AD-A031 296 MASSACHUSETTS INST OF TECH CAMBRIDGE FLUID MECHANICS LAB F/G 13/2
SCALING LAWS FOR WASTEWATER TREATMENT SYSTEMS EMPLOYING COAGULA--ETC(U)
JUL 74 M A DELICHATSIOS, R F PROBSTEIN N00014-67-A-0204-0057

UNCLASSIFIED FML-74-3 NL

1 OF 1
ADA031296

END
DATE
FILMED
11 -76

Fluid Mechanics Laboratory
Publication No. 74-3

SCALING LAWS FOR WASTEWATER TREATMENT SYSTEMS EMPLOYING COAGULATION AND SEDIMENTATION

Michael A. Delichatsios and Ronald F. Probstein

July 1974

FLUID MECHANICS LABORATORY

DEPARTMENT OF MECHANICAL ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SCALING LAWS FOR WASTEWATER TREATMENT SYSTEMS EMPLOYING COAGULATION AND SEDIMENTATION

by

Michael A. Delichatsios [redacted] Ronald F. Probstein

Fluid Mechanics Laboratory

Department of Mechanical Engineering
Massachusetts Institute of Technology

FML-74-3

This work was supported by the Office of Naval Research under Contract No. N00014-67-A-0204-0057

24p.

July 1974

SCALING LAWS FOR WASTEWATER TREATMENT SYSTEMS EMPLOYING COAGULATION AND SEDIMENTATION

Michael A. Delichatsios and Ronald F. Probstein

Mechanical and/or chemical coagulation followed by sedimentation is one of the oldest methods still employed in water purification and wastewater treatment systems. Chemical coagulants and coagulant aids have been studied extensively and optimum dosages have been established for a wide variety of dispersions with different physicochemical properties (e.g., zeta-potential, concentration, etc.)[1,2].

It is also well understood that flow in a dispersed system enhances coagulation over that due to Brownian motion alone. In general, this fact has been applied in an empirical manner to the enhancement of coagulation in practical systems[3]. The reason for this empirical approach is that there is at present only an incomplete understanding of the relationship between particle coagulation, breakup and sedimentation when the flow of a dispersed system in either an agitator tank or a pipe is turbulent. This stems in part from the fact that although turbulence increases the coagulation rate of micron size particles, it also breaks the larger size particles (∿ 100 μm) and impedes sedimentation in an agitator tank.

In this work we develop scaling laws that delineate the regimes in which coagulation, breakup and sedimentation are predominant. It is these processes which are fundamental to most wastewater treatment systems. Although the details of the interactions between the particles or between the particles and the continuous phase are examined for an idealized isotropic turbulent flow, it is shown how the results which are obtained can be applied to dispersed systems in agitator tanks and in turbulent pipe flows.

Based on this analysis and a knowledge of the physicochemical properties of a dispersed system, which can be gained by in situ measurements, we show how a wastewater treatment or water purification system can be rationally designed. Coagulation of the solid particles in the proposed system takes place in a turbulent pipe flow prior to discharging the wastewaters into a sedimentation tank. A similar suggestion for the use of pipelines as aerobic biological reactors has recently appeared in the literature[4].

A specific design is proposed for a small community (e.g., a ship) where space is at a premium. Such a system, which may be classified as a chemical and mechanical one will remove efficiently the settleable and suspended solids content in the wastewaters to the degree required. Experience with land operations[3] has shown that approximately 60% of the BOD_5 will also be removed simultaneously.

The present system, when combined with carbon reactors for the total removal of organic wastes remaining in the effluent after coagulation and sedimentation, may have several advantageous applications in shipboard or land wastewater treatment[5].

SCALING LAWS

To examine the fluid dynamic aspects of the basic processes in a separation system, i.e., coagulation, breakup and sedimentation, it is assumed in what follows that the dispersion is destabilized through the addition of appropriate amounts of coagulants and/or coagulant aids.

We also confine our attention to dilute systems in isotropic turbulent flows.

Coagulation. Turbulent flow coagulation will be more effective than coagulation due to Brownian motion, when the characteristic time for relative diffusion between particles in the turbulent flow is less than the characteristic time for Brownian diffusion.

The characteristic time for Brownian diffusion is[6]

$$\tau_{Br} = \frac{d^2}{D_{Br}} \tag{1}$$

where the Brownian diffusivity

$$D_{Br} = \frac{kT}{3\pi\mu d} \tag{2}$$

and where d is the effective diameter of the particle, which we shall generally consider to be spherical. Here, k is the Boltzmann constant, and T and μ are the absolute temperature and viscosity respectively of the continuous phase.

The characteristic turbulent time for relative particle diffusion is

$$\tau_{turb} = \frac{d}{u_r} \tag{3}$$

where u_r is the root mean square relative particle velocity during collision. Two physically important cases have to be considered, namely, when the particle size is less than or greater than the Kolmogorov microscale of turbulence characterizing the scale of the turbulent eddies. The Kolmogorov microscale is given by

$$\lambda = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \qquad (4)$$

where ν is the kinematic viscosity of the continuous phase and ε is the rate of turbulent energy dissipation per unit mass. Depending upon the particle size compared to this scale, the relative velocity u_r is given by[7]

$$u_r \gtrsim \sqrt{\varepsilon/\nu}\, d \qquad \text{for } d < \lambda \qquad (5a)$$

$$u_r \gtrsim (\varepsilon d)^{1/3} \qquad \text{for } d > \lambda \qquad (5b)$$

Coagulation induced by turbulent flow will dominate when

$$\frac{\tau_{Br}}{\tau_{turb}} \gtrsim 1 \qquad (6)$$

Since Brownian motion is important at the very small particle sizes it is evident that the relevant comparison as to the importance of turbulence in inducing coagulation is measured by the ratio of the Brownian time scale to the turbulent time scale calculated on the particle size being small in comparison with the microscale. From Equations 1-3 and 5a the time scale ratio takes the form

$$\frac{3\pi\mu d^3}{kT}\sqrt{\frac{\varepsilon}{\nu}} \gtrsim 1 \qquad (7)$$

<u>Breakup</u>. A particle will break in a turbulent flow field either from the forces resulting from the unsteady turbulent pressure fluctuations across the particle diameter or from the shear forces associated with the relative motion of the particle with respect to the continuous fluid. For particles dispersed in water the forces due to the pressure fluctuations are larger than the forces arising from the relative motion.

Following Hinze[8] we estimate that for dilute dispersions the maximum particle size is determined by the phenomenon of breakup alone. In this case the maximum particle size will be determined by the criteria that the mean pressure forces across a particle diameter are of the same order of magnitude as the particle's material strength.

The mean pressure forces across the particle diameter are[9]

$$\Delta p \approx \mu\sqrt{\varepsilon/\nu} \qquad \text{for } d < \lambda \qquad (8a)$$

$$\Delta p \approx \rho(\varepsilon d)^{2/3} \qquad \text{for } d > \lambda \qquad (8b)$$

where ρ is the density of the continuous phase. It should be pointed out that for particles whose sizes are less than the Kolmogorov microscale it is viscous shear forces which dominate as implied by Equation 8a, while for particles larger than the Kolmogorov microscale pressure fluctuations from inertia effects are more significant as implied by Equation 8b.

The condition for breakup for each of the above cases is then given by

$$\frac{\Delta p}{\sigma} = \frac{\mu\sqrt{\varepsilon/\nu}}{\sigma} = a \qquad \text{for } d < \lambda \tag{9a}$$

$$\frac{\Delta p}{\sigma} = \frac{\rho(\varepsilon d)^{2/3}}{\sigma} = b \qquad \text{for } d > \lambda \tag{9b}$$

where σ is the particle strength, which in the case of a floc we interpret to be the ultimate shearing or tensile strength[10]. If the particle is a liquid drop, and internal motions are neglected, then the strength of the drop may be interpreted in terms of its surface tension[8], wherein

$$\sigma = \frac{4\gamma}{d} \tag{10}$$

with γ the surface tension. The proportionality constants a and b are empirically determined.

Settling. Gravitational effects will be of importance when the settling velocity of the particle is of the same order of magnitude as the root mean square fluctuating velocity of the turbulent flow. With u_s the settling velocity and $(\overline{u'^2})^{1/2}$ the root mean square turbulent velocity we may express this condition by

$$\frac{u_s}{(\overline{u'^2})^{1/2}} \sim 1 \tag{11}$$

For Stokes flow the settling velocity neglecting concentration effects is[2]

$$u_s = \frac{1}{18} \frac{\rho_p - \rho}{\rho} \frac{gd^2}{\nu} \quad (12)$$

where ρ_p is the particle density and g the gravitational acceleration. The root mean square velocity in an isotropic turbulent flow is given by[11] (cf. Equation 5b)

$$(\overline{u'^2})^{1/2} \approx (\varepsilon L)^{1/3} \quad (13)$$

where L is the Eulerian macroscale of turbulence. The macroscale L is proportional to the scale of the apparatus and expressions for it in particular cases are given below.

Regimes. Based on the foregoing analysis the domains of turbulent coagulation, breakup and sedimentation are plotted in Figure 1. Since several time and length scales are involved in these processes dimensionless co-ordinates can not be used. For this plot we have assumed a destabilized system consisting of particles dispersed in water with typical physical properties $\frac{|\rho_p - \rho|}{\rho} = 0.2$, $\rho = 1$ gr/cm^3, $\nu = 10^{-2}$ cm^2/sec and L = 1 cm or 10 cm.

Curve A calculated from Equation 7, delimits the region where turbulent coagulation begins to dominate over Brownian coagulation. Curve B gives the Kolmogorov microscale. Curve D calculated from Equation 11 characterizes the domain where gravitational effects dominate. The curves C and E are for liquid particles and flocs, respectively, and define the domains where breakup of these types of particles becomes important.

In practice[12] the stable size for drops is larger than the Kolmogorov microscale of turbulence and so Equation 9b is used to draw curve C in Figure 1. The surface tension is taken to be γ = 40 dyne/cm and the constant of proportionality in Equation 9b is taken equal to .04, as deduced from the experimental results of Sprow[12].

For flocs (which consist of particles loosely held together) larger in size than the Kolmogorov microscale, Equation 9b giving the maximum floc size may be written

$$d = \frac{c}{\varepsilon} \qquad (14)$$

where the constant $c = (b\sigma/\rho)^{3/2}$ and σ is the ultimate tensile strength of the particle. From the experimental results of Parker at al.[10] the constant c is determined to be equal to .71 cm^3/sec^3 for ferric floc.

Breakup of flocs less than the Kolmogorov microscale may be important as Equation 9a shows when,

$$\varepsilon = \left(\frac{a\sigma}{\rho}\right)^2 \frac{1}{\nu} = \text{constant} \qquad (15)$$

This result shows that for this case the breakup condition is independent of floc size. For flocs larger than the Kolmogorov microscale, curve E has been calculated from Equation 14. For flocs of a size smaller than the microscale the criterion indicated by Equation 15 of a breakup condition dependent only on energy has been used to draw the lower portion of curve E, with the energy set equal to that corresponding to the intersection of the upper portion of curve E and the curve defining the Kolmogorov microscale.

The drawing of the domains of Figure 1 for any given dispersion is useful in the rational design of a separation system in that it allows a flow path to be chosen to increase the efficiency of coagulation by minimizing breakup or sedimentation effects. The above results can be applied to practical cases of turbulent flows in agitated tanks and pipes. The spatial distribution of the rate of turbulent energy dissipation per unit mass and the macroscale of turbulence in an agitator tank have been measured by Lattke[13] for some typical tank geometries. If the geometry is such that the flow field is approximately homogeneous, the average rate of energy per unit mass supplied to the agitator tank which may be used in conjunction with Figure 1 is given by

$$\varepsilon = \frac{P}{\rho V} \tag{16a}$$

where P is the impeller power input and V the effective tank volume. With D the tank diameter the turbulent macroscale is found from[13]

$$L = 0.04\ D \tag{16b}$$

The turbulent characteristics of fully developed turbulent pipe flow are well known[14]. Recent experiments on the coagulation of micron size particles in turbulent pipe flows[15] have shown that the effective rate of energy dissipation per unit mass is that rate corresponding to the core of the pipe flow[14]

$$\varepsilon = 4 \frac{u_*^3}{D} \tag{17a}$$

where u_* is the friction velocity and D the pipe diameter. The reason for this is that more than ninety per cent of the particles at any given cross-section are to be found in the core of the pipe where the flow is approximately isotropic and has constant turbulent characteristics. The macroscale of turbulence for this case is given by[16]

$$L = 0.05D \tag{17b}$$

SEPARATION SYSTEMS EMPLOYING COAGULATION - A NEW APPROACH

To ensure the rational design and operation of a treatment plant employing coagulation and sedimentation, in addition to the physico-chemical properties (quality) of the system (e.g., viscosity, zeta potential, pH, optimum dosage of coagulants and coagulant aids for destabilization) it is also necessary to understand and utilize the information concerning the fluid mechanical regimes of coagulation and breakup depicted in Figure 1.

In existing technology[17] coagulation generally takes place inside agitator tanks after the addition of the proper amount of coagulants and/or coagulant aids and the product settles in sedimentation tanks[1]. A disadvantage of coagulating the dispersed particles in a flocculator is that the flow field is not homogeneous. In the present paper we propose a new design concept[18] in which coagulation of the suspended solids takes place in a turbulent pipe flow transporting the dispersion directly to the sedimentation tank. To reduce the length of pipe required, floc is recirculated from the sedimentation tank to a point near the inlet end of the pipe. The recirculated dispersion will consist of large flocs but still of a size smaller than the stable size corresponding to the operating turbulent conditions in the pipe flow (see, line E for floc breakup in Figure 1). In order to achieve this condition the diameter of the pipe used for floc recirculation is selected such that the steady floc size corresponding to its turbulent flow conditions is less than the floc size corresponding to the flow conditions in the pipe where coagulation takes place.

The configuration of the proposed system[18] is shown in Figure 2. Following a conventional screen and grit chamber[3], not shown in the figure, the proper amount of coagulant and/or coagulant aid is injected into the pipe flow. A sufficient length of pipe is allowed subsequently to enable the complete mixing of the chemicals with the flow, after which the recirculated floc is added to the flow. The pipe in which the coagulation takes place is long enough that the requisite degree of coagulation of the dispersed solids is achieved prior to discharging the effluent into the sedimentation tank.

COAGULATION AND BREAKUP IN TURBULENT PIPE FLOWS

The two questions which must be answered to implement the suggested approach are (1) the extent of coagulation of the dispersed particles in the pipe flow, and (2) the maximum stable floc size for specified turbulent pipe flows. In the discussion which follows complete destabilization of the dispersed particles is assumed subsequent to the addition of the proper coagulants and/or coagulant aids[1].

The coagulation of particles smaller than the Kolmogorov microscale of turbulence has recently been measured in turbulent flows through a circular pipe[15]. The measured coagulation rate for a fully destabilized dispersion of monodisperse latex particles was found to be expressible by the relation

$$\frac{\omega\tau}{\phi} = 0.8 \qquad (18)$$

where ω is the coagulation frequency. Here,

$$\tau = \left(\frac{\nu}{\varepsilon}\right)^{1/2} \qquad (19)$$

is the Kolmogorov time scale corresponding to the turbulent microscale λ of Equation 4 and ϕ is the volume fraction of the dispersed phase, with the rate of energy dissipation per unit mass ε given by Equation 17a.

Equation 18 verifies a simple kinetic model for the rate of coagulation of particles of diameter d_1 and number density n_1 with particles of diameter d_2 and number density n_2 as expressed by the classical binary collision hard sphere collision frequency

$$\omega_{12} = n_2\, \pi\left(\frac{d_1 + d_2}{2}\right)^2 u_r \qquad (20)$$

where as before u_r is identified as the root mean square relative velocity of the particles during collision. When the effective collision diameter $(\frac{d_1 + d_2}{2})$ is less than the Kolmogorov microscale, the root mean square velocity is[7] (cf. Equation 4)

$$u_r = \sqrt{\frac{1}{15} \frac{\varepsilon}{\nu}} \left(\frac{d_1 + d_2}{2}\right) \tag{21}$$

For a monodisperse dispersion ($d_1 = d_2 = d$) the right hand side of Equation 20 becomes $\frac{1}{2} n\pi d^2 u_r$, where the factor of $\frac{1}{2}$ is required to ensure that each collision is counted only once. Assuming spherical particles the volume fraction of the displaced phase is given by

$$\phi = \frac{1}{6} n\pi d^3 \tag{22}$$

Combining Equations 19-22 leads to the experimentally determined result of Equation 18 but with the constant equal to 0.77. The almost exact agreement with experiment should not be taken literally in view of the approximations involved in this simple theory.

In the presently proposed scheme coagulation takes place in a dispersion with an approximately bimodal particle size distribution; the primary particles having an average particle diameter of the order of one micron while the recirculated floc may have an average floc size approximately two orders of magnitude larger. For a practical domestic wastewater system the rate of turbulent energy dissipation is selected such that the effective collision diameter between primary particles and recirculated floc is less than the Kolmogorov microscale of turbulence. Only the coagulation of the primary small size particles with the larger flocs are of interest inasmuch as two large flocs coagulating into one will form an unstable floc (see Figure 1), which will in general break in a time shorter than their coagulation time. From Equations 20 and 21 with $d_1 << d_2 \equiv d_F$ we have

$$\omega_{1F} = n_F \pi \left(\frac{d_F}{2}\right)^3 \sqrt{\frac{1}{15}\frac{\varepsilon}{\nu}} \tag{23}$$

where the subscript 1 refers to the primary particles and F to the flocs. The volume fraction of the floc dispersion ϕ_F is given by Equation 22 with $n \equiv n_F$ and $d \equiv d_F$, from which Equation 23 may be expressed in the form

$$\frac{\omega_{1F}\,\tau}{\phi_F} = 0.2 \tag{24}$$

The rate of removal of primary particles is then given by the kinetic equation

$$\frac{dn_1}{dt} = -\,\omega_{1F}\,n_1 \tag{25}$$

where we have neglected as small the generation of any particles due to breakup. No experimental results for floc breakup in a pipe flow exist but it is reasonable to assume that it is essentially the flow conditions at the core of pipe flow which determine the stable floc size.

The selection of the floc size and the recirculation flow rate for the proposed system is based on the criteria of minimum breakup and efficient coagulation. It should be noted that floc deposition on the pipe walls during coagulation is not probable in the proposed system as may be seen from Figure 1.

SHIPBOARD WASTEWATER TREATMENT

As a specific example of the application of the proposed system we consider the treatment of the wastewater from a cargo or naval vessel with a population of 200 persons and an average sewage flow[3] of 80 gal/person/day (300ℓ/person/day). The corresponding steady pipe flow rate is approximately 12 gpm (45 ℓ/min) and the concentration of solids for dry weather conditions is taken to be[3] 480 mg/ℓ. In the calculations to follow we take the maximum content of suspended solids in the treated wastewater to be 150 ppm, consistent with present EPA standards. Assuming the density of the solids to be not much different from that of water and their size distribution to be not too broad, then the required reduction in total number of particles compared with those present initially is approximately 4.

The volume fraction of recirculated floc is taken to be 3% of that in the main pipe flow and the flow rate in the recirculation system approximately 5 gpm (19 ℓ/min) of a 10% (by volume) floc dispersion with an average particle diameter of approximately 90 μm. The rate of turbulent energy dissipation per unit mass in the core of the pipe is selected to be near the maximum allowed for a typical ferric floc, 60 erg/sec · gm (see Figure 1), so that breakup is negligible.

The friction velocity appearing in Equation 17a may be found in any standard fluid mechanics text and is

$$u_* = U\sqrt{f/8} \tag{26}$$

where U is the average pipe velocity and f the turbulent friction coefficient for a smooth pipe

$$f = \frac{0.316}{Re^{1/4}} \tag{27}$$

Here, Re is the Reynolds number based on the pipe diameter.

Knowing the required flow rate (17 gpm), from Equations 17a, 26, and 27 the pipe diameter and average pipe flow velocity are calculated to be

$$U = 76 \text{ cm/sec} \quad , \quad D = 4 \text{ cm}$$

Under these conditions the coagulation rate from Equation 24 is

$$\omega_{1F} = 0.5 \text{ sec}^{-1}$$

Integrating Equation 25 the time necessary for the required degree of coagulation is

$$t_c = -\frac{1}{\omega_{1F}} \ln \frac{n_1}{n_{10}} \tag{28}$$

where n_1 is the final and n_{10} the initial particle number density of the primary dispersion. For the present requirements ($n_1/n_{10} = 1/4$) the coagulation time and the required pipe length are then, respectively,

$$t_c = 3 \text{ sec} \quad , \quad \ell = 220 \text{ cm}$$

The size of the sedimentation tank is determined by the size of the large flocs to which the primary particles have stuck and the flow rate of the discharged mixture. Assuming the relative density difference to be $\Delta\rho/\rho = 0.2$ and the minimum size of the flocs to be 80 μm, the settling velocity is calculated from Equation 12 to be

$$u_s = 0.07 \text{ cm/sec}$$

For an effective sedimentation tank height of 50 cm the required residence time and tank volume would be, respectively,

$$t_{res} = 12 \text{ min} \quad , \quad V = 0.8 \text{ m}^3 \text{ (28 ft}^3\text{)}$$

The diameter of the pipe used for recirculating the floc from the sedimentation tank is determined to be equal to 2.7 cm for a flow rate of 5 gpm. The rate of energy dissipation per unit mass will then be equal to 70 erg/sec · gm and the corresponding stable floc size in the pipe is, according to Figure 1, less than the stable floc size corresponding to the operating conditions inside the pipe where coagulation takes place.

The total volume of the present system is approximately 0.85 m^3 (30 ft^3) or almost an order of magnitude less than conventional systems in use[19].

TABLE I. - Shipboard Wastewater Treatment System

Requirements		Characteristics	
Population	200 persons	Pipe diameter (D)	= 4 cm
Sewage flow rate	17 gpm (64 ℓ/min)	Average velocity (U)	= 76 cm/sec
Solids content	480 mg/ℓ	Reynolds number (Re)	= 32,000
Suspended solids in effluent	150 ppm	Pipe length (ℓ)	= 220 cm
		Flow rate of recirculated floc	= 5 gpm (19 ℓ/min) of 10% floc volume
		Pipe diameter for floc recirculation	= 2.7 cm
		Volume of sedimentation tank (V)	= 0.8 m^3 (28 ft^3)
		Volume of entire system	= 0.85 m^3 (30 ft^3)

We have summarized in Table I the engineering requirements and design characteristics of the example discussed.

CONCLUSIONS

The case study presented illustrates how a knowledge of the fluid mechanical aspects of the separation process, as represented in Figure 1, when taken together with the physicochemical properties of the dispersed phase, can be applied to the rational and efficient design of a physicochemical wastewater or a water purification system.

The general advantages of promoting coagulation in a turbulent pipe flow with recirculation instead of in flocculation tanks are:

1. The turbulent flow in a pipe system is almost homogenous so that system control and effectiveness is enhanced.

2. Deposition and breakup of flocs can be prevented by proper system design thereby increasing the efficiency of coagulation.

3. Piping and energy required for wastewater transport can be employed for coagulation.

For the particular limited population shipboard system examined, the volume requirements were considerably reduced in comparison with present systems employing flocculation tanks. No economic comparisons were made but the power required for the floc recirculation is comparable with the impeller power of a flocculator tank so that we may expect the overall system cost to be comparable.

It should be noted that the turbulent pipe flow coagulation system considered for the removal of suspended solids can be readily combined with carbon reactors for the removal of residual organic wastes to form an integrated physicochemical wastewater treatment system[5].

ACKNOWLEDGMENTS

Credits. This work was supported by the Office of Naval Research under Contract No. N00014-67-A-0204-0057.

Authors. Michael A. Delichatsios and Ronald F. Probstein are research assistant and professor, respectively, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts. Michael A. Delichatsios has recently become associated with Factory Mutual Research, Norwood, Massachusetts.

REFERENCES

1. Cohen, J. M. and Hannah, S. A., "Coagulation and Flocculation." In "Water Quality and Treatment," 3rd edition, McGraw-Hill, New York, 66-122 (1971).

2. Weber, W. J., Jr., "Physicochemical Processes for Water Quality Control," Wiley-Interscience, New York (1972).

3. Imhoff, K., Muller, W. J., and Thistlethwayte, D. K. B., "Disposal of Sewage and Other Water-Borne Wastes." Ann Arbor Science Company, Ann Arbor, Mich., 16, 140, 152, 171 (1971).

4. Koch, C. M., and Zandi, I., "Use of Pipelines as Aerobic Biological Reactors." Jour. Water Poll. Control Fed., 45, 2537 (1973).

5. Weber, W. J., Jr., "Physicochemical Systems." In "Progress in Water Technology." L. K. Cecil and W. W. Eckenfelder [Eds.], Pergamon Press, New York (1972).

6. Levich, V. G., "Physicochemical Hydrodynamics." Prentice Hall, Englewood Cliffs, N. J., 207 (1972).

7. Rotta, J. C., "Turbulente Strömungen." B. G. Teubner, Stuttgart, 94 (1972).

8. Hinze, J. O., "Fundamentals of the Hydrodynamic Mechanism of Splitting in Dispersion Processes." Amer. Inst. Chem. Eng. Jour., 1, 289 (1955).

9. Batchelor, G. K., "Pressure Fluctuations in Isotropic Turbulence." Proc. Cambr. Phil. Soc., 47, 359 (1951).

10. Parker, D. S., Kaufman, W. J., and Jenkins, D., "Floc Breakup in Turbulent Flocculation Processes." Jour. San. Eng. Div., Proc. Amer. Soc. Civil Engr., 98, SA1, 79 (1972).

11. Batchelor, G. K., "The Theory of Homogeneous Turbulence." Cambridge Univ. Press, Cambridge, England (1958).

12. Sprow, F. B., "Distribution of Drop Sizes Produced in Turbulent Liquid Dispersion." Chem. Eng. Sci., 22, 435 (1967).

13. Lattke, H., "Untersuchung über Homogenisieren und über Turbulenz in Rührmaschinen." Chem. Techn. 23, 231 (1971).

14. Laufer, J., "The Structure of Turbulence in Fully Developed Pipe Flow." U.S. Natl. Adv. Comm. for Aeronautics, Rept. No. 1174, Washington, D.C. (1954).

15. Delichatsios, M. A., "Coagulation of Colloidal Particles in Turbulent Flows with Applications in Wastewater Treatment." Ph.D. thesis, M.I.T., Cambridge, Mass. (1974).

16. Powe, R. E., and Townes, H. W., "Turbulence Structure for Fully Developed Flow in Rough Pipes." Amer. Soc. Mech. Engr., Paper No. 72-WA/FE-14, New York (1972).

17. Walton, G., "Developments in Water Clarification in U.S.A." In "Water Treatment in the Seventies." R. G. Allen [Ed.], Water Res. Assoc., England, 59-72 (1970).

18. Probstein, R. F. and M. A. Delichatsios, "Method of and Apparatus for Continuous Flow Flocculation and Clarification." U.S. Patent Application, Serial No. 446,666, filed Feb. 28, 1974.

19. Sanders, G. A., et al., "Shipboard Control of Wastes in Immediate Cost-Effective Abatement of Water Pollution From Navy Ships." U.S. Naval Postgraduate School, Monterey, Calif., 15-101 (1972).

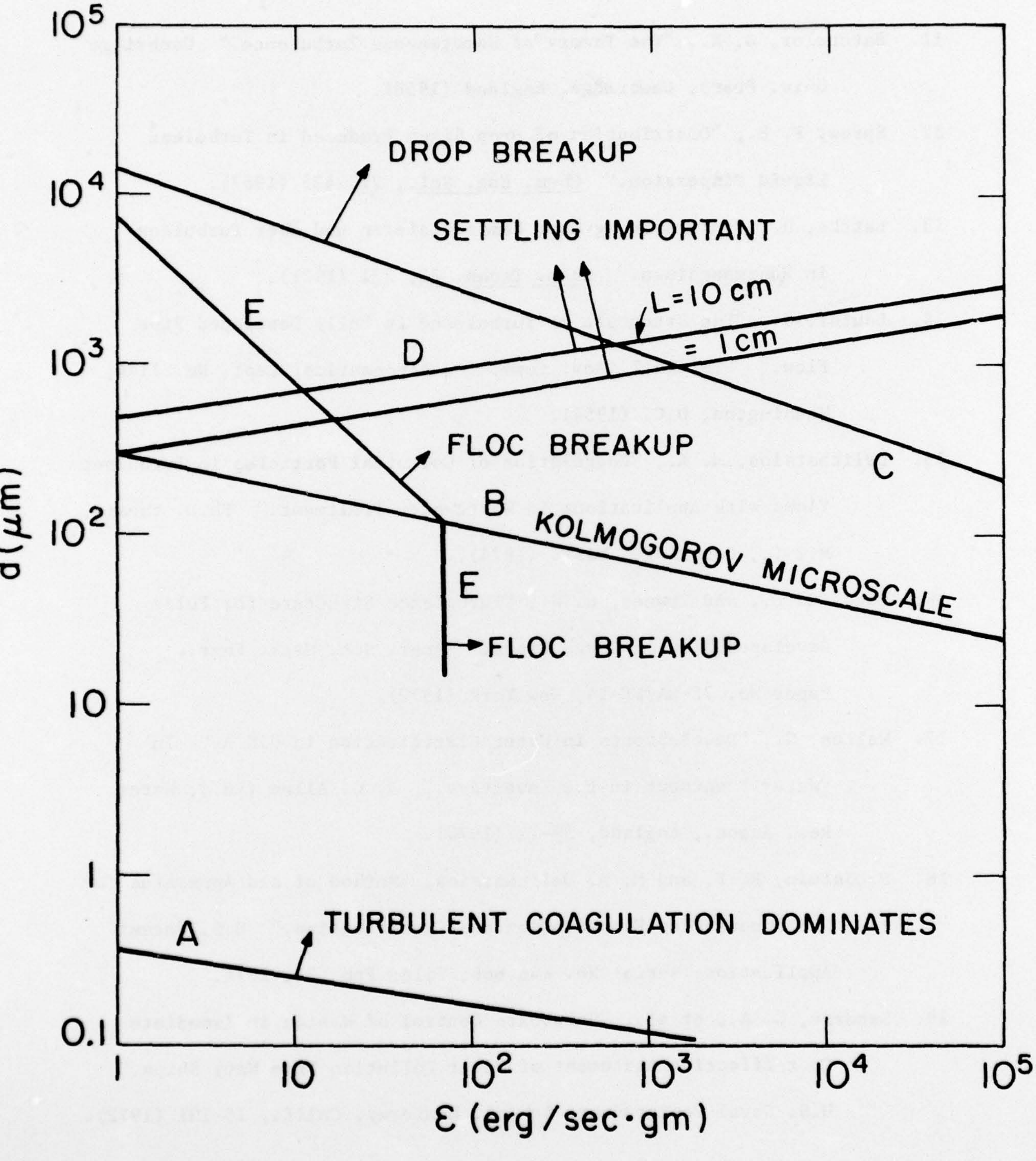

Figure 1. - Domains of turbulent coagulation, breakup and sedimentation for different particle sizes as a function of rate of turbulent energy dissipation per unit mass.

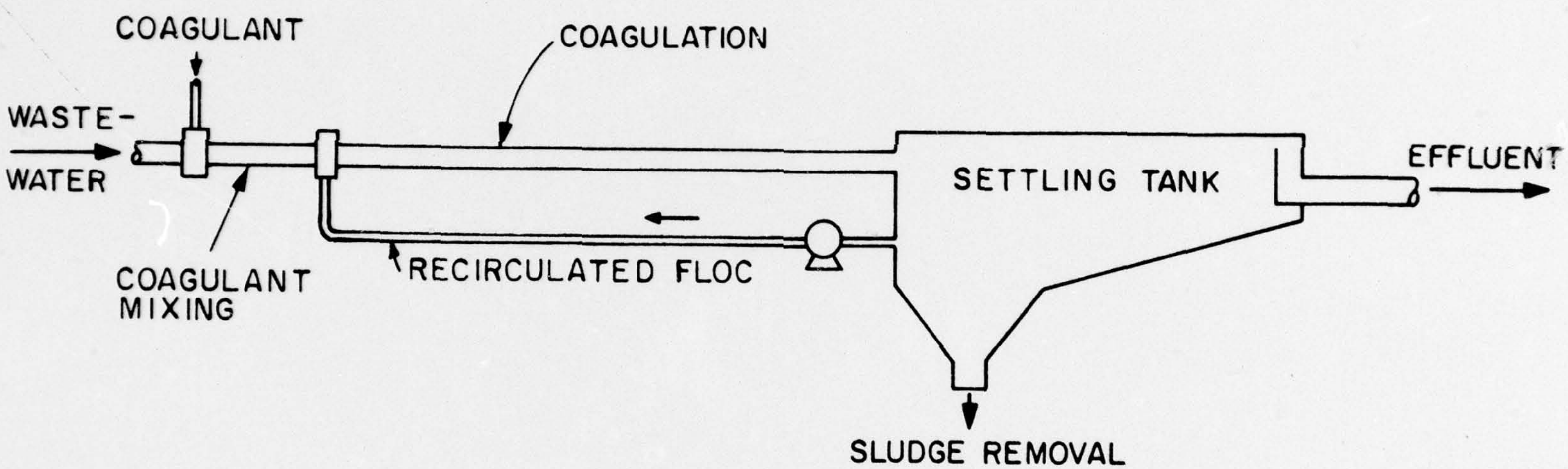

Figure 2. - Proposed coagulation and clarification system using turbulent pipe flow.