medium. Normally, the former is attractive and the latter is repulsive, which could be changed depending on the material properties in some specific cases [4].

3.1.1. van der Waals force

The van der Walls force, also known as London-van der Waals force, originates from a fluctuating electromagnetic field in particles and between particle and solid surface which is induced by the spontaneous magnetic and electrical polarisation. The van der Waals force can be either attractive or repulsive depending on the material property and is always attractive between identical materials. A number of methods have been proposed to calculate the van der Waals interaction energy [7–11]. Basically, there are two computation methods: the microscopic and the macroscopic.

For the microscopic methods, perturbation theory was initially adopted to solve the Schrödinger equation for the interactions between two hydrogen atoms at a large separation distance by Wang [12] and London [13], and they considered the interactions between the protons and electrons of the two atoms in the calculation. Their study provides a basis of quantum-mechanical analysis of the interaction between two non-polar molecules. Margenau [14] improved the analysis with consideration of higher moments. The retardation effect for the interactions was further investigated by Casimir and Polder [15] when the separation distance was shorter than the characteristic wavelength of radiation. Subsequently, Hamaker [11] proposed a simplified microscopic approximation in which the interaction between two solids is pair-wise additive. In another words, the total interaction force can be obtained by simply summing up the forces over all pairs of atoms in both solids. It is worth mentioning that Hamker's microscopic method neglects the retardation effect and many-body interactions. However, the influence of neighbouring atoms cannot be ignored, especially for condensed medium such as liquid. As a result, the pair additivity is difficult to be implemented for interacting objects in aqueous medium.

A more rigorous approach, macroscopic theory, was proposed in order to account for the aforementioned challenges. Dzyaloshinskii et al. [9] developed a new theory to avoid the problem of additivity encountered in the microscopic methods, known as Lifshitz theory. In this theory, large subjects are treated as a continuous medium without considering the atomic structure. The interaction forces between the subjects are calculated based on the bulk material properties including dielectric constants and refractive indices. The retardation effect is implicitly considered in the full Lifshitz treatment, but it is readily take account of the effect via modifying the Hamaker constant. In terms of calculation of Hamaker constant, various approaches have been developed and details can be found in the literatures [16–19].

Hamaker constants are most accurately calculated by Lifshitz theory, which determines the magnitude of the interaction through the frequency dependent dielectric properties of the intervening media [9, 18]. The Hamaker constant is estimated from the frequency dependent dielectric properties of the individual materials comprising the system as

$$A_{132} = \frac{3}{2}kT \begin{pmatrix} \frac{1}{2} \left(\frac{\varepsilon_1(iv_0) - \varepsilon_3(iv_0)}{\varepsilon_1(iv_0) + \varepsilon_3(iv_0)} \right) \left(\frac{\varepsilon_2(iv_0) - \varepsilon_1(iv_0)}{\varepsilon_2(iv_0) + \varepsilon_1(iv_0)} \right) \\ + \sum_{j=1}^{\infty} \left(\frac{\varepsilon_1(iv_j) - \varepsilon_3(iv_j)}{\varepsilon_1(iv_j) + \varepsilon_3(iv_j)} \right) \left(\frac{\varepsilon_2(iv_j) - \varepsilon_1(iv_j)}{\varepsilon_2(iv_j) + \varepsilon_1(iv_j)} \right) \end{pmatrix}$$
(1)

where A_{132} is the Hamaker constant between particles '1' and the plate '3' in medium '2' and is a measure of the magnitude of the interaction between two objects. Israelachvili [20] proposed a simplified expression for the function $\varepsilon(iv_j)$ based on the refractive index and the absorption frequency of materials.

$$\varepsilon(iv_j) = 1 + \frac{n^2 - 1}{v^2} \tag{2}$$

In practice, it is difficult to obtain all the parameters in Eq. (2), mainly the absorption frequency. Assuming the absorption frequencies of the three media are the same, the Tabor-Winterton (TW) expression was developed to overcome the difficulties, shown as [21]

$$A_{132} \approx \frac{3}{4} k_B T \left(\frac{\varepsilon_1 - \varepsilon_3}{\varepsilon_1 + \varepsilon_3} \right) \left(\frac{\varepsilon_2 - \varepsilon_3}{\varepsilon_2 + \varepsilon_3} \right) + \frac{3h\nu_e}{8\sqrt{2}} \frac{\left(n_1^2 - n_3^2 \right) \left(n_2^2 - n_3^2 \right)}{\left(n_1^2 + n_3^2 \right)^{0.5} \left(n_2^2 + n_3^2 \right)^{0.5} \left[\left(n_1^2 + n_3^2 \right)^{0.5} + \left(n_2^2 + n_3^2 \right)^{0.5} \right]}$$
(3)

where the refractive index n_i and zero frequency term $\varepsilon_{0,i}$ are the temperature-dependent factors for van der Waals interaction, k_B is the Boltzmann constant, and T is the absolute temperature of the system. The zero frequency term for most of the aqueous colloids is about equal to 3kT/4 or around 3×10^{-21} J. Water has a dielectric constant of about 80 at room temperature and non-polar media have values in the range 2–3.

In consideration of the retardation effect, Suzuki and Higuchi [22] proposed an approximated expression for the van der Waals interaction potential between the sphere and the plate as

$$F_{vdw} = \frac{-A_{132}}{6kT} \frac{\overline{\lambda} (\overline{\lambda} + 22.232H)}{H^2 (\overline{\lambda} + 11.116H)^2}$$
(4)

where *a* is the radius of the sphere, *h* is the minimum surface-to-surface separation between the sphere and the plate, and *H* (*h*/*a*) and $\overline{\lambda}$ (λ /*a*) are the separation distance between the sphere and plate surface and the dimensionless characteristic wavelength, respectively, as illustrated in **Figure 1**. λ is the characteristic wavelength of the interaction which has a value of about 100 nm for most materials.

3.1.2. Electrostatic double layer force

Because of the electric double layer (EDL) force, particles can be well dispersed in liquids other than forming aggregation. The EDL force originates from the repulsion between the charged surfaces of the particles and solid surfaces immersed in liquids of high dielectric constants. The charges form the so-called electric double layer in the vicinity of the particles and the solid surfaces. The charging mechanism of a solid surface in a liquid medium can be categorised into two: (1) ionisation or dissociation of surface groups on the solid surface and (2) adsorption or binding of ions from electrolyte solutions onto a surface with oppositely charged sites or an



Figure 1. Interaction between the sphere and the plate.

originally uncharged solid surface. For a single particle suspended in a liquid medium, the particle is covered by the electric double layer (**Figure 2**). With consideration of the finite size of ions, Stern [23] developed an electric double layer model in which one immobilised layer of ions is absorbed onto the particle surface and the other layer is filled with diffusive space charges from the liquid medium (**Figure 2**). The former layer is termed as Stern layer and the latter layer is called as diffuse or Gouy layer.

Due to the nonuniform distribution of charges around the charged surface, electric potential reduces gradually with the separation distance from the solid surface to the bulk liquid phase. In the electric double layer model, several potentials are defined including surface potential on the solid surface, Stern potential at the Stern layer and zeta potential (ζ) at slipping plane. Assuming ions of identical property and average surface charge over the whole solid surface, the electric potential (ψ) and the average charge distribution in the diffuse layer of the electric double layer can be computed based on the non-linear Poisson-Boltzmann equation (PBE) as [24–26]

$$\nabla^2 \psi = \frac{-1}{\varepsilon_0 \varepsilon} \sum_i n_i^0 z_i e \exp\left(\frac{-z_i e \psi}{k_B T}\right)$$
(5)

where n^0 is the number density of ions in bulk, *i* represents the component *i*, *z* and *e* are the valence and the elementary electric charge, ε_0 is the permittivity of vacuum, and ε is the static dielectric constant.

As illustrated in **Figure 2**, a particle approaches a solid surface in an electrolyte solution or two charged particles approach each other, and their diffuse layers would overlap with each other. EDL force is repulsive for two surfaces with charges of same sign, while it becomes attractive for two particles with charges of opposite sign. The accuracy of calculating the EDL interaction is influenced by various factors. To simplify the calculation, two important assumptions are



Figure 2. Schematic of a diffuse double layer of a charged particle in the vicinity of a charged solid/wall surface.

made: interactions with constant surface potential and constant surface charge density. For the constant surface potential cases, surface-chemical equilibrium is maintained while two particles/ surfaces are approaching in a very short time. This may not be realistic for some practical cases [27]. For the constant surface charge cases, two particles/surfaces have fixed surface charge densities in the approaching process. These two assumptions are applied to the potential and charge on the particle/solid surfaces, whereas the interaction between electrical double layers is determined by the potential at the Stern plane. The charges at the Stern layer may behave differently from those on the particle/solid surface during the approach process. Recently, Barisik et al. [28] and Zhao et al. [29] have applied a complex charge regulation as boundary conditions to calculate the EDL interactions in nanoscale.

Generally, the EDL interaction energy can be computed based on two methods. One method is to directly solve the Poisson-Boltzmann equation for systems of particle/solid surfaces. Normally, it is difficult to obtain simple analytical solutions by this method. The other method is to construct the formula based on known expressions for each of the surfaces involved without consideration of influences of the other surfaces. The approximations of EDL interaction energy obtained in this way are often more attractive for practical applications which require fairy accuracy and simplicity [30].

3.1.3. Sphere-plate double layer interactions

In 1934, Derjaguin [31] developed an integration method to calculate the electric double layer interactions between two spheres in a dilute suspension. It has become a widely adopted method in colloidal chemistry since then. The EDL interaction energy between two spheres with overlapping electric double layers can be calculated as

$$V_{edl} = \frac{2\pi a_1 a_2}{a_1 + a_2} \int_{h}^{\infty} v_E dh$$
(6)

where *h* denotes the minimum separation distance between two sphere surfaces, and a_1 and a_2 are the radii of two spheres. The EDL interaction force can be obtained by differentiating the interaction energy, V_{edl} , with the separation distance, *h*, as

$$F_{edl} = \frac{2\pi a_1 a_2}{a_1 + a_2} v_E(h)$$
(7)

It should be noted that the above expressions are only applicable for cases in which $\kappa a_p > 5$ and $h \ll a_p$ are valid. By allowing one of the radii to approach infinity, the sphere-plate interactions can be derived from the sphere-sphere interactions. Assuming constant surface potential, a theoretical expression of EDL interaction energy between a sphere and a plane was developed by Hogg et al. [32] as

$$V_{edl} = \pi \varepsilon_0 \varepsilon a \left(\xi_p^2 + \xi_w^2\right) \left[\frac{2\xi_p^2 \xi_w^2}{\xi_p^2 + \xi_w^2} \ln \left[\frac{1 + \exp\left(-\kappa h\right)}{1 - \exp\left(-\kappa h\right)} \right] + \ln\left[1 - \exp\left(-2\kappa h\right)\right] \right].$$
(8)

The electrical double layer (EDL) interaction force can be obtained by differentiating electrical double layer interaction energy with separation between two surfaces.

$$F_{edl} = -\frac{\partial V_{edl}}{\partial h} = 2\pi\varepsilon_0\varepsilon a\kappa \left(\xi_p^2 + \xi_w^2\right) \left[\frac{2\xi_p^2\xi_w^2}{\xi_p^2 + \xi_w^2}\frac{\exp\left(-\kappa h\right)}{1 - \exp\left(-2\kappa h\right)} - \frac{\exp\left(-2\kappa h\right)}{1 - \exp\left(-2\kappa h\right)}\right]$$
(9)

where ζ_p and ζ_w denote the zeta potentials of colloid particle and channel wall, respectively. ε_0 and ε_r represent the permittivity of vacuum and relative permittivity, respectively. The EDL thickness, also known as Debye length, κ^{-1} is defined as

$$\kappa^{-1} = \left(\frac{2e^2 z^2 n_{\infty}}{\varepsilon k_B T}\right)^{-0.5} \tag{10}$$

where *e* represents the electron charge, *z* is the valance of ions and n_{∞} denotes the bulk number density of ions. When the conditions of $h \ll a_p$ and $\kappa a_p \gg 1$ are satisfied, the expressions above can work well with cases of small potential. Alternatively, the EDL interaction energy can be computed with either the linear superposition method or the complete numerical solution of the nonlinear Poisson-Boltzmann equation [33]. Considering ion-ion interactions, a complex statistical mechanical model was developed for calculating the EDL interaction based on the thermodynamic entropy and Helmholtz free energy approach. Different boundary conditions have been studied, such as charge regulation and constant surface charge density [28, 34, 35].

The total interaction energy, *V*, in the DLVO theory is obtained by the summation of the electrostatic and van der Waals contributions as illustrated in **Figure 3**. With the electronic double layer potential and van der Waals potential described under previous mentioned assumptions, the total interaction is calculated as



Figure 3. Example diagram of potential energy vs. separation distance [36].

$$V = V_{vdw} + V_{edl} \tag{11}$$

Eq. (11) gives both a theoretical framework to predict and compare experimentally measured colloidal interactions, and the knowledge of how surface interactions can be controlled.

3.2. Non-DLVO forces

In the classical DLVO theory, van der Waals and electrical double layer interactions play vital roles in colloidal particle interactions. This theory has been successfully utilised to explain many experimental observations. Whereas, there are situations in which theoretical predications based on interactions of electrical double layer and van der Waals force cannot provide reasonable agreement with experimental results [6, 37]. For instance, the classic DLVO theory fails to explain the interactions with ultra-short separation distance (i.e., shorter than a few nanometres). The continuum theories are not valid in such short distances, and bulk material properties (e.g., refractive index, density, and dielectric constant) cannot be used to describe such interactions. For these cases, some additional non-DLVO forces can be introduced into the DLVO theory, such as Born repulsion [38], polymer bridging [39], hydration forces [40], hydrophobic interaction [41], and steric interaction [42]. In this section, a brief introduction for non-DLVO forces is provided and more details can be found in a comprehensive review by Liang [4].

Polymer bridging theory applies to polymer flocculation. It is postulated that polymer bridges are built between neighbouring solid particles in a suspension in order to form a loose porous 3D network of solid particles (i.e., floc). When the detailed spatial variation of the short-range forces are not crucial, Elimelech et al. [30] reported that the microscopically averaged Born repulsion could be a convenient approach to consider effects of non-DLVO interactions. As particles interact with adsorbed fluid layers, solvation or hydration forces begin to take effects. Grabbe and Horn [43] suggested that the repulsive hydration force plays a dominant role for two interacting silica surfaces in a short range immersed in an electrolyte solution (NaCl). Unlike the electric double layer force, the hydration force was found to be independent on the electrolyte concentration over the range in their experiments. However, the physical mechanism of the hydration force is still unclear. The anomalous polarisation of water near the interfaces could generate the hydration force. It also could originate from the entropic repulsion of thermally activated molecular groups from protrusions on the surfaces [44-46]. Water molecules between two hydrophobic surfaces tend to migrate from the narrow gap to the bulk liquid at extremely short separation distance. It is because that the opportunities for hydrogen bonding are unlimited in the bulk liquid and free energy is lower than in the gap. As a result, an attractive force, hydrophobic force, would be generated between the two surfaces. This attractive force works in much greater range (up to 80 nm) than the van der Waals force and is one to two orders of magnitude stronger [41, 47, 48]. When two polymer-covered particles approach to each other, steric or osmotic forces would be developed between the particles. The steric force is related to the repulsive entropic force caused by the entropy of confining these chains for overlapping polymer molecules. So far, theories of steric forces are not wellestablished. Many components can affect the magnitude of the steric forces, such as bonding stress between the polymer molecules, the quantity or coverage of polymer molecules on each solid surface and solid surfaces (i.e., reversible process or not) [49–52].

4. Temperature control in microfluidic systems

Temperature is a crucial parameter in many microfluidic applications, for example, microscale milk pasteurisation unit [53], polymerase chain reaction (PCR) [54, 55], mixing [56], and temperature gradient focusing [57] or separation [58]. Lab-on-a-chip devices and systems are compact and multi-functional platforms which can be integrated into a small chip. Temperature control is one of the important functions in various microfluidic applications. In this section, different techniques for temperature control in microfluidic systems will be summarised into two categories: bulk temperature control and temperature gradient control [59].

4.1. Bulk temperature

The bulk temperatures of liquids in microfluidic systems are uniformly distributed and it can be changed by either external heating or internal heating approaches. A number of techniques have been implemented for various applications.

To control the bulk temperature of the liquids, the external heating approaches usually use either commercial heaters (e.g., Peltier elements) or preheat/cool liquids prior to being injected into microchannels. Velve Casquillas et al. [60] designed an external temperature control system with two Peltier elements that is able to readily vary the temperature of yeast channel underneath the temperature control channel (shown in **Figure 4a**). By using this system, they can rapidly regulate the yeast channel temperature in a wide range (5–45°C within 10 s). Similarly, Khandurina et al. [61] utilised two Peltier elements as a sandwich assembly to directly heat up a microfluidic chip for the polymerase chain reaction (PCR) (**Figure 4b**). This



Figure 4. (a) A schematic of the temperature control device by an external Peltier element; the yeast channel is placed below the temperature control channel [60] and (b) schematic of the dual Peltier assembly for rapid thermal cycling followed by electrophoretic analysis on-chip [61].



Figure 5. (a) Peltier thermocycler for the PCR microreactor and (b) a photograph of the serpentine polycarbonate microchannel [55].

compact setup is able to complete 10 thermal cycles within 20 min. With the similar configuration, Yang et al. [55] fabricated a serpentine microchannel on a thin polycarbonate plate (thickness: 0.75 mm) as a PCR microreactor (**Figure 5**). They used thermocouples to measure the surface temperatures of the intrachamber temperature and Peltier elements. With the developed device, they performed 30 thermal cycles in 30 min and the heating rate and cooling rate are 7–8 and 5–6°C/s, respectively.

Furthermore, Maltezos et al. [62] chose using liquid metal in combination with Peltiers to explore the limits of PCR speed in a microchip. Sample tubes were first immerged in a liquid medium (gallium eutectic) and then sandwiched between two high-powered Peltier elements. Heat can be rapidly transferred between the DNA/RNA in the sample tubes and the Peltier elements via the liquid interface. High heating rate and cooling rate can be up to 106 and 89°C/s in their experiments, respectively.

On the other side, the direct integration of heating or cooling elements into microfluidic systems is a popular method. Integrated heating approaches are able to reduce the whole system size and improve its portability.

Joule heating has been the most widely-used technique as an integrated heating solution for the temperature control in microfluidic systems. Lao et al. [63] filled platinum into siliconbased microchannels as in-chip heaters and sensors. A well-controlled thermal environment (\pm 1°C) was achieved for gas and liquid phase reactions (**Figure 6**). The silicon microchannel was thermally isolated by a thin silicon nitride membrane to save power consumption. Precise and prompt temperature control was facilitated with a digital feedback system developed by them (heating rate: 20°C/s, cooling rate: 10°C/s, and response time: 5 s). By using similar serpentine channel configurations, Wu et al. [64] injected silver paint into the PDMS microchannels as integrated microheaters and took an advantage of compressed air for rapid cooling in parallel channels. Heating rate was 20°C/s and error of temperature was about \pm 0.5°C in the steady state. With this device, DNA can be successfully amplified in 25 thermal cycles with 1 min per cycle. Instead of applying metal, de Mello et al. [65] made use of ionic



Figure 6. Top view of the microchip showing the patterned heaters and temperature sensors [63].

liquids ([BMIM][PF₆] and [BMIM][Tf₂N]) as heating elements. The ionic liquid was Joule heated by an AC current (power: 1 W, frequency: 50 Hz, and voltage: \leq 3.75 kV). By controlling the applied voltage of the ionic liquids, the bulk temperature was regulated from 50 to 90°C with an accuracy of 0.2°C.

Other than the commonly used physical heating approach (i.e., Joule heating), chemical approach can be another integrated option. To locally control the temperature in a microchannel, Guijt et al. [66] made use of heat adsorption and dissipation via endothermic and exothermic chemical reactions, respectively (**Figure 7a**). Heating/cooling can be achieved in a temperature control channel (TCC) where two reagents from separate reactant channels (RC₁ and RC₂) merged and had chemical reaction. Heating was achieved with a dissolution of 97 wt% H_2SO_4 (Reagent 1) in water (Reagent 2), while cooling was realised with the evaporation process acetone (Reagent 1) in the air (Reagent 2). A wide temperature range from -3 to 76°C with a ramp rate of 1°C/s can be realised in the central channel by manipulating the flow rate ratio between two reagents (shown in **Figure 7b**).



Figure 7. (a) Two reactant channels (RC) merging into a temperature control channel (TCC) and (b) layout of the device used for demonstration experiments [66].

4.2. Temperature gradient

For several applications such as Soret effect and droplet actuation, temperature gradients are demanded in microfluidic systems. Temperature gradients have been generated in either a controlled temperature profile or an arbitrary way by various techniques.

As illustrated in **Figure 8a**, Mao et al. [67] generated a linear temperature gradient along the horizontal direction of the PDMS microchannel by using the pre-heated liquid approach. Hot and cold fluids were channelled into two side channels separately, and a stable temperature gradient has been established in the central channel (**Figure 8b**). Zhao et al. [68] implemented this approach for studies on thermophoresis using a microchip made of stainless steel. Due to a higher conductivity of stainless steel than PDMS, a wider range of variations for both bulk temperature and temperature gradient (1.5×10^4 K/m) can be formed in the microchannel. In order to fabricate similar structures in PDMS microchip, Yan et al. [69] proposed a fast prototyping method for single-layer PDMS microfluidic devices with abrupt depth variations by combining the laser ablation and NOA81 moulding. The whole fabrication process can be completed within 2 h. This method can readily produce PDMS microfluidic devices with micrometre and millimetre structures in one step. Moreover, this method can be applied in a non-clean-room environment and does not require complicated and expensive soft lithography equipment or etching processes.

Instead of preheating liquids, Vigolo et al. [70] chose to use silver-filled epoxy with a similar parallel channel configuration to generate temperature gradients in a microchannel. This microscale heating element can be powered by two ordinary AAA batteries. Thus, this design shows its potential as a cost effective and portable solution for thermal control of microfluidic devices. Alternatively, the parallel-channel configuration has also been implemented for control of bulk temperatures in microchannels. It can be readily realised by changing the directions of preheated liquid and DC electric current [71–73].

In addition to regulating bulk temperatures, Peltier elements can be utilised to establish a constant temperature gradient in microfluidic systems. Matsui et al. [74] designed and fabricated a hybrid temperature gradient focusing (TGF) chip (materials: PDMS/glass) by applying two Peltier elements. A range of temperature gradient can be formed along the horizontal



Figure 8. (a) Schematic diagram of a device with an on-chip linear temperature gradient and (b) a plot of temperature vs. position of the temperature gradient device [67].

direction of the microchannel (**Figure 9**). The maximum temperature gradient generated in their device was 13.75°C/mm.

Jiao et al. [75] designed a microfluidic droplet manipulation system with integration of four microheaters (materials: titanium and platinum) generating planar temperature gradients in the square region (10 mm × 10 mm). By controlling the frequency and amplitude of square wave signals, they successfully manipulated the trajectory of a microdroplet based on the periodic thermocapillary actuation caused by temperature gradients. Yap et al. [76] deposited a thin film platinum heater in a microchannel to control the thermal field for droplet formation in a bifurcated microchannel. The trajectory and splitting of the droplet can be controlled by modulating viscosity and interfacial tension of liquids under different heating conditions. Because of the temperature gradients generated by metal microheaters, the PDMS microchannel would undergo a slight dilation. The temperature-induced dilation changed the height of the microchannel so that the bubble would be driven away from the constricted region. Selva et al. [77] successfully controlled the bubble motion by utilising this thermomechanical actuation under temperature variation. Miralles et al. [78] from the same research group optimised their previous design by using localised heating resistor whose size was smaller than the droplet size.

The aforementioned designs of temperature-gradient devices are not suitable for researches on the microscale mechanism of particle deposition in microchannels due to the obstruction of heating or cooling elements along the optical path of microscope for observation or inconsistency of the directions of temperature gradient and particle deposition. The authors' group has developed a novel design of temperature-gradient microchip to investigate particle deposition in microchannels [79].

There are three major parts for the temperature-gradient microchip (**Figure 10**), including a microchannel, a thermoelectric cooler (TEC) unit as cold end, and a thin glass slide coated with indium tin oxide (ITO) film as hot end. A temperature gradient can be established along the vertical direction inside the microchannel, by cooling the top surface of the microchip with the TEC unit and heating the bottom surface with the ITO film heater.



Figure 9. Schematic drawing of temperature gradient focusing apparatus [74].



Temperature-gradient Microchip

Figure 10. Schematic of the temperature-gradient microchip, consisting of the PDMS microchannel, the glass slide coated with the ITO film and the TEC unit. Various temperature gradients can be achieved by cooling the top surface of the microchip with the TEC unit and heating the bottom surface with the ITO film heater. (figure is for not drawn to scale) [79].

The microchannel can be fabricated with polydimethylsiloxane (PDMS) using standard soft lithography techniques. The PDMS monomer and the curing agent are fully mixed in a mass ratio of 10:1, and then they are vacuumed for 45 min to evacuate air bubbles remaining in the PDMS mixture. The mixture is applied onto the master mould constructed by SU8 on a silicon wafer. PDMS is cured after being heated with the wafer in an oven at 80°C for about 1 h. A thin layer of polymerised PDMS (e.g., 1 mm in thickness) is peeled off from the mould. Two cylindrical openings are then punched at both ends of the microchannel as the inlet and outlet for sample fluids.

For the ITO glass slide, a thin indium tin oxide film (e.g., 200 nm in thickness) is deposited on one side of a glass slide (e.g., 0.71 mm in thickness) as a heater for the microchip. Indium tin oxide is a solid mixture including 90% In₂O₃ and 10% SnO₂ by mass. On the other side of the glass slide, a thin PDMS film was coated on the bare glass surface. The ITO glass heater has three major advantages for the particle deposition study. (1) The ITO glass (10 ohms/sq) can easily generate heat by Joule heating when being connected into an electrical circuit. The heat dissipation rate of the ITO glass can be well controlled by regulating the applied electrical current and voltage. (2) The ITO glass has excellent optical transparency allowing direct observation on particle deposition onto the bottom surface of the microchannel along the direction of the applied temperature gradient. The bottom view of the particle deposition can be readily captured via using an inverted microscope equipped with a CCD camera. (3) A wide range of customised dimensions and patterns can be precisely achieved for ITO heaters by implementing the standard photolithography techniques.

A closed microchannel is formed via irreversibly oxygen plasma bonding the treated ITO glass slide and the PDMS block with microchannel structure. The bonded microchannel is heated in

the oven to reinforce the plasma-bonding strength. The thermoelectric cooler (TEC) unit is mounted on the top of the bonded microchannel to provide a stable cold end over the microchannel. The temperatures of hot/cold ends can be readily adjusted via the DC power supplies for the ITO film heater and the TEC unit, respectively. Moreover, the temperature gradient can be well controlled in the microchannel along the same direction as the particle deposition. Thermal conductive silicon paste can be applied in the gap between the TEC unit and the PDMS microchip to enhance the heat conduction. This specially designed temperaturegradient microfluidic system provides a useful tool for researches on dynamics of particle deposition under different thermal conditions. To the best knowledge of the authors, it could be the first microfluidic device allowing to directly observe the dynamic process of particle deposition along the direction of applied temperature gradient.

5. Particle deposition in microchannels

Particle deposition onto solid surfaces has been intensively studied in both experimental and theoretical approaches. In this section, major works on particle deposition in microchannels are reviewed.

5.1. Experimental studies

Experiments are usually conducted in three types of setup, including cylindrical, parallel-plate channels, and impingement jet chamber. Various parameters have been evaluated experimentally in terms of their effects on particle deposition, such as pH, electrolyte concentration, particle, and solid surface.

5.1.1. Effect of pH on particle deposition

The repulsive interaction would exist between charged particles of same like sign and hinder fouling behaviour. The zeta potentials of the particle and microchannel surface determine the magnitude of the repulsion and are closely related to the pH value of working fluid. The pH value can control the charge signs of the particle and channel surface. Newson et al. [80] investigated the mechanisms of deposition, removal and sticking in a haematite/water system (particle diameter: 0.2 μ m and concentration: 100 ppm). They found that the sticking coefficient of particles from turbulent water suspension (Re: 11,000–14,000) was significantly dependent upon the pH value of suspension. Perry and Kandlikar [36] also adjusted the pH value of the nanofluids and were able to effectively mitigate particulate fouling. The reduction of the deposition rate was mainly attributed to the augmented EDL repulsion as pH was increased.

5.1.2. Effect of the ion concentration on particle deposition

Gu and Li studied the influence of the electrolyte concentration on deposition of silicon oil microdrops onto cylindrical surfaces via both experimental and numerical approaches [81, 82]. They found that the increase of the Sherwood number (dimensionless mass transport rate)

resulted from the neutralisation effect of the electrolyte concentration $(10^{-6}-10^{-3} \text{ M})$ which crucially determined the zeta potentials of bare glass tube surfaces and silicon oil drops. Moreover, they found that the Sherwood number was increased significantly with the increase of the cationic surfactant concentration (CTAB, $10^{-6}-10^{-4}$ M) but was reduced monotonically with adding anionic surfactant (SDS) into the oil droplet emulsion. Kar et al. [83] performed experiments with CaCO₃ microparticles and hollow fibre membrane to study the effect of salt concentration gradients on particle deposition. They reported that the diffusiophoretic particle transport has crucial influence on particle deposition when different electrolyte ions of salts in solution have different diffusion coefficients. Furthermore, Guha et al. [84] found the diffusiophoresis has significant influence on the colloidal fouling in a low salinity reverse osmosis system.

5.1.3. Effect of properties of particle and wall on particle deposition

Salim et al. [85] investigated the effects of protein (fibrinogen and lysozyme) adsorption on the electroosmotic flow (EOF) behaviour of the plasma-polymerised glass microchannel surfaces. Three types of plasma-polymerised surfaces (pp.TG, pp.AAm, and pp.AAc) were tested which had different surface charges and charge densities. They observed a non-fouling phenomenon with tetraglyme coating in the presence of protein, and this coating provided stable EOF performance in the glass microchannel.

Mustin and Stoeber [86] conducted experiments with polystyrene microsphere suspensions in a PDMS microchannel. They found that the dynamics of channel blockage was influenced by particle size distribution besides the particle size alone. Recently, they performed another experiment in a mini impingement jet flow cell made of PDMS for particle deposition (**Figure 11**) [87]. They noticed discrepancies between the experimental measurements and numerical simulation results based on both DLVO and extended DLVO theories, and proposed the surface roughness and electrostatic charge heterogeneity of the PDMS surface could be the most plausible reason for such discrepancies.



Figure 11. (a) Cross-section view of the deposition chamber and (b) flow cell on substrate without clamping [87].

5.1.4. Effect of external field on particle deposition

In the previous literature, transport of micron-size particles is normally simplified as a mass transfer process that is majorly affected by Brownian diffusivity. However, gravity or a constant body force exerted on the particles could have significant influence on the deposition process, even for such tiny colloidal particle size (less than 1 μ m). Yiantsios and Karabelas [88] reported that gravity played a key role for the deposition rate of spherical Ballotini glass particles (diameter: 1.8 μ m). Gravity could control the particle transport boundary layer in a horizontal narrow channel under laminar flow over a fairly wide range of flow rate. They [89] conducted further experiments on the effects of physicochemical and hydrodynamic conditions by using dilute microsized glass particle suspensions (diameter: 1.5 μ m) in a parallel-plate channel. They concluded that gravity was a determining factor for deposition at low wall shear stresses. While the hydrodynamic wall shear stress was increased, particle deposition rates were noticeably decreased because of hydrodynamic lift or drag forces hindering transport or attachment.

Stamm et al. [90] experimentally examined the initial stage of cluster growth in a particle-laden flow in a microchannel and investigated the parametric effects of a void fraction, flow shear strain rate and channel height to particle diameter ratio. Thereafter, Gudipaty et al. [91] studied the cluster formation of colloidal particles in a PDMS microchannel and found that the clusters were initiated by the attachment of individual flowing particle onto the bottom surface. However, they have not either addressed the physical mechanism of the initial particle attachment to the surface or observed the adherence process in the experiments.

Unni and Yang [92] experimentally investigated the dynamics of particle deposition in an electroosmotic flow using video microscope, and reported that the increased surface coverage at higher salt concentrations resulted from weakened EDL repulsion with particles being adsorbed onto the channel surface. Hydrodynamic blocking became relatively weaker with lower electric field strengths because the surface blocking was majorly caused by electrical interactions.

5.1.5. Effect of temperature on particle deposition

Most of the researches about deposition of micro-/nanoparticles in microchannel are conducted in room temperature environment, seldom with high bulk temperature or temperature gradient, which is a crucial factor for heat exchangers in reality. Yan et al. [73] investigated the effect of bulk solution temperature on particle deposition in a microchannel under wellcontrolled temperature conditions using a microfluidic temperature control device. To the best knowledge of the authors, this was the first attempt to study the thermal effect on the deposition of colloidal particles in an aqueous dispersion onto a microchannel wall. It is found that the temperature of solution has a considerable effect on the particle deposition in microchannels. The static particle deposition rate (Sherwood number) has been measured over a range of temperatures between 20 and 70°C. It is found that the Sherwood number is monotonically increased up to 265%, with the solution temperature within the test range. They developed a deterministic model based on the Derjaguin-Landau-Verwey-Overbeek theory with consideration of temperature dependence, and found that by increasing the solution temperature, the attraction energy (van der Waals force) between the particles and the solid surface is increased while the repulsive energy (electric double layer force) is decreased. Moreover, they further studied the hydrodynamic effects on particle deposition in microchannels at elevated temperatures, including steady flow and pulsatile flow [71, 72]. The dimensionless particle deposition rate (Sherwood number) was found to be reduced with the Reynolds number and changed insignificantly for the Reynolds number beyond 0.091 (0.5 mL/h) within the tested range with a given solution temperature (324.85 K) and an electrolyte concentration (5×10^{-4} M). Under the pulsatile flow condition, the normalised particle deposition rate was found to be reduced significantly as the flow oscillation frequency was increased from 0 Hz to 1 Hz, while keeping the steady flow component and the amplitude of the flow oscillation unchanged.

5.2. Theoretical modelling/studies

Spielman and Friedlander [93] theoretically analysed the effect of the electrical double layer on particle deposition based on the equation of convective diffusion in an external force field. They reported that the deposition process of Brownian particles was equivalent to ordinary convective diffusion in the bulk with a first-order surface reaction at the collector. With respect to the net interaction potential, a formula can be derived for the surface reaction coefficient.

Another analytical model was developed by Adamczyk and Van De Ven [94] for particle deposition kinetics onto the surfaces of parallel-plate and cylindrical channels (**Figure 12**). As governing equation, the mass transport equation was formulated with consideration of electrical double layer force, van der Waals force, and external forces such as gravity. The 'perfect sink' boundary condition was applied to solve the mass transport equation. Different dimensionless parameters (Ad, Pe, Dl, and Gr) were proposed to account for dispersion, convection/ diffusion, electrical double layer, and gravity, respectively.

Studies on particle deposition onto permeable surfaces are practically meaningful for membrane filtration industry. Song and Elimelech [95, 96] theoretically studied this phenomenon in



Figure 12. Schematics of parallel-plate and cylindrical channels [94].

a system of parallel-plate channel. The convection-diffusion equation was solved numerically with consideration of lateral transport. The lateral transport would be induced by inertial lift, permeation drag, and transport that are determined by the collective effect of gravity force and surface forces. Parametric studies were systematically carried out regarding the initial particle deposition rate, including the effects of permeation velocity, cross flow velocity, particle size, and solution ionic strength.

Since the distribution of surface charge is not uniform in practice, Nazemifard et al. [97, 98] performed a trajectory analysis of particles close to a micropatterned charged plate based on the radial impinging jet setup for the influences of surface charge heterogeneity on deposition efficiency and particle trajectory. The surface charge heterogeneity was controlled by concentric bands with varied properties, such as geometric dimension and types of surface charges. In their analysis, the van der Waals, electrostatic double layer force, hydrodynamic force, and gravity, have been taken into consideration. Due to the coupled effects of colloidal and hydrodynamic forces, the deposition efficiencies and particle trajectories were remarkably influenced by surface charge heterogeneity when a particle flowed radially away from the stagnation point in the radial jet impingement setup. This analysis demonstrates how the existing particle transport models could possibly be modified in consideration of chemical heterogeneity and additional surface interactions. Similarly, Chatterjee et al. [99] applied the convection-diffusion-migration equation (Eulerian model) with fully developed Poiseuille flow velocity profile to investigate the transport of particles in patchy heterogeneous cylindrical microchannels (Figure 13). They evaluated the effects of surface chemical heterogeneity on particle transport and deposition, and found that particles tend to travel further along the microchannel in the heterogeneous channels compared to the homogeneously favourable channels.

Using a soft-sphere discrete element method, Marshall [100] studied the caption of particles by wall and particle aggregation in a microchannel. According to their results, the particle lift-off from the wall was caused by adhesion and collision with particle aggregate or a passing particle when a single particle with a large size was attached to the wall. The fluid forces were not the direct reason for the particle lift-off.

Unni and Yang [92] developed an electrokinetic particle transport model in a parallel-plate microchannel (**Figure 14**) based on the Stochastic Langevin equation. They incorporated random Brownian motion of colloidal particles and the hydrodynamic, electrical, DLVO colloidal interactions into the equation. Based on the developed model, particle trajectories can be stochastically simulated using Brownian dynamics simulation and the surface coverage was calculated under a range of electrical and physicochemical conditions.

In the absence of repulsive energy barrier, Jin et al. proposed concurrent modelling for the effects of interaction forces and hydrodynamics on particle deposition on rough spherical surfaces [101]. The model considered the hydrodynamic retardation functions and flow field profiles. Their works showed that the hydrodynamic effects remarkably affect the particle deposition behaviours which were different from the predictions based on DLVO forces alone. In addition, surface roughness played an important role in particle deposition experiment/ simulation. They conducted another study on deposition of colloidal particles and reported a non-monotonic, non-linear effect of nanoscale roughness on particle deposition without



Figure 13. Schematic of patchy heterogeneous cylindrical microchannels. (a) 3D schematic representation of positively charged particles deposition along the microchannel. (b) 2D axisymmetric view of the microchannel geometry. (c) The zoomed view of one pitch length [99].

energy barrier using both the convection-diffusion model and parallel-plate chamber experimental system [102]. Their results showed particle deposition flux could reach the minimum value when a critical roughness size was provided.



Figure 14. (a) Schematic of electrokinetic transport of a particle in a parallel-plate channel. (b) Forces acting on a moving particle in the vicinity of an attached particle and the channel wall [92].

Based on the Derjaguin-Landau-Verwey-Overbeek theory, Yan et al. [73] developed a qualitative theoretical model with consideration of the temperature effect for the first time. All the driving forces during the whole particle deposition process are temperature dependent, so the particle deposition is determined by the collective effects of the variations of the forces caused by temperature changes. By plotting interaction potential curves and energy barriers, the effect of bulk solution temperature can be clearly seen in **Figure 15** that the interaction potential



Figure 15. Dimensionless particle-wall interaction potential curves for three different solution temperatures (T = 293.15, 323.15, and 343.15 K). Curves are obtained with the temperature dependent Hamaker constant, zeta potential and the thickness of electric double layer. Inset shows the energy barrier that polystyrene particles should overcome to achieve deposition onto the PMMA surface at different temperatures for the DI water case [73].

curves are varied with the bulk solution temperature and the energy barrier reduces considerably with increasing the bulk solution temperature as shown in the inset of **Figure 15**.

Furthermore, Yan et al. [71] developed a simplified one-dimensional mass transport model (i.e., Eulerian model) for calculating the particle deposition rate in microchannel flows at elevated temperatures. A schematic of microparticles flowing through a microchannel at an elevated temperature (T) is shown in **Figure 16**. For a dilute spherical particle monodispersion in the absence of chemical reactions, the interactions between particles are neglected. The deposition rate of particles from solution onto the microchannel surface at the steady state can be described by the general convection-diffusion equation as

$$\nabla \cdot \mathbf{j} = -\nabla \cdot (\mathbf{D} \cdot \nabla n) + \nabla \cdot (\mathbf{u}n) + \nabla \left(\frac{D\mathbf{F}}{k_B T_0}n\right) = 0, \tag{12}$$

where **j** is the particle flux vector (the number of particles per unit area per second), the particle flux comprises three components as shown in Eq. (12): Brownian diffusion, fluid convection, and migration under external forces. Besides, the particle flux **j** can be decomposed into two portions along the *x*-direction and *y*-direction, $\mathbf{j} = j_x \mathbf{x} + j_y \mathbf{y}$, *n* is the local particle number concentration, **D** is the diffusion coefficient tensor, **u** is the particle velocity, **F** indicates external forces exerted on the particles, k_B is the Boltzmann constant, and T_0 is the reference temperature. By an appropriate scaling with the dimensionless parameters given in **Table 1**, the mass transport equation can be expressed in a dimensionless form as

Dimensionless parameters	Expression
Scaled particle flux	$J_x = \frac{a_p j_x}{n_{\infty,p} D_{\infty'}} J_y = \frac{a_p j_y}{n_{\infty,p} D_{\infty}}$
Scaled particle concentration	$\overline{n} = \frac{n}{n_{r,p}}$
Scaled external force	$\overline{F} = \frac{a_p F}{k_B T_0}$
Scaled interaction energy	$\overline{V} = \frac{V}{k_B T_0}$
Scaled particle-wall separation distance	$H = \frac{h}{a_p} = \frac{y - a_p}{a_p}$
Scaled distance from channel entrance	$X = \frac{x}{w}$
Scaled particle ratio	$R = rac{a_p}{w}$
Peclet number	$Pe=rac{3U_{avg}a_p^3}{2w^2D_\infty}$
Hydrodynamic retardation functions [101]	$f_1(H) = 1 - 0.399 \exp\left(-0.14869H\right) - 0.601 \exp\left(-1.2015 H^{0.92667}\right)$
	$f_3(H) = 1 - 0.3752 \exp\left(-3.906H\right) - 0.625 \exp\left(-3.105H^{0.15}\right)$
	$f_4(H) = 1 - 1.23122 \exp\left(-0.2734H\right) + 0.8189 \exp\left(-0.175H^{1.2643}\right)$

Table 1. Dimensionless parameters utilised for the mass transport equation [71].

$$-f_4(H)R^2\frac{\partial^2\overline{n}}{\partial X^2} + \left\{Pef_3(H)(H+1)[2-(H+1)R]\right\}\frac{\partial\overline{n}}{\partial X} + \frac{\partial}{\partial H}\left(-f_1(H)\frac{\partial\overline{n}}{\partial H} + f_1(H)\overline{F}\overline{n}\right) = 0.$$
(13)

All the forces acting on particles are along the vertical direction (*y*-axis in **Figure 16**), and they are colloidal forces (van der Waals force $\overline{\mathbf{F}}_{vdw}$ and electric double layer force $\overline{\mathbf{F}}_{edl}$) and external forces (gravity $\overline{\mathbf{F}}_{G}$, hydrodynamic lift force $\overline{\mathbf{F}}_{L}$, and thermophoretic force $\overline{\mathbf{F}}_{T}$). The thermophoretic force is neglected because of its low magnitude compared to other forces in the study [73]. The non-DLVO forces are excluded for simplicity. Hence, the total force ($\mathbf{F} = \mathbf{F}_{y}$) can be treated as a scalar in the following sections. The dimensionless total force (\overline{F}) is calculated as

$$\overline{F} = \overline{F}_y = \overline{F}_{edl} + \overline{F}_{vdw} + \overline{F}_G + \overline{F}_L.$$
(14)

The potential of each force is computed by integrating the force over the separation distance between a particle and the channel surface (*H*). The total potential (\overline{V}) can be obtained by using superposition of individual potentials: the van der Waals potential (\overline{V}_{vdw}), the EDL potential (\overline{V}_{edl}), and the potentials contributed by gravity and lift force (\overline{V}_G , \overline{V}_L),

$$\overline{V} = \overline{V}_{edl} + \overline{V}_{vdw} + \overline{V}_G + \overline{V}_L = \int \overline{F}_{edl} dH + \int \overline{F}_{vdw} dH + \int \overline{F}_G dH + \int \overline{F}_L dH$$
(15)

As the scaled particle ratio ($R = a_p/w$) in Eq. (13) is about the order of 10^{-3} ($a_p \ll w$) for their experiment system, the particle diffusion term (first term in Eq. (13)) and the particle convection term (second term in Eq. (5)) in *x*-direction can be neglected for the low Peclet number (<1) in the present study. Besides, the variation of the deposition rate for a dilute particle solution

Particle Deposition in Microfluidic Devices at Elevated Temperatures 127 http://dx.doi.org/10.5772/intechopen.78240



Figure 16. Schematic of microparticle transport in a microchannel. The forces on the particle are van der Waals force (F_{vdw}), gravity force (F_G), electric double layer force (F_{edl}), thermophoretic force (F_T), and hydrodynamic lift force (F_L). The radius of the particle is a_{pr} the minimum separation distance between the particle surface and the bottom surface of the microchannel is h, the flow velocity distribution is U(y), and the applied temperature gradient in the microchannel is ∇T (the figure is not drawn to scale) [71].

along the *x*-direction in downstream was found to be insignificant [96, 103]. Consequently, the mass transport equation can be further simplified to one-dimensional as

$$\frac{\partial}{\partial H} \left(-f_1(H) \frac{\partial \overline{n}}{\partial H} + f_1(H) \overline{F} \overline{n} \right) = 0.$$
(16)

Eq. (16) can be solved with the boundary conditions as

$$\overline{n} = 0, \text{ at } H = H_0 \tag{17}$$

$$\overline{n} = 1, \text{ at } H = H_{\infty}. \tag{18}$$

Eq. (17) refers to the 'Perfect sink' boundary condition. H_0 indicates the minimum dimensionless particle-wall distance (h_0/a_p) . This boundary condition has been widely used in particle deposition studies, and it assumes that all particles are irreversibly adhered to the solid surface when they move into the primary energy minimum (PEM) region. It can be explained by that the attractive van der Waals force in the PEM region becomes much stronger than the repulsive electric double layer force. Thus, the particles would deposit onto the solid surfaces. The second boundary condition, given by Eq. (18), states a natural boundary condition for the particle concentration. The particle concentration gets close to that in the bulk phase when the particle-wall distance becomes an 'infinite' distance. Having obtained dimensionless concentration distribution (\overline{n}) along the dimensionless separation distance (*H*) in Eq. (6), the particle deposition flux to the channel surface can be found as

$$J_0 = -f_1(H_0) \left(\frac{d\overline{n}}{dH}\right)_{H=H_0}.$$
(19)

Here, J_0 is the particle number flux at $H = H_0$. The negative sign on the right hand side of Eq. (9) indicates that the particle number flux is toward the solid surface. Moreover, the dimensionless particle deposition rate onto the channel surface can be quantified by the Sherwood number

$$\operatorname{Sh}_{num} = -\frac{j_0}{\left(D_{\infty}n_{\infty,p}/a_p\right)} = f_1(H_0) \left(\frac{d\overline{n}}{dH}\right)_{H=H_0}.$$
(20)

The thermal effects on the particle deposition rate (i.e., Sherwood number) are influenced by the temperature dependences of all the forces ($\overline{\mathbf{F}}_{vdw}$, $\overline{\mathbf{F}}_{edl}$, $\overline{\mathbf{F}}_{G}$, and $\overline{\mathbf{F}}_{L}$) acting on the particles. For van der Waals force, the Hamaker constant is a temperature dependent parameter. For EDL force, EDL thickness, zeta potential, and relative dielectric constants of materials are varied with the temperature. For gravity and hydrodynamic lift forces, the magnitude of forces is changed due to the variations of density and viscosity of liquid. Details of the calculations for the temperature dependences can be found in [71, 73].

For the first time, based on the DLVO theory with considering the temperature-dependent interactions, a simplified one-dimensional mass transport model was developed and it can serve as a semi-quantitative approach for describing particle deposition phenomena in microchannel flows at elevated temperatures.

6. Summary and future prospects

Particle deposition and particulate fouling have been ubiquitous phenomena in natural and industry processes. Thermal effects (i.e., temperature and temperature gradient) on particle deposition are important but always 'ignored' in literatures. Most of the published research works about micro-/nanoparticles deposition in a microchannel were conducted in the room temperature environment, seldom with consideration of elevated bulk temperature or temperature gradient, which is a crucial factor for thermal driven fouling phenomena in reality. Especially, the microscale mechanism of particle deposition in microchannel at elevated temperature was still in its infancy. In this chapter, researches on particle deposition and particulate fouling on surfaces have been extensively reviewed both theoretically and experimentally from the published works. This chapter has summarised relevant concepts of particle deposition, key parameters, and experimental techniques (e.g., device design) as well as theoretical methodologies (e.g., modelling). The physics of particle deposition phenomena under different parametric influences has been discussed in detail. The authors have presented a new microfluidic temperature-gradient device that can be used to directly observe particle deposition along the direction of temperature gradient with a single-particle resolution. Moreover, a simplified mass transport model (Eulerian model) with consideration of thermal effects has been presented to describe the particle deposition phenomena in microchannels at elevated temperatures based on the Derjaguin-Landau-Verwey-Overbeek theory. Both the theoretical modelling and experimental measurements have shown that the thermal effects have profound the impact on particle deposition in microchannels.

Future research in this field lies in the development of investigations on coupling effects of thermal field and other external fields, such as optical, acoustic, and magnetic fields [104–106]. Microfluidic devices and systems offer ideal experimental platforms which provide well-controlled external fields applied to the particle deposition process. Especially, the dynamic behaviour of particle deposition under complex external fields can be observed directly with a resolution of micrometre even nanometre (e.g., single molecule detection). With such unique information, trans-scale theoretical modelling which can bridge the gap between particle kinetics in microscale and fouling phenomena in macroscale will be highly appreciated. The current investigations at elevated temperatures rely on either ensemble average value of a population of particles (i.e., average particle deposition rate) or bulk property of fouling (i.e., fouling resistance). When the deposition of single nanoparticle at elevated temperatures can be reliably investigated, researchers will be able to understand the dynamic processes of nanoparticle deposition in microchannels which elucidates particulate fouling of nanofluids in heat exchangers and nanomaterial drug delivery *in vivo* in details.

Acknowledgements

This work has been partially supported by the National Key Research & Development Program of China (2016YFB0401502), the National Natural Science Foundation of China (61574065, 51561135014, and U1501244), Science and Technology Planning Project of Guangdong Province (2016B090906004), Special Fund Project of Science and Technology Application in Guangdong (2017B020240002), PCSIRT Project No. IRT_17R40, the National 111 Project, the MOE International Laboratory for Optical Information Technologies, and the Cultivation Project of National Engineering Technology Center of Optofluidic Materials and Devices (2017B090903008). Zhibin Yan also acknowledges the financial support by the Foundation for Distinguished Young Talents in Higher Education of Guangdong, China and the Research and Cultivation Fund for Young Faculty supported by South China Normal University (SCNU). Xiaoyang Huang and Chun Yang appreciate the financial support from the Ministry of Education of Singapore under Grant No. RG80/15 and RG97/13, respectively.

Nomenclature

a _p	particle radius (m)
a_1	radius of interacting particle 1 (m)

<i>a</i> ₂	radius of interacting particle 2 (m)
A ₁₃₂	Hamaker constant for the interaction between substances 1 and 2 in medium 3 (J) $$
В	width of the microchannel (m)
w	half channel height (m)
D_x	diffusivity in X direction (m ² /s)
D_y	diffusivity in Y direction (m ² /s)
D_T	thermal diffusion coefficient (m ² /s)
D_{∞}	Stokes-Einstein diffusivity (m ² /s)
Dl	double layer number in the HHF expression for the EDL interaction
Da	double layer asymmetry number in the HHF expression for the EDL interac- tion
$f_1(H)$	UHCC correction function for diffusivity perpendicular to the solid surface
$f_{3}(H)$	UHCC correction function for diffusivity parallel to the solid surface
$f_4(H)$	UHCC correction function for diffusivity along the flow direction (X)
F_x	X component of the total force exerted on the particle (N)
F_y	Y component of the total force exerted on the particle (N)
\overline{F}_{edl}	dimensionless EDL interaction force
\overline{F}_{vdw}	dimensionless van der Waals interaction force
\overline{F}_G	dimensionless gravity force
\overline{F}_L	dimensionless hydrodynamic lift force
\overline{F}_T	dimensionless thermophoretic force
h	minimum separation distance between particle and wall (m)
Н	dimensionless particle-wall separation
H_0	dimensionless primary energy minimum separation
H_{∞}	dimensionless particle-wall separation in bulk fluid
j_x	particle flux in X direction (m ^{-2} s ^{-1})
j_y	particle flux in Y direction (m ^{-2} s ^{-1})
\overline{J}_x	dimensionless mass flux in X direction

\overline{J}_y	dimensionless mass flux in Y direction
k_B	Boltzmann's constant (1.38064852 \times 10 ⁻²³ J/K)
L	length of the microchannel (m)
п	particle number concentration (/m ³)
\overline{n}	dimensionless particle number concentration
n _{∞,p}	particle number concentration in bulk liquid (/m ³)
Pe	Peclet number based on average flow velocity
Q	volume flow rate of liquid (m ³ /s)
Re	Reynolds number based on average flow velocity
Sh	Sherwood number
t	time (s)
Т	absolute temperature (K)
T_0	reference temperature (293.15 K)
<i>U</i> _{avg}	average flow velocity in microchannels (m/s)
\overline{V}	dimensionless total interaction potential
\overline{V}_{edl}	dimensionless EDL interaction potential
\overline{V}_{vdw}	dimensionless van der Waals interaction potential
\overline{V}_G	dimensionless gravity potential
\overline{V}_L	dimensionless lift potential
\overline{V}_T	dimensionless thermophoretic potential
z	ionic valence
е	elementary electric charge (1.602176620898 \times 10 ⁻¹⁹ C)
Greek symbols	
ε	dielectric constant
\mathcal{E}_0	absolute dielectric constant of vacuum (8.845 \times $10^{-12}C^2\!/N$ $m^2)$
ξ	zeta potential (V)
λ	London retardation wavelength (100 nm)
К	Debye-Hückel parameter (m)
μ	dynamic viscosity of liquid (N s/m ²)

- ν kinematic viscosity of liquid (m²/s)
- ρ density (kg/m³)
- ψ electric potential (V)
- τ ratio of particle radius (*a_p*) to the Debye length (κ^{-1})

ω

mobility of particle

Author details

Zhibin Yan^{1,2,3}*, Xiaoyang Huang³, Chun Yang³, Mingliang Jin^{1,2} and Lingling Shui^{1,2}

*Address all correspondence to: zhibin.yan@m.scnu.edu.cn

1 Guangdong Provincial Key Laboratory of Optical Information Materials and Technology and Institute of Electronic Paper Displays, South China Academy of Advanced Optoelectronics, South China Normal University, Guangzhou, P. R. China

2 National Center for International Research on Green Optoelectronics, South China Normal University, Guangzhou, P. R. China

3 School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

References

- [1] Liu R. A Study of Fouling in a Heat Exchanger with an Application of an Electronic Antifouling Technology. Pennsylvania, United States: Drexel University; 1999. pp. 286-286
- [2] Bott TR. Fouling of Heat Exchangers. Amsterdam, Netherlands: Elsevier Science B.V.; 1995
- [3] Yang C, Dabros T, Li D, Czarnecki J, Masliyah JH. Kinetics of particle transport to a solid surface from an impinging jet under surface and external force fields. Journal of Colloid and Interface Science. 1998;**208**(1):226-240
- [4] Liang Y, Hilal N, Langston P, Starov V. Interaction forces between colloidal particles in liquid: Theory and experiment. Advances in Colloid and Interface Science. 2007;134–135: 151-166
- [5] Derjaguin BV, Landau EM. Theory of the stability of strongly charged lyophobic sols and of the adhesion of strongly charged particles in solutions of electrolytes. Acta Physicochimica. 1941;14:633-662
- [6] Verwey EJW, Overbeek JTG. Theory of the stability of lyophobic colloids. Nature. 1948; 162:315-316

- [7] Ninham BW, Parsegian VA. van der Waals Forces. Biophysical Journal. 1970;**10**(7):646-663
- [8] Hough DB, White LR. The calculation of Hamaker constants from liftshitz theory with applications to wetting phenomena. Advances in Colloid and Interface Science. 1980;14 (1):3-41
- [9] Dzyaloshinskii IE, Lifshitz EM, Pitaevskii LP. General theory of van der Waals forces. Soviet Physics Uspekhi. 1961;4(2):153
- [10] Bowen WR, Jenner F. Theoretical descriptions of membrane filtration of colloids and fine particles: An assessment and review. Advances in Colloid and Interface Science. 1995;56: 141-200
- [11] Hamaker HC. The London-van der Waals attraction between spherical particles. Physica. 1937;4(10):1058-1072
- [12] Wang S. The mutual influence between the two atoms of hydrogen. Zeitschrift für Physik. 1927;28:663-666
- [13] London F. Zur Theorie und Systematik der Molekularkräfte. Zeitschrift für Physik. 1930;
 63(3):245-279
- [14] Margenau H. The role of quadrupole forces in van der Waals attractions. Physical Review. 1931;38(4):747-756
- [15] Casimir HBG, Polder D. The influence of retardation on the London-van der Waals forces. Physical Review. 1948;73(4):360-372
- [16] Prieve DC, Russel WB. Simplified predictions of Hamaker constants from Lifshitz theory. Journal of Colloid and Interface Science. 1988;125(1):1-13
- [17] Israelachvili JN. The calculation of van der Waals dispersion forces between macroscopic bodies. Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences. 1972;331(1584):39-55
- [18] Horn RG, Israelachvili JN. Direct measurement of structural forces between two surfaces in a nonpolar liquid. The Journal of Chemical Physics. 1981;75(3):1400-1411
- [19] Gregory J. The calculation of Hamaker constants. Advances in Colloid and Interface Science. 1970;2(4):396-417
- [20] Israelachvili JN. Intermolecular and Surface Forces. 1st ed. Burlington, MA: Academic Press; 1992
- [21] Tabor D, Winterton RHS. The direct measurement of normal and retarded van der Waals forces. In: Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences. 1969;312(1511):435-450
- [22] Suzuki A, Ho NFH, Higuchi WI. Predictions of the particle size distribution changes in emulsions and suspensions by digital computation. Journal of Colloid and Interface Science. 1969;29(3):552-564

- [23] Stern O. The theory of the electrolytic double shift. Zeitscrift für Elektrochemie. 1924;30: 508-516
- [24] Russel WB, Saville DA, Schowalter WR. Colloidal Dispersions. Cambridge, UK: Cambridge University Press; 1989
- [25] van de Ven TGM. Colloidal Hydrodynamics. Boston USA: Academic Press; 1989
- [26] Anderson JL. Journal of Fluid Mechanics. 1991;222:692-694
- [27] Frens G, Overbeek JTG. Repeptization and the theory of electrocratic colloids. Journal of Colloid and Interface Science. 1972;**38**(2):376-387
- [28] Barisik M, Atalay S, Beskok A, Qian S. Size dependent surface charge properties of silica nanoparticles. The Journal of Physical Chemistry C. 2014;118(4):1836-1842
- [29] Zhao C, Ebeling D, Siretanu I, van den Ende D, Mugele F. Extracting local surface charges and charge regulation behavior from atomic force microscopy measurements at heterogeneous solid-electrolyte interfaces. Nanoscale. 2015;7(39):16298-16311
- [30] Elimelech M, Gregory J, Jia X, Williams RA. Particle Deposition & Aggregation: Measurement, Modelling and Simulation. Oxford: Butterworth-Heinemann; 1995
- [31] Derjaguin BV. Analysis of friction and adhesion, IV. The theory of the adhesion of small particles. Kolloid Zeitschrift. 1934;69:155-164
- [32] Hogg R, Healy TW, Fuerstenau DW. Mutual coagulation of colloidal dispersions. Transactions of the Faraday Society. 1966;62:1638-1651
- [33] Adamczyk Z, Warszyński P. Role of electrostatic interactions in particle adsorption. Advances in Colloid and Interface Science. 1996;63(0):41-149
- [34] Kralj-Iglič V, Iglič A. A simple statistical mechanical approach to the free energy of the electric double layer including the excluded volume effect. Journal de Physique II. 1996;6
 (4):477-491
- [35] Briscoe WH, Attard P. Counterion-only electrical double layer: A constrained entropy approach. The Journal of Chemical Physics. 2002;117(11):5452-5464
- [36] Perry J, Kandlikar S. Fouling and its mitigation in silicon microchannels used for IC chip cooling. Microfluidics and Nanofluidics. 2008;5(3):357-371
- [37] Elimelech M. Particle deposition on ideal collectors from dilute flowing suspensions: Mathematical formulation, numerical solution, and simulations. Separations Technology. 1994;4(4):186-212
- [38] Ruckenstein E, Prieve DC. Adsorption and desorption of particles and their chromatographic separation. AICHE Journal. 1976;**22**(2):276-283

- [39] Healy TW, La Mer VK. The energetics of flocculation and redispersion by polymers. Journal of Colloid Science. 1964;**19**(4):323-332
- [40] Pashley RM, Israelachvili JN. Dlvo and hydration forces between mica surfaces in Mg²⁺, Ca²⁺, Sr²⁺, and Ba²⁺ chloride solutions. Journal of Colloid and Interface Science. 1984;97(2):446-455
- [41] Claesson PM, Christenson HK. Very long range attractive forces between uncharged hydrocarbon and fluorocarbon surfaces in water. The Journal of Physical Chemistry. 1988;92(6):1650-1655
- [42] Tipping E. Colloids in the aquatic environment. Chemistry and Industry (Chichester). 1988;15:485-490
- [43] Grabbe A, Horn RG. Double-layer and hydration forces measured between silica sheets subjected to various surface treatments. Journal of Colloid and Interface Science. 1993; 157(2):375-383
- [44] Leckband D, Israelachvili J. Intermolecular forces in biology. Quarterly Reviews of Biophysics. 2001;34(02):105-267
- [45] Ruckenstein E, Manciu M. The coupling between the hydration and double layer interactions. Langmuir. 2002;18(20):7584-7593
- [46] Israelachvili JN, Wennerstrom H. Hydration in electrical double layers. Nature. 1997;385 (6618):690-690
- [47] Rabinovich YI, Derjaguin BV. Interaction of hydrophobized filaments in aqueous electrolyte solutions. Colloids and Surfaces. 1988;**30**(3–4):243-251
- [48] Israelachvili JN, Pashley RM. Measurement of the hydrophobic interaction between two hydrophobic surfaces in aqueous electrolyte solutions. Journal of Colloid and Interface Science. 1984;98(2):500-514
- [49] Milner ST, Witten TA, Cates ME. Theory of the grafted polymer brush. Macromolecules. 1988;21(8):2610-2619
- [50] Vrij A. Polymers at interfaces and the interactions in colloidal dispersions. Pure and Applied Chemistry. 1976;48(4):471-483
- [51] Napper DH. The steric stabilization of hydrosols by nonionic macromolecules. Journal of Colloid and Interface Science. 1969;**29**(1):168-170
- [52] de Gennes PG. Polymers at an interface; a simplified view. Advances in Colloid and Interface Science. 1987;27(3):189-209
- [53] Tuckerman DB, Pease RFW, Guo Z, Hu JE, Yildirim O, Deane G, Wood L. Microchannel heat transfer: Early history, commercial applications, and emerging opportunities. ASME Conference Proceedings. 2011;2011(44649):739-756

- [54] Mavraki E, Moschou D, Kokkoris G, Vourdas N, Chatzandroulis S, Tserepi A. A continuous flow μPCR device with integrated microheaters on a flexible polyimide substrate. Procedia Engineering. 2011;25(0):1245-1248
- [55] Yang J, Liu Y, Rauch CB, Stevens RL, Liu RH, Lenigk R, Grodzinski P. High sensitivity PCR assay in plastic micro reactors. Lab on a Chip. 2002;**2**(4):179-187
- [56] Kim S-J, Wang F, Burns MA, Kurabayashi K. Temperature-programmed natural convection for micromixing and biochemical reaction in a single microfluidic chamber. Analytical Chemistry. 2009;81(11):4510-4516
- [57] Becker M, Mansouri A, Beilein C, Janasek D. Temperature gradient focusing in miniaturized free-flow electrophoresis devices. Electrophoresis. 2009;**30**(24):4206-4212
- [58] Edwards TL, Gale BK, Frazier AB. A microfabricated thermal field-flow fractionation system. Analytical Chemistry. 2002;74(6):1211-1216
- [59] Miralles V, Huerre A, Malloggi F, Jullien M-C. A review of heating and temperature control in microfluidic systems: Techniques and applications. Diagnostics. 2013;**3**(1):33-67
- [60] Velve Casquillas G, Fu C, Le Berre M, Cramer J, Meance S, Plecis A, Baigl D, Greffet J-J, Chen Y, Piel M, Tran PT. Fast microfluidic temperature control for high resolution live cell imaging. Lab on a Chip. 2011;11(3):484-489
- [61] Khandurina J, McKnight TE, Jacobson SC, Waters LC, Foote RS, Ramsey JM. Integrated system for rapid PCR-based DNA analysis in microfluidic devices. Analytical Chemistry. 2000;72(13):2995-3000
- [62] Maltezos G, Johnston M, Taganov K, Srichantaratsamee C, Gorman J, Baltimore D, Chantratita W, Scherer A. Exploring the limits of ultrafast polymerase chain reaction using liquid for thermal heat exchange: A proof of principle. Applied Physics Letters. 2010;97(26):264101
- [63] Lao AIK, Lee TMH, Hsing IM, Ip NY. Precise temperature control of microfluidic chamber for gas and liquid phase reactions. Sensors and Actuators A: Physical. 2000;**84**(1–2):11-17
- [64] Wu J, Cao W, Wen W, Chang DC, Sheng P. Polydimethylsiloxane microfluidic chip with integrated microheater and thermal sensor. Biomicrofluidics. 2009;**3**(1):012005
- [65] de Mello AJ, Habgood M, Lancaster NL, Welton T, Wootton RCR. Precise temperature control in microfluidic devices using joule heating of ionic liquids. Lab on a Chip. 2004;4 (5):417-419
- [66] Guijt RM, Dodge A, van Dedem GWK, de Rooij NF, Verpoorte E. Chemical and physical processes for integrated temperature control in microfluidic devices. Lab on a Chip. 2003; 3(1):1-4
- [67] Mao H, Yang T, Cremer PS. A microfluidic device with a linear temperature gradient for parallel and combinatorial measurements. Journal of the American Chemical Society. 2002;124(16):4432-4435

- [68] Zhao Y, Zhao C, He J, Zhou Y, Yang C. Collective effects on thermophoresis of colloids: A microfluidic study within the framework of DLVO theory. Soft Matter. 2013;9(32): 7726-7734
- [69] Yan Z, Huang X, Yang C. Rapid prototyping of single-layer microfluidic PDMS devices with abrupt depth variations under non-clean-room conditions by using laser ablation and UV-curable polymer. Microfluidics and Nanofluidics. 2017;21(6):108
- [70] Vigolo D, Rusconi R, Piazza R, Stone HA. A portable device for temperature control along microchannels. Lab on a Chip. 2010;**10**(6):795-798
- [71] Yan Z, Huang X, Yang C. Hydrodynamic effects on particle deposition in microchannel flows at elevated temperatures. Journal of Heat Transfer. 2017;**140**(1):012402-012410
- [72] Yan Z, Huang X, Yang C. Particulate fouling and mitigation approach in microchannel heat exchanger. In: ASME 2016 5th International Conference on Micro/Nanoscale Heat and Mass Transfer. American Society of Mechanical Engineers; 2016
- [73] Yan Z, Huang X, Yang C. Deposition of colloidal particles in a microchannel at elevated temperatures. Microfluidics and Nanofluidics. 2015;**18**(3):403-414
- [74] Matsui T, Franzke J, Manz A, Janasek D. Temperature gradient focusing in a PDMS/glass hybrid microfluidic chip. Electrophoresis. 2007;**28**(24):4606-4611
- [75] Jiao ZJ, Huang XY, Nguyen NT. Manipulation of a droplet in a planar channel by periodic thermocapillary actuation. Journal of Micromechanics and Microengineering. 2008;18(4):045027
- [76] Yap Y-F, Tan S-H, Nguyen N-T, Sohel Murshed SM, Wong T-N, Yobas L. Thermally mediated control of liquid microdroplets at a bifurcation. Journal of Physics D: Applied Physics. 2009;42(6):065503
- [77] Selva B, Cantat I, Jullien M-C. Temperature-induced migration of a bubble in a soft microcavity. Physics of Fluids. 2011;23(5):052002
- [78] Miralles V, Huerre A, Williams H, Fournie B, Jullien M-C. A versatile technology for droplet-based microfluidics: Thermomechanical actuation. Lab on a Chip. 2015;15(9): 2133-2139
- [79] Yan Z, Huang X, Yang C. Kinetics of Colloidal Particle Deposition in Microfluidic Systems under Temperature Gradients: Experiment and Modelling. Submitted
- [80] Newson IH, Miller GA, Haynes JW, Bott TR, Williamson RD. Particulate fouling: Studies of deposition, removal and sticking mechanisms in a haematite/water system. In: UK national conference on heat transfer. Glasgow, United Kingdom; 1988
- [81] Gu Y, Li D. Deposition of spherical particles onto cylindrical solid surfaces: II. Experimental studies. Journal of Colloid and Interface Science. 2002;248(2):329-339
- [82] Gu Y, Li D. Deposition of spherical particles onto cylindrical solid surfaces: I. numerical simulations. Journal of Colloid and Interface Science. 2002;248(2):315-328

- [83] Kar A, Guha R, Dani N, Velegol D, Kumar M. Particle deposition on microporous membranes can be enhanced or reduced by salt gradients. Langmuir. 2014;**30**(3):793-799
- [84] Guha R, Shang X, Zydney AL, Velegol D, Kumar M. Diffusiophoresis contributes significantly to colloidal fouling in low salinity reverse osmosis systems. Journal of Membrane Science. 2015;479(0):67-76
- [85] Salim M, Wright PC, McArthur SL. Studies of electroosmotic flow and the effects of protein adsorption in plasma-polymerized microchannel surfaces. Electrophoresis. 2009;30(11):1877-1887
- [86] Mustin B, Stoeber B. Deposition of particles from polydisperse suspensions in microfluidic systems. Microfluidics and Nanofluidics. 2010;9(4–5):905-913
- [87] Mustin B, Stoeber B. Single layer deposition of polystyrene particles onto planar polydimethylsiloxane substrates. Langmuir. 2016;**32**(1):88-101
- [88] Yiantsios SG, Karabelas AJ. The effect of gravity on the deposition of micron-sized particles on smooth surfaces. International Journal of Multiphase Flow. 1998;**24**(2):283-293
- [89] Yiantsios SG, Karabelas AJ. Deposition of micron-sized particles on flat surfaces: Effects of hydrodynamic and physicochemical conditions on particle attachment efficiency. Chemical Engineering Science. 2003;58(14):3105-3113
- [90] Stamm MT, Gudipaty T, Rush C, Jiang L, Zohar Y. Particle aggregation rate in a microchannel due to a dilute suspension flow. Microfluidics and Nanofluidics. 2011;11(4): 395-403
- [91] Gudipaty T, Stamm MT, Cheung LSL, Jiang L, Zohar Y. Cluster formation and growth in microchannel flow of dilute particle suspensions. Microfluidics and Nanofluidics. 2011; 10(3):661-669
- [92] Unni HN, Yang C. Colloidal particle deposition from electrokinetic flow in a microfluidic channel. Electrophoresis. 2009;**30**(5):732-741
- [93] Spielman LA, Friedlander SK. Role of the electrical double layer in particle deposition by convective diffusion. Journal of Colloid and Interface Science. 1974;46(1):22-31
- [94] Adamczyk Z, Van De Ven TGM. Deposition of particles under external forces in laminar flow through parallel-plate and cylindrical channels. Journal of Colloid and Interface Science. 1981;80(2):340-356
- [95] Song L, Elimelech M. Calculation of particle deposition rate under unfavourable particlesurface interactions. Journal of the Chemical Society, Faraday Transactions. 1993;89(18): 3443-3452
- [96] Song L, Elimelech M. Particle deposition onto a permeable surface in laminar flow. Journal of Colloid and Interface Science. 1995;173(1):165-180

- [97] Nazemifard N, Masliyah JH, Bhattacharjee S. Particle deposition onto micropatterned charge heterogeneous substrates: Trajectory analysis. Journal of Colloid and Interface Science. 2006;**293**(1):1-15
- [98] Nazemifard N, Masliyah JH, Bhattacharjee S. Particle deposition onto charge heterogeneous surfaces: Convection-diffusion-migration model. Langmuir. 2006;22(24):9879-9893
- [99] Chatterjee R, Bhattacharjee S, Mitra SK. Particle transport in patterned cylindrical microchannels. Microfluidics and Nanofluidics. 2012;**12**(1–4):41-51
- [100] Marshall JS. Particle aggregation and capture by walls in a particulate aerosol channel flow. Journal of Aerosol Science. 2007;**38**(3):333-351
- [101] Jin C, Ren CL, Emelko MB. Concurrent modeling of hydrodynamics and interaction forces improves particle deposition predictions. Environmental Science & Technology. 2016;50(8):4401-4412
- [102] Jin C, Glawdel T, Ren CL, Emelko MB. Non-linear, non-monotonic effect of nano-scale roughness on particle deposition in absence of an energy barrier: Experiments and modeling. Scientific Reports. 2015;5:17747
- [103] Unni HN. Transport and deposition of colloidal particles in microchannel flow. In: School of Mechanical and Aerospace Engineering. Singapore: Nanyang Technological University; 2007
- [104] Patel MV, Tovar AR, Lee AP. Lateral cavity acoustic transducer as an on-chip cell/particle microfluidic switch. Lab on a Chip. 2012;**12**(1):139-145
- [105] Ashkin A, Dziedzic JM, Bjorkholm JE, Chu S. Observation of a single-beam gradient force optical trap for dielectric particles. Optics Letters. 1986;11(5):288-290
- [106] Sheikholeslami M, Hayat T, Alsaedi A. Numerical simulation of nanofluid forced convection heat transfer improvement in existence of magnetic field using lattice Boltzmann method. International Journal of Heat and Mass Transfer. 2017;108:1870-1883





IntechOpen