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Environmental implications of aggregation phenomena: Current understanding ☆

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Abstract

This review highlights the current understanding of the aggregation phenomena of importance in Industrial Environmental Protection Technology; namely of particle aggregation in wastewater and gas emission treatment. The wastewaters and gaseous emissions from Forest Industry are our main focus. The complexity and variety of interfaces employed in chemical and biological methods of wastewater treatment and in purification of emission gases from aerosol particles is a challenge for a comparison analysis. The goals of this literature research are to delineate the most important similarities and key differences between aggregation phenomena on such different interfaces and to provide a coherent conception of environmental technology methods from the colloidal and surface science perspectives.

Keywords: Agglomeration; Aggregation; Coagulation; Flocculation; Flocculation mechanisms; Electrocoagulation; Condensation; Bioflocculation; Bioflocculation mechanisms; Aerosols; Particles; Combustion born particles; Fly ash particles; Particle size; Particle charge; Particle growth; Shear; Turbulence; Acoustic field; Acoustic wake; Sonication; Electric field; Bipolar charging; Elecroprecipitation; Aggregation kernel; Morphology; Activated sludge; Bioflocs; Flocs structure; Flocs stability; Aerobic granules; Anaerobic granules; Synthetic polymers; Extracellular polymeric compounds; Exopolymers; Fractal; Fractal dimensions; Chain structure; Brownian diffusion; DLVO theory; Surface forces; Gaseous emission; Purification; Particles removal; Wastewaters; Wastewaters treatment; TEM; CLSM; SEM; AFM

1. Introduction

The environmental importance of industrial wastewaters and gaseous emission treatment is undoubted. The development of treatment methods requires a deep fundamental understanding of the underlying phenomena. In environmental technology, wastewater treatment belongs altogether to a different domain than does the treatment of gaseous emissions. However, the universality of surface phenomena involved in the treatment technology of both media suggests that it could be possible to find a unified interfacial conception of environmental technology. This could facilitate the education process for students and environmentalists, enrich the toolkit of specialists dealing with each area of environmental technology, and allow one technological domain to benefit directly from development in the other.

1.1. Brief introduction into air and water pollution from forest industry

The most significant atmospheric emissions from the forest industry are various sulphur compounds, nitrogen oxides, and particulate matter (dust and ash).

Pulp and paper production requires large amounts of water, but most of the water used in pulp mills conforming to modern standards is recycled. The main water pollutants from the forest industry contain wood polymers, fillers, process and auxiliary chemicals and their reaction products in the form of suspended solids, and colloidal and dissolved matter, as well as non-process elements (e.g. manganese and copper ions). Among toxic compounds are fatty acids, resin acids, tannins, and chlorinated organic

☆ **Major recent advances** Deepened understanding of aggregation phenomena from improved modelling combined with real-life experimental studies of aerosol and hydrosol coagulation under different conditions of motion, applied charge etc, including those using fractal theories; deeper insight into mechanisms of bioflocculation; extended implementation of aggregation in environmental technology by incorporating pre-flocculation into e.g. membrane filtration and bio-treatment methods.

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compounds. Electrochemically, the pollutant species are negatively charged, with zeta potentials usually between −60 and −10 mV.

An overview of treatment methods for wastewaters from pulping and papermaking is given for example in Ref. [1]. We did not find recent reviews on the treatment of gas emissions in the forest industry.

1.2. Role of aggregation in environmental technology

Examples of aggregation phenomena encountered in environmental technology are coagulation of dissolved and dispersed matter caused by multivalent ions introduced chemically or by dissolution of metal electrodes; flocculation by synthetic nonionic and cationic polymers and by exopolymers produced by bacterial cells in activated sludge; agglomeration of aerosols in electric and acoustic fields prior to treatment in electroprecipitators, agglomeration by shear and turbulence occurring in cyclones and so on.

The role played by aggregation phenomena in the processes of wastewater and gas emissions purification cannot be overestimated. Not only are such processes as wastewater treatment with polyvalent metal salts coagulants and synthetic polymeric flocculants based entirely on aggregation, but in a range of other environmental treatment processes like biological wastewater treatment or dust particle separation from emission gases, aggregation is one of the crucial factors for the purification process efficiency. For example, the formation of activated sludge flocs in clarifiers and aerated lagoons determines biomass settling and separation from purified water. In upflow anaerobic sludge blanket bioreactors, the biomass retention is promoted by bacterial self-aggregation into dense granules and hence the formation of a strong, active granular sludge bed becomes important for optimal operation of the bioreactors. Fine particles of dust and other pollutants in gas streams are agglomerated to form larger particles that are more easily filtered in the downstream processing.

The complexity and variety of interfaces and phenomena employed in modern methods of wastewater and gaseous emission treatment is a challenge for the comparison analysis.

1.3. Scope

The goals of this literature survey are to identify the most important similarities and key differences between aggregation phenomena on such different interfaces, and to give a coherent conceptual view of aggregation phenomena implications in environmental technology.

To our knowledge, no recent attempts have been made to review the understanding of the aggregation phenomena involved into both effluent and gas emission treatment *in sync* and provide a coherent conceptual picture of environmental technology methods from the colloidal and interfacial point of view. From the abundance of recent literature on effluents and gas emission treatment and from theoretical and experimental studies of aggregation, we selected the works that enhance our understanding of such diverse aggregation phenomena involved in today's industrial environmental protection, especially within the forest industry. Due to its somewhat different nature, attachment of solid particles to air bubbles employed in the flotation treatment of wastewaters and paper de-inking are omitted from this contribution. The period surveyed is mainly 2002–2005.

1.4. Previous reviews

Several creditable reviews dealing with different aspects of relevance should be mentioned:

1. Jiang [2•] reviews the history of chemical coagulation and its effects on water quality control, compares the efficiency of pre-polymerised inorganic coagulants with that of conventional coagulants and points out the most favorable coagulant species for water treatment.
2. Flocculation modelling review by Thomas et al. [3••] thoroughly discusses the developments in flocculation modelling with reference to the classical analytical expression of aggregation kinetics of colloidal solutions by Smoluchowski. [4].
3. Modelling of colloidal particle aggregation is reviewed by Taboada-Serrano et al. [5]. Recent contributions to the understanding of colloidal particle aggregation are discussed from the perspective of developments following the classical treatment and new molecular approaches.
4. Zhang et al. [6•] review algorithms used in the simulation of aerosol dynamics for air quality models. Coagulation, condensation growth, nucleation and gas/particle mass transfer are discussed using sectional and modal approaches.
5. Hulshoff et al. [7••] review physical, microbial, and thermodynamic theories of anaerobic sludge granulation that have been proposed during the past 20 years.
6. Methods in floc strength analysis are overviewed by Jarvis et al. [8•]. Data on floc strength obtained with different strength tests such as oscillating multigrid mixer, micromanipulation and micromechanics are compared.
7. Water distribution within activated sludge is discussed by Vaxelaire and Cezac [9].
8. Somasundaran et al. [10] comprehensively discuss experimental and modelling studies on flocculation and dispersion of colloidal suspensions by polymers and surfactants.
9. The essentiality of hydrodynamic shear force in the formation and performance of granular sludge (and of biofilm) is discussed in the contribution by Liu and Tay [11].

2. Preview

In this section, we compare the proposed mechanisms of particle aggregation in air and in water.

Particles in air experience strong long-range van der Waals attractive interactions, which are essentially electrostatic, arising from the dipole field of an atom reflected back by a second atom that has been polarized by this field. In an aqueous medium, the interaction strength is reduced by an order of magnitude. For example, the interaction between hydrocarbons across water is about 10% of that across a vacuum; mainly an entropic term dominates over the dispersion contribution [12].