The effects of chip-shaped solids on valve head loss characteristics
by David Allan Johnson

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Civil Engineering
Montana State University

Abstract:
The main purpose of this study was to determine the head loss characteristics of different valves in a pipe line carrying a mixture of water and chip-shaped solids. Since the head loss caused by a valve is given by HL = KL (v^2)/(2g), this study involved determining values of the loss coefficient, KL, for each valve at different flow conditions. Observations were also made on the efficiency of each valve with respect to use in a solid-liquid pipe line.

The following four valves were tested in this study: ball valve, plug valve, v-ball valve, and pinch valve. Tests were conducted on each valve for various closures at velocities of 4, 6, 8, and 10 fps with chip concentrations of 0, 10, and 20 percent.

The loss coefficient was observed to (1) be approximately constant with respect to velocity at velocities greater than 6 fps for a given closure and percent concentration, (2) increase with increasing chip concentration, and (3) increase with increasing valve closure. For design purposes, empirical relationships of the following forms were derived for each valv6: ((KL)c)/((KL)0) = e^bC and ((KL)c)/((KL)0) = 1+mC These equations give the loss coefficient (KL)C for a given concentration as a function of the concentration C and the clear water loss coefficient (KL)0 for a given valve closure.

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LIST OF SYMBOLS

A	-	Any cross-sectional area.
a	-	Straight line y-intercept.
b	-	Slope of straight line.
C	-	Volumetric chip concentration.
CVAL	-	Valve closure in percent of constriction.
COEF	-	Correlation coefficient.
CCl_4	-	Carbon tetrachloride.
D	-	Pipe diameter.
DPHD	-	Differential pressure head between tap 1 and any other tap.
E	-	Sum of squared errors.
e	-	Base of Naperian logarithms.
E_L	-	Energy loss.
EVAR	-	Estimate of variance about regression.
f	-	Friction factor.
fps	-	Feet per second.
g	-	Gravitational acceleration.
gpm	-	Gallons per minute.
H_L	-	Valve head loss.
Hg	-	Mercury.
HGL	-	Hydraulic grade line.
ID	-	Inside diameter of any pipe.
K_L	-	Valve head loss coefficient.
L	-	Length of any reach of pipe.

mm - Millimeter.

n - Number of observations.

OD - Outside diameter of pipe.

p - Pressure.

pcf - Pounds per cubic foot.

Q - Flow rate in gpm.

S - Specific gravity of any fluid.

s - Statistical variance.

v - Nominal velocity in fps.

XVAL - X-distance corresponding to center of valve in test section.

x - Distance from first pressure tap in test section to any other tap.

y - Level of fluid in manometer tubes.

z - Height of water above fluid in manometer tubes.

Δ - Difference in any reading or measurement.

γ - Specific weight in pcf of any fluid.

μ - Theoretical mean of infinite population.

$>$ - Greater than.

ϵ - Any $\pm$ error.

$\partial p/\partial x$ - Change in pressure with respect to distance.

Subscripts

i - Pressure tap number.

u - Upstream.

d - Downstream.

v - Valve area.

p - Pipe area.

m - Mixture flow rate.

w - Clear water supply flow rate.

f - Fluid flowing.

c - Carbon tetrachloride.

m - Mercury.

n - Some pressure tap downstream of tap 1.

o - Loss coefficient for clear water.

c - Loss coefficient for a given concentration.

ABSTRACT

The main purpose of this study was to determine the head loss characteristics of different valves in a pipe line carrying a mixture of water and chip-shaped solids. Since the head loss caused by a valve is given by $H_L = K_L \frac{v^2}{2g}$, this study involved determining values of the loss coefficient, K_L, for each valve at different flow conditions. Observations were also made on the efficiency of each valve with respect to use in a solid-liquid pipe line.

The following four valves were tested in this study: ball valve, plug valve, v-ball valve, and pinch valve. Tests were conducted on each valve for various closures at velocities of 4, 6, 8, and 10 fps with chip concentrations of 0, 10, and 20 percent.

The loss coefficient was observed to (1) be approximately constant with respect to velocity at velocities greater than 6 fps for a given closure and percent concentration, (2) increase with increasing chip concentration, and (3) increase with increasing valve closure. For design purposes, empirical relationships of the following forms were derived for each valve:

$$\frac{(K_L)_c}{(K_L)_o} = e^{bC} \quad \text{and} \quad \frac{(K_L)_c}{(K_L)_o} = 1 + mC.$$

These equations give the loss coefficient $(K_L)_c$ for a given concentration as a function of the concentration C and the clear water loss coefficient $(K_L)_o$ for a given valve closure.

CHAPTER I

INTRODUCTION

A. Background material

The transportation of solids by pipe line is not new. For many years chemical, mining, and dredging operations have included short-haul slurry pipe lines. In the past few years, however, increased attention has been given to the hydraulics of transporting solids by pipe lines over longer distances. Currently, considerable research is being done on solids pipe lines in the United States, Canada, and other foreign countries. Also, several long distance pipe line transportation systems have been built and operated successfully. It is generally concluded that because of continuous operation and low operating costs, pipe lines can compete economically with other existing methods. Zandi and Govatos (12) discuss solids pipe lines and give 30 references to articles discussing solids transportation and industrial pipe line installations.

A feasibility study in 1965 by Hunt (4) showed that a pipe line system could also be used to convey wood chips, economically, from forest to pulp mill. As a result, a research project was initiated at Montana State University to investigate the hydraulics of such a transportation system. The project was sponsored through a cooperative agreement by the Intermountain Forest and Range Experiment Station, United States Forest Service, and the Department of Civil Engineering and Engineering Mechanics at Montana State University. Up to this date studies have been completed under the above cooperative agreement on the following subjects: specific gravity of saturated wood chips, pump performance characteristics, head losses in axi-symmetric pipe expansions, head losses of a modified gate valve, pipe line frictional losses, and a water hammer analysis of a high pressure chip injection system.

A study of the head loss characteristics of four different types of valves in a pipe line carrying a mixture of water and chips is presented in this paper. Results of this study will provide design information on valve head losses and hence power requirements for construction of a full-scale operating system. Tests were conducted on a v-ball valve, a ball valve, a plug valve, and a pinch valve. Results of the modified gate valve study mentioned above are also presented in this paper. The tests were performed in the civil engineering section of Ryon Laboratory on the campus of Montana State University.

B. Objectives of study

Flow through a valve is a relatively complex phenomenon and head losses generally cannot be determined analytically. Because of the variety of flow passageways in different valves, head loss characteristics must be determined experimentally. The energy equation for a liquid written between points upstream (subscript 1) and downstream (subscript 2) of a valve is

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + \text{losses}_{1-2} \qquad (1)$$

where p is pressure in psf, γ is the specific weight of the fluid flowing in pcf, v is the nominal velocity, z is the elevation above a datum, g is the gravitational acceleration, and the loss term includes the loss due to pipe line friction and the loss caused by the valve. For a horizontal, constant diameter pipe this simplifies to

$$\text{losses}_{1-2} = \frac{p_1 - p_2}{\gamma} \qquad (2)$$

where p_1 and p_2 must be determined experimentally. Once the losses for a given flow condition are determined, it is desirable to equate them to a function of some commonly known parameter such that head losses may be estimated for similar flow conditions. The Darcy-Weisbach equation, giving the head loss as a function of velocity, was developed for pipe line friction losses. Similarly, head losses caused by valves and other fittings are expressed as

$$H_L = K_L \frac{v^2}{2g} \qquad (3)$$

where K_L is an empirical head loss coefficient.

The main objective of this study, then, was to determine experimentally the values of the loss coefficient, K_L, for each valve at different flow conditions. Velocity, valve closure, and chip concentration were varied and the effects on K_L determined. Flat rectangular plastic chips with a specific gravity slightly greater than that of water were used to simulate wood chips. In addition to head loss data, observations were also made on the mechanical efficiency of each valve with respect to use in a solid-liquid pipe line.

C. Literature review

A literature survey was conducted in an attempt to find information on head losses caused by valves in solid-liquid lines for comparison with values obtained in this study. Virtually no information was found on valve head losses in solid-liquid pipe lines. In fact, very little recent information was found on valve head losses in general. Published analytical and experimental information on valve head losses tends to be the result of work done several years ago and on the older types of valves. More recent work has apparently been done by valve manufacturers and private firms and not released for public consumption.

The following information was found on the effect of closure, concentration, and velocity on the loss coefficient. Rouse (8) gives the following loss coefficients, K_L, for various valves at different valve closures for clear water flow.

Gate Valve		Plug Globe or Stop Valve	
Fully Open	0.19	Fully Open	4.0
3/4 Open	1.15	3/4 Open	4.6
1/2 Open	5.6	1/2 Open	6.4
1/4 Open	24.0	1/4 Open	78.0

Diaphragm Valve		Plug Valve with Screwed Ends	
Fully Open	2.3	Fully Open	0.77
3/4 Open	2.6	90% Open	2.86
1/2 Open	4.3	80% Open	9.6
1/4 Open	21.0	70% Open	28.0

No information about the effect of concentration on the head loss coefficient was found. However, Charley (1) did some work on the effect of chip-shaped solids on head losses in pipe expansions. He found that, for flow rates greater than 226 gpm, the loss coefficient for a pipe expansion appeared to decrease with an increase in chip concentration.

The Crane Company (2) implies that the loss coefficient, K_L, does not vary with Reynolds number and hence velocity for fully turbulent clear water flow. The valve head loss equation $H_L = K_L \frac{v^2}{2g}$ is similar to Darcy's equation $H_L = f\frac{L}{D}\frac{v^2}{2g}$. Thus, a log-log plot of loss coefficient, K_L, versus Reynolds number would be expected to yield a graph similar to the well-known Moody diagram for pipe friction losses. The Crane Company claims that in the fully-developed turbulent region of a log-log plot of K_L versus R_e or velocity, the loss coefficient, K_L, for clear water would be constant as is the friction factor for Moody's diagram. However, no information was given on how K_L varies with velocity for flow of water and solids.

CHAPTER II

THEORY OF HEAD LOSSES CAUSED BY VALVES

Some knowledge of the characteristics of flow through a valve is necessary before developing the experimental methods used to determine the loss characteristics of the various valves. Flow of a fluid through a valve is a relatively complex phenomenon. The addition of solid particles to the fluid further complicates the characteristics of the flow. As indicated in the preceding chapter, no published theoretical work on flow of solid-liquid mixtures through valves was found. Thus, the following discussion gives a general description of (1) the head loss mechanism, as developed by application of the basic laws of fluid mechanics, and (2) the effects of valve closure, chip concentration, and velocity on head losses as reported in related solid-liquid transportation studies.

A. Basic head loss mechanism

A valve is essentially an irregular constriction in a pipe line. For any given flow condition, the equation of continuity requires an acceleration of the fluid through the constriction and a deceleration downstream from the valve. At the same time, the energy equation requires a reduction in pressure head to coincide with the increasing velocity through the valve. In other words, the constriction caused by the valve results in a conversion of pressure head or potential energy to velocity head or kinetic energy. In the region downstream from the valve, the energy conversion is reversed and pressure head is recovered as the fluid slows and again assumes uniform flow conditions. However, because of energy losses, this transformation is less than 100 percent efficient and the initial pressure head is not completely recovered.

A certain amount of energy is dissipated by turbulence and friction in the valve and in the region downstream from the valve. Since the continuity equation requires the velocity head to return to its initial value during the recovery process, this dissipated energy is lost at the expense of pressure head only. The resulting $\Delta p/\gamma$ is known as the head loss. The magnitude of this head loss is affected by valve closure, chip concentration, and velocity as discussed below. A section of pipe line with a valve is shown in Fig. 1 with the corresponding velocity, hydraulic, and energy grade lines.

B. Effects of valve closure, chip concentration, and velocity

As seen in the above discussion, valve head losses are a result of energy dissipated by turbulence and friction. Specific causes of this energy dissipation are given below. The constriction or closure of the valve causes turbulence in three ways. The reduction in area through the valve causes an acceleration of the fluid. As a result of the increased velocity, zones of high shear form which in turn disturb the velocity distribution or cause turbulence. As the degree of constriction is increased, the velocity, shear forces, and hence turbulence increase. The geometric shape of the passageway through the valve also aids in the formation of turbulence by disrupting the streamlines of flow in the pipe line.

Turbulence also forms in the region just downstream from the valve as a result of the constriction. As seen in Fig. 1, the constriction in the pipe line results in a positive pressure gradient $\frac{\partial p}{\partial x} > 0$ in the region downstream from the valve. According to V. L. Streeter (10) this positive pressure gradient induces boundary layer separation along the

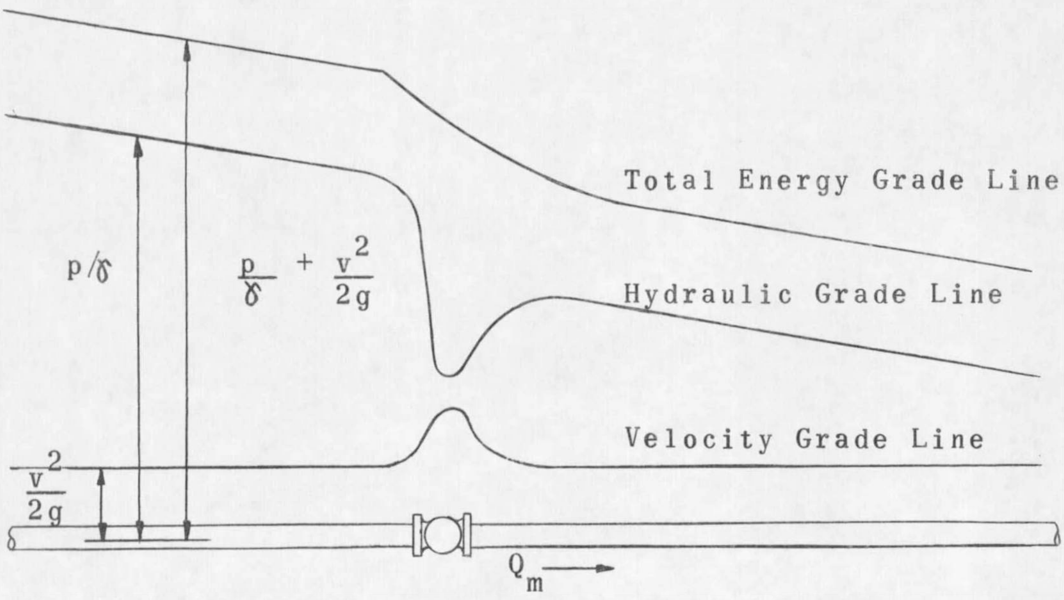

Fig. 1. Grade lines showing effect of constriction

pipe walls in this region which results in back flow and the formation of additional eddies. The turbulence caused by the valve is eventually damped out and the flow is essentially uniform again at the point where the hydraulic grade line becomes a sloping straight line. The distance between the valve and this point is referred to as the settling length. The settling length increases with the amount of turbulence or energy dissipated.

According to the above discussion, then, turbulence and the corresponding dissipation of energy are directly related to the degree of constriction caused by the valve. Therefore, head loss and hence the loss coefficient can be predicted to increase as the valve closure is increased. This is in agreement with the clear water loss coefficients given by Rouse (8).

The presence of chip-shaped solids in the fluid also affects the flow characteristics. However, the effect of solids on valve head losses is not nearly as obvious as that of valve closure. Solid particles have both beneficial and detrimental effects. According to the results of experiments on the flow of solid-liquid mixtures in pipes by J. W. Daily and T. K. Chu as reported by M. Hino (3), approximately neutrally buoyant particles cause (1) an increase in the turbulence intensity over that for clear water, and (2) a reduction in the settling length. In other words, solid particles break up large eddies into smaller, high velocity eddies which, in effect, increase the intensity of the turbulence. Although the intensity of turbulence is increased, the reduced settling length caused by the presence of solid particles indicates that the turbulence is damped out quicker than for clear water. This in turn indicates that less energy is dissipated and hence, the head losses are smaller. According to R. W. Charley (1), these facts account for the observed decrease in the head losses caused by axi-symmetric pipe expansions for flow of a solid-liquid mixture.

However, S. L. Soo (9) reports that because of physical contact between the particles and the walls, the addition of solid particles to the flow causes an increase in friction and flow resistance along the boundaries of a conduit. Energy dissipation and hence head losses would apparently increase with an increasing volume of particles or chips in the fluid flowing. In a partially closed valve, chips tend to collect in pockets and crevices, resulting in a sort of "semi-plugged" condition and increased flow resistance. Friction between the chips and turbulence caused by the relative motion of the chips also dissipate small amounts of energy. In summary, then, the presence of chips appears to cause a reduction in head losses by increasing the turbulence intensity which in turn reduces the settling length. On the other hand, chips apparently also increase the head losses because of energy dissipated by increased friction and flow resistance. Thus, without further evidence, a theoretical prediction of the net effect of chips on the head loss cannot be made.

Preliminary analysis of the data from the previously mentioned gate valve tests indicates that for a given velocity and valve closure, chip-shaped solids increase the head loss over that for clear water, contrary to the conclusions of Charley (1). Therefore, on the basis of trends shown by the gate valve tests, it can be predicted that the net effect of chip-shaped solids should be that of increasing the head loss and the loss coefficient, K_L.

As reported by Rouse (8) and others, the clear water valve head loss coefficient, K_L, is generally assumed to be constant for any velocity. In other words, the head loss increases with velocity but the ratio $\frac{H_L}{v^2/2g}$ remains approximately constant.

In conclusion, then, it can be predicted that the valve head loss coefficient should increase with increasing valve closure and chip concentration but remain constant with increasing velocity.

CHAPTER III

EXPERIMENTAL METHODS

In order to achieve the objectives of this study, the following experimental procedures were followed: (1) determination of the head loss coefficient, K_L, (2) determination of valve areas, and (3) determination of the mixture velocity and percent concentration.

A. Determination of loss coefficient, K_L

The head loss, in feet of fluid flowing, occurring at a valve in a pipe line is measured as the difference between the upstream and downstream portions of the hydraulic grade line when both lines are projected to a point over the valve. Fig. 2 shows a typical hydraulic grade line, HGL, and the head loss, H_L, caused by a valve. To determine the head loss and hence the effect of velocity, closure, and concentration on the loss coefficient, K_L, the hydraulic grade lines for the various flow conditions must be established.

A series of pressure taps along the test section, as discussed in Chapter IV, and a differential manometer board (Appendix B) provided information needed to establish the hydraulic grade line. The manometer board gave the pressure head differences, $DPHD_i$, between the first pressure tap in the test section and the other pressure taps at distances x_i downstream of the first tap as shown in Fig. 2. A set of two-dimensional data (x_i, $DPHD_i$) was thus obtained where the