MONTANA STATE UNIVERSITY

The hydraulic transportation of solids in pipelines
by Robert Raymond Faddick

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Civil Engineering
Montana State University
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Abstract:
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A dimensional analysis of a two-phase flow system produced five parameters: mixture friction factor, Reynolds number, particle concentration, specific gravity, and a parameter relating particle size and shape to pipe diameter. The parameters were applicable to mixtures of large plateshaped particles (such as woodchips) and water flowing in smooth pipes.

A limited experimental program provided four sets of headloss data using plastic chips to compliment four sets of available woodchip data. A plot of each of the eight tests on Stanton-type diagrams showed that the mixture friction factor increased with decreasing Reynolds number, increased with concentration, increased as the particle geometry - pipe diameter ratio decreased at a given Reynolds number, increased with particle specific gravity in the heterogeneous suspension regime and increased with increasing absolute values of particle-fluid specific gravity differential, in the sliding-bed regime. : The data were correlated by a curve fitting technique using a second order polynomial relating all the parameters except chip, specific gravity whose variation was considered too small to be included in the correlation equation. An error analysis indicated that 78 per cent of all the data were within 25 per cent of the values predicted by the correlation equation.

THE HYDRAULIC TRANSPORTATION OF SOLIDS IN PIPELINES

by

ROBERT RAYMOND FADDICK

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil Engineering

Approved:

Head, Major Department

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MONTANA STATE UNIVERSITY
Bozeman, Montana

March, 1970

ACKNOWLEDGEMENTS

This investigation was performed in Ryon Laboratory at Montana State University in Bozeman, Montana, under the supervision of Dr. William A. Hunt, Principal Investigator.

The project was sponsored by the Forest Engineering Research Branch of the Intermountain Forest Range Experiment Station, United States Forest Service, Department of Agriculture, as part of a cooperative aid agreement with the Department of Civil Engineering and Engineering Mechanics of Montana State University.

Because of the size and complexity of the program many people from several departments were involved. Their assistance was appreciated. In particular, the author would like to express his gratitude to his supervising professor, Dr. William A. Hunt, for his guidance and to Ronald E. Schmidt, Hydraulic Research Engineer of the Intermountain Station for his aid in operating the pipeline.

Finally, sincerest thanks to the author's wife, Mary, for her encouragement and assistance.

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ABSTRACT

The application of the Durand equation relating head-losses of mixtures of solids and water in pipelines to the hydraulic transport of woodchip mixtures and simulated wood-chip mixtures was studied. The coefficients of the Durand equation were found to vary five-fold when correlating available headloss data for the hydraulic transport of woodchip mixtures in pipes of different diameters.

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CHAPTER I

INTRODUCTION

Although the pipeline transport of solids has been a commercial reality for a number of decades, there is still a dearth of design methods for predicting headlosses of mixtures of water and solids. The theory of hydraulic transport of solids in pipelines has not advanced sufficiently to the point where a commercial operation may be developed without pilot plant studies. This is particularly true for predicting the headlosses of mixtures of woodchips in water. Interest has been expressed in many countries in the hydraulic transport of woodchip mixtures as a means of realizing greater benefits to the pulp and paper industry. The chief advantage of this type of transportation is the more efficient utilization of small diameter timber for pulp and paper. The concept of pipelining pulpwood chips appears to have originated in 1957 with the Pulp and Paper Research Institute of Canada (PPRIC), but at present (1968), a commercial pipeline for transporting woodchips is not known to exist.

In 1961, Montana State University, in cooperation with the Intermountain Forest and Range Experiment Station of the United States Forest Service in Ogden, Utah, began extensive investigations into the feasibility of pipelining mixtures of woodchips and water. Through a rather complete program of experimental and economic studies these institutions are establishing criteria to design, construct, and operate a woodchip pipeline system. This report deals with one of the phases of the overall study: headloss-concentration-velocity correlations for steady state flow of woodchips in a pipeline.

The first objective of this study is to critically examine the Durand-type correlation for predicting the headloss for mixtures of woodchips and water and also for mixtures of simulated woodchips and water transported in pipelines. A second objective is to define the variables necessary to describe the flow of mixtures of woodchips and water in pipelines. A third objective is to investigate a possible method for presenting the results of a limited experimental program in the form of Stanton-type diagrams to show the effects of volumetric concentration, specific gravity, and scale factor (particle size to pipe diameter) on the friction factor-Reynolds number correlations for flow in smooth pipes. A search was made for data evaluating the loss due to friction for the transportation of pulpwood chips and water in various diameter pipes. Data from these sources were utilized along with the experimental data collected in this particular study to assist in the formulation of the headloss correlation.

CHAPTER II

REVIEW OF LIQUID-SOLID FLOW STUDIES

Some 110 years have elapsed since the first recorded attempt (6)[1] to transport solid particles of a macroscopic scale through a pipeline. Since that time much effort has been spent on the investigation of the flow of suspended solids in pipelines. If the flow of clear fluids in pipes is considered to be first generation research, then the pipeline transport of a particulate suspension in a fluid may be considered to be second generation research. The third generation of research, the pipeline transport of encapsulated solids in a fluid, is now under investigation by the Alberta Research Council (1).

Although considerable research has been done in the field of transportation of solids by pipelines, theory still lags practice. Much of the available headloss data (33), while showing systematic trends, display such wide variations and so many inconsistencies that they cannot be considered reliable guidelines for the design engineer.

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[1]Numbers in parentheses refer to numbered references in the Literature Cited.

Due to the phenomenological complexities of fluid turbulence and distribution of solids in two-phase pipe flow, the attempts to develop a single correlation relating headloss to mixture velocity, volumetric concentration of solids and pipe diameter have not been entirely successful. Empirical equations have been established by researchers (11, 20, 32) to predict headlosses for given flow mixtures and concentrations of solids having certain physical properties, e.g. sands and gravels. It has been found (15, 33) that extension of these relationships to pipes with diameters different from those used in obtaining the particular correlations has proven unsatisfactory in predicting headlosses for mixtures of solids and water. Therefore, pipeline designers have been forced to resort to pilot plant studies for the design information necessary to establish full-scale pipeline operations. Much of the work has been done by commercial organizations and has not been released because of proprietary rights.

The work that is available and pertinent to this study is outlined below. Included are a discussion of the two-phase flow regimes in pipelines and some methods for delineating the flow regimes followed by a review of the Durand headloss correlation. Past research on the transport of woodchip mixtures in pipelines is discussed with emphasis placed on the correlation equations and flow regimes. Finally, the Durand headloss correlation, as it applies to woodchip mixtures, is critically examined.

Flow Regimes

The classification of flow regimes of woodchips in pipelines is similar to that of sediment in open channels. In the latter, suspension flow, saltation flow and bedload flow may exist distinctly but all are usually present in some degree. Suspension flow implies that the sediment is maintained in suspension in the mainstream by the turbulence of the fluid, usually water. Saltation flow describes the regime in which heavier grains are transported by bouncing or jumping along the channel bed. Bedload flow is restricted to the case where the sediment is rolled or dragged along the channel bed by the channel flow but is not lifted into the mainstream of the moving water.

The flow regimes for conduit flow of solids are classified as follows:

1. Homogeneous flow
2. Heterogeneous suspension flow
3. Heterogeneous saltation flow
4. Bedload

Homogeneous flow regimes are those in which particles are small enough and in sufficient quantity to give the mixture an apparent viscosity different from that of the carrying fluid. The particles are held in uniform suspension by Brownian movement.

Heterogeneous flow regimes are those in which the fluid and solids comprise two distinct phases: the transporting medium and the discrete particles. The conveying liquid retains its own viscosity. Heterogeneous suspension flow occurs when the intensity of turbulence is sufficient to support all the solids in suspension although the concentration of solids or bulk density of the mixture may not be uniform throughout the cross-section of flow area.

Heterogeneous saltation flow occurs when the intensity of turbulence cannot support all the particles and the gravitational forces causes the heavier particles to settle out of suspension. The particles are then bounced or rolled along the pipe invert by the motion of the flow.

A bedload forms when some of the particles are deposited either in a moving or stationary bed on the bottom of the pipe. The stationary bed is not completely immobile but its rate of movement is noticeably slower than the mainstream flow above the bed. The remainder of the particles are usually in heterogeneous saltation flow along the surface of the bed and in heterogeneous suspension flow above the bed.

Methods for Delineating Flow Regimes

The delineations of the flow regimes are more qualitative than quantitative because of the difficulty in separating the regimes. The characteristics of the mixture flow are a function of the particle properties (size, shape, and specific gravity), the fluid properties (density, viscosity), the intensity of turbulence, and the concentration of particles. As the interrelationship of these variables is not understood, the mechanisms of the transport process have not been formulated in an explicit equation.

Other investigators have delineated the flow classifications in various ways which differ from the manner presented above. For example, Durand (11) chose the particle size to differentiate between the regimes, that is, the nominal particle diameter d_n, which is the diameter of a sphere having the same volume as the particle. Later Durand's co-workers, Condolios, Chapus, and Constans (7), apparently realizing the limitations of d_n in delineating the flow regimes, noted that their more recent investigations indicated that both the particle size and concentration were implicit factors in the delineation of the heterogeneous suspension flow regime but they did not elaborate on this point.

Govier and Charles (15) attempted to simplify the flow regimes as those comprising settling or non-settling slurries. A settling slurry was defined as equivalent to the bedload flow described previously. The non-settling slurry was defined as equivalent to either heterogeneous suspension flow or homogeneous flow depending upon the fineness of the solids being transported. Generally, the finer the particle size for a given particle specific gravity, the lower is its settling velocity, and the greater is its chance to form a non-settling slurry. A slurry which was in the transition zone between the settling and non-settling state corresponded to the heterogeneous saltation flow described previously. Govier and Charles were aware of the importance of the concentration of solids and the intensity of the fluid turbulence in distinguishing between settling and non-settling slurries. They did not incorporate these parameters directly in the categorization of the slurries. However, Govier and Charles realized that the particle settling velocity embodied more of the particle properties than just the particle size so it was chosen to distinguish between the two types of slurries. They also observed that increasing particle concentration permitted larger particles to form non-settling slurries.

Condolios et al. (8) and Wasp et al. (29) have cited cases where the addition of fine particles to a mixture of water and coarse particles has changed the flow regime sufficiently to decrease the energy requirements for transport below that for transporting the coarse mixture alone.

Methods for determining the particular flow regime for a given combination of particle properties and concentrations and flow properties have not been satisfactorily established. Methods for making these determinations would enable designers to avoid certain undesirable flow regimes. For example, although the minimum headlosses for a given concentration generally occur where the bedload regime begins to form (11), it is the regime in which plugging is imminent due to excessive deposition. Heterogeneous suspension flow may be undesirable also due to high velocities consequently causing high power requirements.

Although flow regimes cannot be determined analytically, they can be observed during tests designed to measure the energy requirements for transporting a given mixture.

Durand Headloss Correlation

The most popular headloss correlation for solids-transport in a pipeline using water as the fluid is that of Durand (11) who performed an extensive series of tests transporting sands and gravels (grain size of 0.14 to 5.1 mm) in water through pipes ranging from 1.5 to 28 in. in diameter. Durand proposed the empirical equation:

$$\phi = K\psi^m \qquad \text{(2.1)}$$

where $\phi = (i_m - i)/C_V \cdot i$;

i_m = hydraulic gradient of the mixture expressed as ft of water/ft of pipe length;

i = hydraulic gradient of clear-water flow, ft/ft;

C_V = volumetric concentration of solids (fraction),

K = constant, 180 from Gibert (14);

$\psi = V_m^2 \sqrt{gd_n/V_s^2} / gD$

V_m = mean velocity of mixture flow, fps;

g = gravitational acceleration, ft/sec^2;

d_n = weighted mean nominal particle diameter, ft, which is the diameter of a sphere of the same volume as the particle;

V_s = particle settling velocity, fps;

D = internal pipe diameter, ft; and

m = exponent, -1.5 from Gibert (14).

Eq. (2.1) is valid for sands and gravels with a specific gravity, s, of 2.65. To include the effect of specific gravity of other solids Durand and Condolios (10) modified the relationship as follows:

$$\phi = 124 \left[\frac{gD(s-1)}{V_m^2} \cdot \frac{V_s}{\sqrt{gd_n(s-1)}} \right]^{1.5} \qquad \text{........ (2.2)}$$

or $$\phi = 85 \left[\frac{gD(s-1)}{V_m^2} \cdot \frac{V_s}{\sqrt{gd_n}} \right]^{1.5} \qquad \text{........ (2.3)}$$

Eq. (2.1) is usually seen in an expanded form in the literature either as Eq. (2.2) or Eq. (2.3). The differences between the two forms are the value of the coefficient K and the term (s-1), the apparent specific gravity of the solids submerged in water. The latter term is retained in the denominator of Eq. (2.2) and increases the value of K. In Eq. (2.3) the coefficient K = 180 has been divided by $(s-1)^{1.5}$ with s = 2.65.

Other correlations have been proposed by Newitt _et al_. (20), Worster (32), and Spells (27), but they have not been readily accepted, generally because very small diameter pipes were used in the laboratory tests to substantiate the formulations of the correlations.

Woodchip Pipeline Research

For the past decade various researchers have investigated the transportation of pulpwood chips in pipelines. McColl (19) of PPRIC undertook a study to determine the feasibility of transporting 1/2-in. laboratory-cut chips in a 2-in. diameter copper pipe. From his study he concluded that pulpwood chips were amenable to transportation by pipeline. Because McColl did not consider the headloss data to be reliable, for unspecified reasons, he did not present any correlations between headlosses and flow.

In a broader study by this Institute, Elliott and de Montmorency (12) investigated the chemical, mechanical, hydraulic and economic aspects of the transportation of field-cut chips in an 8-in. diameter aluminum pipe. The chemical pulping tests indicated that no appreciable loss of pulp strength was likely to be caused by the amount of residence time expected in a commercial pipeline. While Elliott and de Montmorency did not present an equation for the correlation of the headloss to flow characteristics, they did provide a logarithmic plot of $\emptyset$ versus $V_m/\sqrt{D}$. Later Stepanoff (28) claimed that the PPRIC data fitted the form:

$$\phi = 4gD/V_m^{\,2} \qquad \text{(2.4)}$$

Elliott and de Montmorency's data gave:

$$\phi = 1.25\ (4gD/V_m^{\,2})^{1.03} \qquad \text{(2.5)}$$

for 41 measurements taken in the 8-in. pipe. Adding McColl's 18 measurements taken in the 2-in. pipe to the data from Elliott and de Montmorency, the combined data gave the expression:

$$\phi = 1.29\ (4gD/V_m^{\,2})^{0.935} \qquad \text{(2.6)}$$

Both Eq. (2.5) and Eq. (2.6) yield values of ϕ from 10 to 24 per cent higher than Eq. (2.4) as given by Stepanoff.

Faddick (13) measured the headlosses of pulpwood chips in a 4-in diameter aluminum pipe for maximum volumetric concentrations of only 17 per cent compared to Elliott and de Montmorency's 30 per cent. A line of best fit through the 59 data points produced the relation:

$$\phi = 2.51\ (4gD/V_m^{\,2})^{1.42} \qquad \text{(2.7)}$$

Wasp et al. (30) in an economic study utilizing both Elliott and de Montmorency's and Faddick's data noted that the latter's headlosses, when projected to an 8-in. diameter pipe produced values generally 25 per cent higher than Elliott and de Montmorency's.

As this investigation neared completion the author received headloss data for woodchip mixtures in a 6-in. diameter pyrex pipe from a woodchip study in progress under the direction of A. Soucy at Laval University (26). The data were in tabulated form and no immediate comparison with a Durand-type equation was made. Instead, a comparison of the woodchip data was postponed to Chapter V in which the individual studies of McColl, Faddick, Soucy, and Elliott and de Montmorency in 2-, 4-, 6-, and 8-in. diameter pipes, respectively, were compared by means of a simplified version of the Durand equation. All the available woodchip data are listed in Appendix G.

Flow Regimes for Woodchip Transport

Because no data are available for delineating the various woodchip flow regimes the following description is stated in general terms based on visual observations by Faddick (13). The homogeneous flow regime is not applicable to woodchip transport. Heterogeneous suspension flow may occur for low volumetric concentrations (about 10 per cent) and high mixture velocities, (about 10 fps in a 4-in. pipe) but this combination is not the most economical according to Hunt's (16) economic analysis of a woodchip pipeline. Therefore, this flow regime will not be considered. Heterogeneous saltation flow without a bedload, but which may include moving dune formations, is also not economical due to the small volumetric concentrations (less than 15 per cent) which characterize this regime.

Assuming a minimum volumetric concentration of 20 per cent and mixture velocities ranging from 3 to 8 fps in pipe sizes from 4 to 10 in. in diameter (16, 13) as the probable range for commercial operations, the mode of transport in an economical system would be a sliding bedload flow. The regime would be heterogeneous saltation flow at the upper surface of the bed and heterogeneous suspension flow above the bed. The lower portion of the bed would slide not quite as a continuous phase because the upper portion of the bed, as previously mentioned, would be in saltation and the velocity of the upper portion of the bed during this type of flow would exceed the velocity of the lower portion of the bed. A bedload of saturated woodchips always slides along the pipe invert. Granular solids differ in that a bedload of sand or gravel can slide but it also can be relatively stationary with only the upper portion of the bedload showing noticeable forward motion.

Discussion of the Correlations

The correlations reviewed display certain weaknesses which may explain some of the discrepancies encountered when applied to systems other than those for which they were developed.

Condolios, Chapus, and Constans (8) noted that the strength of Durand's equation lies in its ability to predict satisfactorily the headlosses for uniform sands and gravels, mixtures of sands and gravels with two different grain sizes in varying proportions, mixtures of sands and gravels with a wide grain distribution, and for natural sands. A weakness of the correlation is that it cannot be applied to solids of neutral buoyancy. When the specific gravity of solids is equal to that of water, Eqs. (2.2) and (2.3) yield a mixture hydraulic gradient equal to the clear-water hydraulic gradient. But this may not always be the case. Woodchips have a specific gravity which depends upon moisture content and may range from 0.7 to 1.125. Yet the headloss produced by a mixture of woodchips and water is significantly greater than that for water (13).

Zandi and Govatos (33) have demonstrated that while Eq. (2.1) is the best available correlation it appears to be overextended when applied to an accumulation of data which they collected from many published and unpublished studies on slurry flow in pipes.

Babcock (3) in a series of carefully-controlled tests, experimented extensively with the Durand equation, Eq. (2.1), and found that the mixture hydraulic gradient i_m, was not linearly dependent on the volumetric concentration C_v, at low concentrations and high velocities. He also observed that the term gd_n/Vs^2, which is a form of drag coefficient C_d, had a vague role in that a logarithmic plot of ϕ versus $V_m^2/gD(s-1)$ for several sands showed all the points to fall on a straight line whereas a graph of ϕ versus $V_m^2\sqrt{C_d}\,/gD(s-1)$ for the same data showed the points to fall on several parallel lines. Babcock concluded that the dimensionless groupings of ϕ and ψ of Eq. (2.1) were the cause of excessive scatter in his data, and that Eq. (2.1) may not describe a two-phase flow system properly.

Questions concerning the validity of applying Eq. (2.1) to all solids transported in pipelines have not been confined only to experimental verification. Barr (4) has contended that the equation does not provide a valid correlation of experimental data because it violates similarity criteria based on ratios of forces. He claims that Eq. (2.1) is incomplete in that it lacks a d/D ratio (some particle dimension to pipe diameter), and a viscosity term, but it retains V_s, the particle settling velocity, and i, the clear-water hydraulic gradient, both of which he considers to be extraneous. Rearrangement of the expression for ψ in Eq. (2.1) will yield the ratio d_n/D along with the ratios V_m/V_s and $V_m/\sqrt{gD}$. Barr apparently discounts this rearrangement because none of the more common combinations of pressure, gravity, friction, or inertial forces will give the accompanying ratio of mixture velocity to particle settling velocity. He suggests that the particle settling velocity is certainly a valid property for describing the free-fall characteristic of a single particle; the question is whether the particle settling velocity is a valid property for describing the pipeline flow of a mixture of particles.

A simplified version of the Durand equation, Eq. (2.1) formulated in an attempt to correlate the headloss for the pipeline transport of woodchips can be expressed in the form of Eq. (2.4) as suggested by Stepanoff (28), that is

$$\emptyset = K\ (4gD/V_m{}^2)^m = K\ (\psi_1)^m \qquad \ldots\ldots\ldots\ldots\ldots \quad (2.8)$$

The validity of the form is questioned when the data observed by McColl, Faddick and Elliott in 2-, 4-, and 8-in. diameter pipes are used to determine the coefficient K and the exponent m (Eqs. 2.6, 7, and 5). Table I shows the variation of K and m using the data from the 2-in., 4-, and 8-in. diameter pipes.

TABLE I.

K, m for $\emptyset = K\ (\psi_1)^m$ based on headloss data of woodchip mixtures in 2-, 4-, 8-in. diameter pipes.

Investigator	Pipe Diameter, in inches	Coefficient, K	Exponent, m
(1)	(2)	(3)	(4)
All PPRIC tests	2,8	1.29	0.935
Faddick	4	2.51	1.42
Elliott, de Montmorency	8	1.25	1.03

As the woodchips used in these investigations were basically the same size for all the tests, the variation in K and m may have two explanations: (1) differences in the technique used in obtaining the data and differences in the precision with which the data were taken, provided variations of the magnitude indicated; and (2) a correlating equation of this form is not suitable for extrapolating the headloss data for a mixture of woodchips and water to pipes of a diameter different from that used for obtaining the specific values of K and m.

In other words, on the basis of the data presented, it appears that the ratio of the size of the chips to the diameter of the pipe may have a significant effect on the mixture headloss.

If Durand's equation is apparently not an adequate headloss correlation for a woodchip mixture, then the fact that this equation works for sands and gravels of different sizes, requires additional comment. The ratios of nominal particle diameter to pipe diameter (d_n/D) ranged from about 0.0003 to 0.02. Durand's upper value of d_n/D just approaches the lower value of the chip size to pipe diameter ratio used in the woodchip tests. The ratios for the woodchip tests are given in Chapter III. Although the sand and gravel shapes were not specified in Durand's study, they were undoubtedly not as flat and rectangular as woodchips. Other factors may also have been involved. For example, Durand's study never utilized volumetric concentrations greater than 20 per cent whereas concentrations as high as 40 per cent were attained in the woodchip tests. In addition, all the tests by Durand were performed in steel pipes whose roughnesses were not specified. The major differences between Durand's tests and the woodchip tests appear to have been the relatively larger size and flatter shape of the woodchips over the sands and gravels. It is possible then, that there is a critical size and/or shape of particle in a given pipe diameter beyond which the mixture headloss as given by Eq. (2.1) changes significantly.

Because the Durand equation is not in a form applicable to neutrally-buoyant particles and because a simplified version of the Durand equation does not appear to account for the ratio of chip size to pipe diameter, this investigation was initiated to study another approach to the correlation of headloss and pipeline flow of a mixture of simulated woodchips in water. The approach described in the following chapter considers the use of the Stanton diagram with modifications to account for the properties of the solid phase.

CHAPTER III

METHOD OF INVESTIGATION

A determination of a headloss correlation for transporting solids in pipelines requires an understanding of two-phase flow characteristics.

Soo (25) has outlined two methods for the study of the dynamics of multiphase systems.

1. "Treating the dynamics of single particles and then trying to extend to a multiple particle system in an analogous manner as in molecular (kinetic) theory."

2. "Modifying the continuum mechanics of a single fluid in such a way as to account for the presence of particles."

He further states, "extension to multiple particle systems from dynamics of single particles has not been particularly successful except in isolated cases."

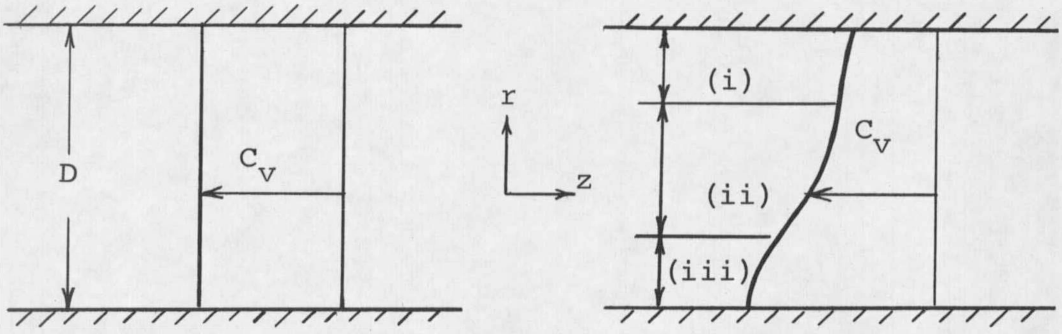
Flow Characteristics of Woodchip Mixtures

Two-phase flows of woodchips and water do not comprise a continuum because the discrete particles in a given volume of flowing mixture are spaced such that it is possible to isolate a differential volume which may contain all liquid, all solid, or part of both. However, because of the difficulties in experimentally determining the internal shear mechanisms of such a flow, the system is most expediently analyzed by the continuum concept when applying the equation of momentum to elemental volumes large enough to contain the average properties of the entire mixture.

The flow regime of woodchips and water can be either heterogeneous suspension flow (Fig. 3-1a), heterogeneous saltation flow, sliding bed flow, or a combination of all three. These regimes have been described in the previous chapter. In the general case (Fig. 3-1b), the concentration profile is nonuniform and unsteady, i.e.,

$$C_V = C_V\ (r,\ \theta,\ z,\ t) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3.1)$$

Individual particles migrate depending on the intensity of the turbulent velocity fluctuations u, v, w in the z, r, θ directions, respectively. However, for steady flow of the mixture, the time-averaged concentration profile, (Fig. 3-1b) undergoes no net change over the length of test section.



a. Heterogeneous suspension flow, uniform concentration profile, ($\partial C_V/\partial\theta = \partial C_V/\partial r = 0$). Turbulent velocity fluctuations predominate.

b. (i)-Heterogeneous suspension flow
(ii)-Heterogeneous saltation flow
(iii)-Sliding bed flow
Non-uniform concentration profile, ($\partial C_V/\partial\theta \neq 0$; $\partial C_V/\partial r \neq 0$). Gravity effects predominate.

Fig. 3-1. Concentration Profiles

The mixture flow is assumed to be steady, incompressible and turbulent throughout a test section of constant diameter giving

$$\frac{\partial C_V}{\partial z} = 0 \qquad \text{.......................} \quad (3.2)$$

and

$$\frac{\partial C_V}{\partial t} = 0 \qquad \text{.......................} \quad (3.3)$$

The mixture density is by definition:

$$\rho_m = \rho(1+C_V(s-1)), \qquad \text{.................} \quad (3.4)$$

giving the following relations for the mixture density:

$$\frac{\partial \rho_m}{\partial r} \neq 0; \quad \frac{\partial \rho_m}{\partial \theta} \neq 0 \qquad \text{.................} \quad (3.5)$$

The mixture density thus varies across the cross section of the pipe. The mixture density and particle concentrations are interrelated as shown by Eq. (3.4). Their distribution is affected by the interrelationship between the gravity force acting on the submerged particles and the level of turbulent fluctuations inherent in the mixture flow. The interrelationship between gravity and turbulence is only qualitative but suffices to demonstrate the complexities of two-phase flow.

When the specific gravity of the particles is near that of the carrying medium, the mixture density for normal transport concentrations will not vary greatly over the cross section of the pipe. For example, a volumetric concentration of 30 per cent of saturated woodchips ($s \simeq 1.13$) in water gives a bulk mixture density ρ_m, equal