Drag Reduction in Hydraulics Flows

Hubert CHANSON[(a)] and QIAO Gaolin[(b)]
(a) Lecturer in Hydraulics/Fluid Mechanics; (b) Ph.D. student
Department of Civil Engineering, The University of Queensland
Brisbane QLD 4072, Australia

SUMMARY In hydraulic flows, the interactions between particles and turbulence can induce some drag reduction as observed with dilute polymer solutions, sediment laden flows and self-aerated flows. Data on drag reduction with suspended sediment flows, coal-water flows with dilute polymer and self-aerated flows are re-analysed. The mechanisms of drag reduction are explained and some analogies between these flows are developed. It is suggested that the presence of particles next to the bottom increases the effective viscosity of the mixture and the sublayer thickness. The results provide a better analysis of water-particle flows and a more accurate prediction of drag reduction.

NOTATION

C_p	= polymer concentration;
C_s	= mean volumetric sediment concentration;
C_e	= mean air concentration defined in term of 90% maximum air content;
d	= flow depth (m);
d_s	= mean sediment particle diameter (m);
f	= friction factor of non-aerated flow;
f_e	= friction factor for aerated flow;
f_s	= friction factor of suspended laden flow;
Q	= discharge (m^3/s);
q	= discharge per unit width (m^2/s);
U_w	= mean flow velocity (m/s) : $U_w = q_w/d$;
W	= channel width (m);
ρ	= density (kg/m^3);
∅	= diameter (m);

Subscript

s	= sediment;
w	= water flow.

1. INTRODUCTION

Since the clear evidence of drag reduction with dilute polymer solutions [15], new applications of polymer solutions were developed in oil well operations and crude oil transportation, firefighting equipment, sewage and floodwater disposal, marine applications, transport of solids resulting from mining operations.

Over the past forty years, extensive research has been conducted to study the mechanisms of drag reduction by dilute polymer solutions and also by other active and passive means : e.g. surfactants, riblets, LEBU, particle addition, bubble injection in liquid flows.

In most hydraulic and civil engineering applications, the fluid is water and the flow is turbulent. In this paper, the authors will consider drag reduction in turbulent water flows, and in particular the interactions between particles and turbulence. Three different applications are developed. It will be shown that there is an analogy between each case of drag reduction.

2. MECHANISMS OF DRAG REDUCTION

Recent experimental results [2, 8] show that the main mechanisms of drag reduction include :

A- a reduction of the vertical velocity fluctuations observed with solid particles [13], dilute polymer solutions [19] and turbulent manipulators (e.g LEBU);

B- a modification of the turbulent bursting process detected with particles, dilute polymer solutions, riblets and LEBU; and

C- an increase of the sub-layer thickness clearly observed in air-water flows, sediment-laden flows, flows with riblets or polymer additives.

Hence the reduction of friction losses is caused by modifications and perturbations of the fluid sublayer next to the solid boundaries. In a turbulent flow, the presence of particles in the sublayer may induce some volumetric effects (interactions particle-turbulent structure), a modification of the physical properties of the flowing fluid (density, viscosity, surface tension), a change of the chemical properties of the flow (electromagnetic, chemical interactions) or a combination of these three processes.

Three cases of drag reduction with different types of particles are presented : sediment-laden flows (solid particles), coal-water flows with dilute polymer solutions (solid particles and polymer macromolecules) and free-surface aerated flows (air particles).

3. SEDIMENT LADEN FLOWS

In laboratory and river flows, suspended sediment is observed to increase the flow velocity and to decrease the friction factor. Historical cases include observations of suspended silt flood flows in the Nile [1], Indus [10] and Mississippi [12] rivers. Other examples are summarised in table I and figure 1.

Figure 1 presents model and prototype data of friction factor reduction as a function of the mean volumetric sediment concentration C_s. Note that most data were obtained with suspended sediments without depositing material. Also the data of BUCKLEY [1] must be considered with great care as the changes in friction factor due to variation in bed configuration might be important.

Despite controversies, the velocity distribution in the inner flow region follows the classical logarithmic profile [5, 11] and exhibits a viscous sublayer. The presence of sediment particles in the flow layers next to the bottom increases the density and the viscosity of the flow and induce a thickening of the sublayer and a reduction of bottom shear stress. By analogy with dilute polymer solutions, an increase of the viscosity in the flow layers next to the boundary might explain the observed drag reduction in suspended particle flows.

It must be emphasised however that drag reduction in suspended sediment flows is observed only : (A) for starved bed flows or rising flood flows (i.e. with no sediment deposition), and (B) with micro-particles.

Table I - Suspended-laden flow experiments

Ref (1)	Q_w m^3/s (2)	C_s (3)	U_w m/s (4)	Comments (5)
[2]	900 to 6700	120 to 1,620 g/m^3	0.5 to 1.4	Prototype data (silt). Nile river at Beleida discharge station.
	47 to 68	14 to 2,050 g/m^3	0.52 to 0.68	Prototype data (silt). Canal derivation from the Nile river.
[16]	0.03 to 0.15	0 to 3,190 g/m^3	0.55 to 1.2	Flume data. Silica sand ($d_s = 0.16$ mm). W = 0.84 m.
[17]	0.014	0 to 8,100 g/m^3	0.69 to 0.70	Flume data. Sand ($d_s = 0.1$ and 0.15 mm). W = 0.27 m.
[14]		40,000 ppm		Fine sediments (clays).
[7]	0.29 to 1.68 L/s	130 to 380 g/m^3	0.06 to 0.32	Flume data. Clay. W = 0.08 m. d = 0.06 m
[18]	0.044 to 0.06	0.5 to 2.1%	1.9	Flume data. Sand (d_s = 0.15 mm). W = 0.3 m.
[13]	0.42 to 1.3 L/s	8.9 to 3.5%	0.077 to 0.236	Flume data. Polystyrene or glass (ρ_s = 1030 or 2500 kg/m^3): $d_s = 0.088$ to 1.1 mm. W=0.20 m. d=0.0275 m.

An increase of friction is indeed observed with large particle sizes. RASHIDI et al. [13] investigated particularly the effects of particle size, density and concentration. Their results indicate that the particle density has little effects but the particle size is an important parameter. Large particles (d_s = 1.1 mm) cause an increase in the number of turbulent bursts, an increase of Reynolds stresses and larger friction losses. But small particles (d_s = 0.088 mm) bring about a decrease in the number of wall ejections, Reynolds stresses and friction losses. And these effects are enhanced by the particle concentration. Also LYN [11] highlighted the importance of the ratio of the sublayer thickness over the flow depth and suggested an increase of friction factor for sediment laden flows in shallow waters and for small sediment concentrations. In the case of GUST's [7] experiments, drag reduction ranging from 52 up to 75% are obtained with ratio of sublayer thickness to depth from 3.3 up to 9.2%.

4. COAL-WATER FLOWS

Pipelines are frequently used in mining operations to transport coal slurries. In coal-water flows (CWF), typical coal concentrations could range up to 60%. The addition of dilute polymer enables an increase of discharge capacity and a reduction of the risks of coal plug. Laboratory observations indicate that the structure of CWF includes a central core with large size coal particles and a layer of fluid next to the wall with small coal concentrations and small size particles (fig. 2). With the injection of polymer, the interactions between the polymer macromolecules and these thin coal particles next to the wall are very important.

In a coal-water mixture with polymer injection, the attachment rate between polymer molecules and coal particles, and the ensuing bridging flocculation determine the drag efficiency of polymer additives. With large coal concentrations and polymer concentrations, the rate of particle collision is important. Polymer molecules have a high probability to be attached to coal particles and to induce flocculation, and these molecules will not interact with the turbulent flow structures. As a result the drag reduction effects are reduced with large polymer and coal concentrations. Flocculation must be avoided to obtain a better drag reduction.

Experimental investigations (table II) indicate that : 1- the addition of polymer produces a drag reduction but smaller than for polymer-water solution; and 2- the magnitude of the drag reduction depends upon the polymer concentration and the coal concentration. Indeed, for a given coal concentration, there is an optimum polymer concentration at which drag reduction is maximum (fig. 3). For coal concentrations up to 15%, a polymer concentration of about 150-200 ppm will provide the maximum drag reduction. On figure 3, it is believed that differences between the results of GOLDA [6] and KIM et al. [9] are caused by different experimental conditions (table II).

It must emphasised that the drag reduction depends strongly upon the preparation and the injection process of the polymer solution. The polymer solution must be carefully prepared to ensure that macromolecules have time to relax and reach a flat conformation before the mixing. Further it must be injected at the walls or as close as possible as to the sublayer region.

Table II - Coal-water flow experiments

Ref	U_w m/s	C_s	C_p	Comments
(1)	(2)	(3)	(4)	(5)
[6]	0.3 to 2.3	2.9 to 15.2%	0 to 440 ppm	Pipe (Ø 0.04 & 0.25 m). d_s = 0.5 mm. ρ_s = 1390 kg/m^3. Polymer : polyacrylamide Separan AP45.
	1.6 to 4	13.6%	0 to 100 ppm	Pipe (Ø 0.25 m). d_s = 1 & 8 mm. ρ_s = 1598 & 1634 kg/m^3. Polymer : polyacrylamide Sepaflux CE5174.
[9]	3.35	0, 5 & 10%	50 to 400 ppm	Pipe (Ø 9.8 mm). d_s = 40 µm. ρ_s = 1417 kg/m^3. Polymers : polyethylene oxide & polyacrylamide.

Note : C_s : mean coal concentration

5. FREE-SURFACE AERATED FLOWS

In high-velocity open channel flows, free-surface aeration occurs when the turbulent boundary layer becomes fully developed (fig. 4). Downstream of the inception point of air entrainment, air bubbles, entrapped at the free-surface, are diffused downwards. When the air reaches the bottom of the channel, the air bubbles interact with the shear layers next to the bottom. The re-analysis of model and prototype data [3, 4] shows clearly a reduction of the flow resistance which can be expressed as :

$$\frac{f_e}{f} = 0.5 * \left(1 + \tanh\left(0.628 * \frac{0.514 - C_e}{C_e * (1 - C_e)}\right)\right) \qquad (1)$$

where C_e is the mean air content.

Drag reduction is observed also by injecting micro-bubbles in turbulent boundary layer flows (see review in [4]). In free-surface aerated flows and in bubble-modified boundary layers, an air concentration boundary layer is observed next to the bottom with bubble sizes less than the millimetre. Such bubbles behave as rigid spherical particles and block the development of turbulent bursts. Further the presence of bubbles next to the invert increases the effective of the mixture and the sublayer thickness. Both processes induce a substantial drag reduction.

It is worth mentioning a series of gas-liquid lubrication experiments performed in Soviet Union [2]. Continuous gas injections were used to reduce skin friction in a liquid boundary layer below the hull of river barges. Drag reduction is caused by a continuous air film developing along the hull and forming a thin lubricating film. Measurements were performed on both models and prototypes with low velocities (e.g. 0.5 to 0.7 m/s on models, 1 to 1.5 m/s on prototype). Model tests indicated total drag reduction of 10 to 20%. Full-scale tests of river barges showed measured reduction in total drag of about 10 to 20%. Note that there is no information on the stability of the ventilated cavity with higher vessel speeds.

6. CONCLUSION

This paper reviews several cases of drag reduction observed in hydraulic flows. In each case, the reduction of the flow resistance is caused by the interactions between small-size particles and turbulent structures next to solid boundaries.

In sediment-laden flows, drag reduction is observed with micro-particles (e.g. clay, silt, sand) and in absence of sediment deposition (e.g. rising flood flows).

In coal-water flows, drag reduction is obtained with polymer additives. But the interactions between the polymer molecules and coal particles affect greatly the drag reduction efficiency. With coal concentrations up to 15%, polymer concentrations of about 150 to 200 ppm provide the maximum drag reduction.

In free-surface aerated flows, the presence of air bubbles next to the chute invert modifies the structure of the turbulence in the sublayer and can cause substantial drag reduction.

It must be emphasised that further work is required to obtain a better understanding of the complete mechanisms of drag reduction. For example, the prediction of drag reduction in suspended-sediment flows is still somewhat of an art.

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Fig. 1 - Observations of drag reduction in sediment-laden flows

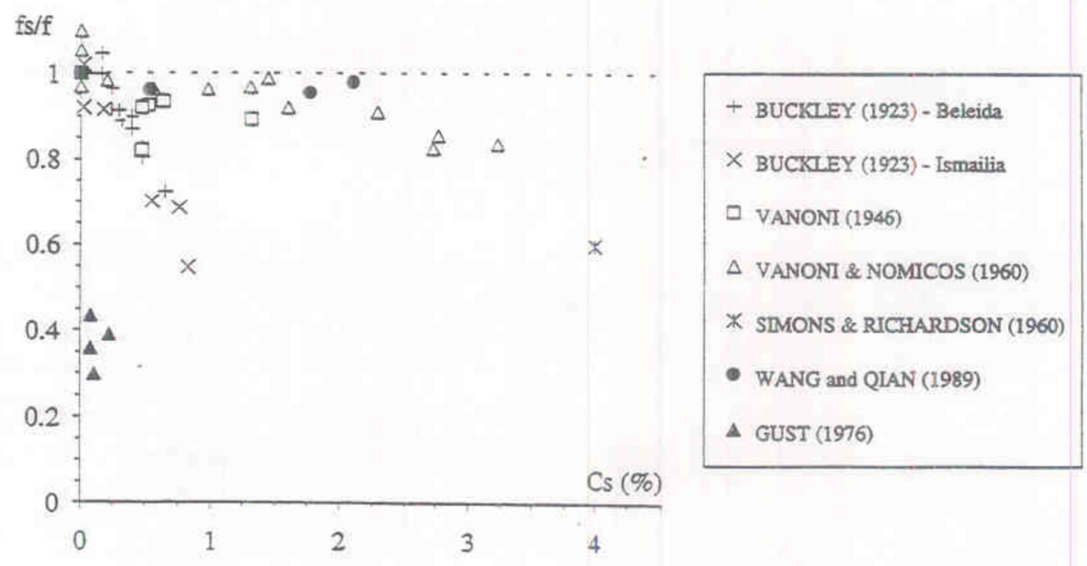


Fig. 2 - Typical structure of Coal-Water Flow in pipes

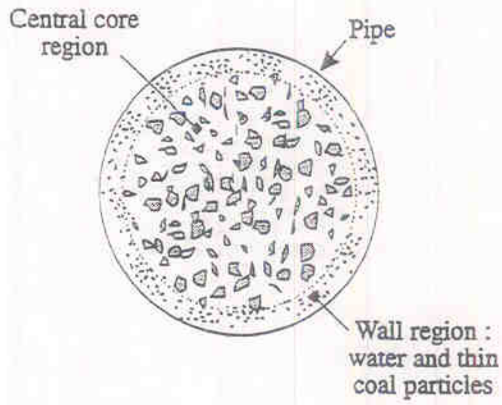


Fig. 3 - Drag reduction versus polymer concentration

	U_w (m/s)	Ø (mm)	d_s (mm)	Polymer
GOLDA	0.9	40.6	0.5	PAA
KIM et al.	3.35	9.8	0.04	PEO

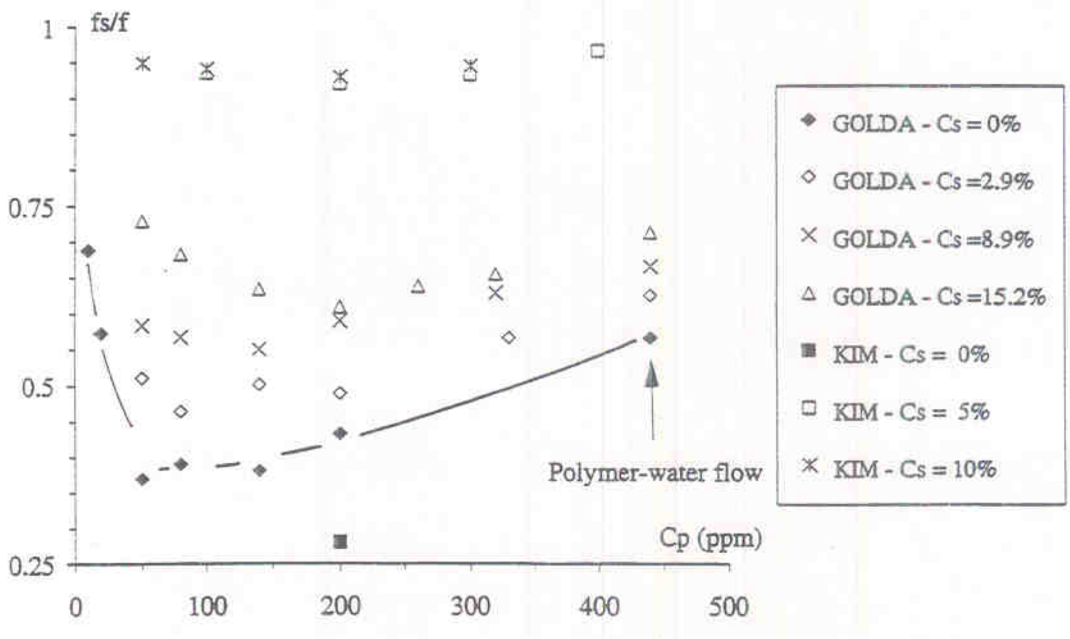
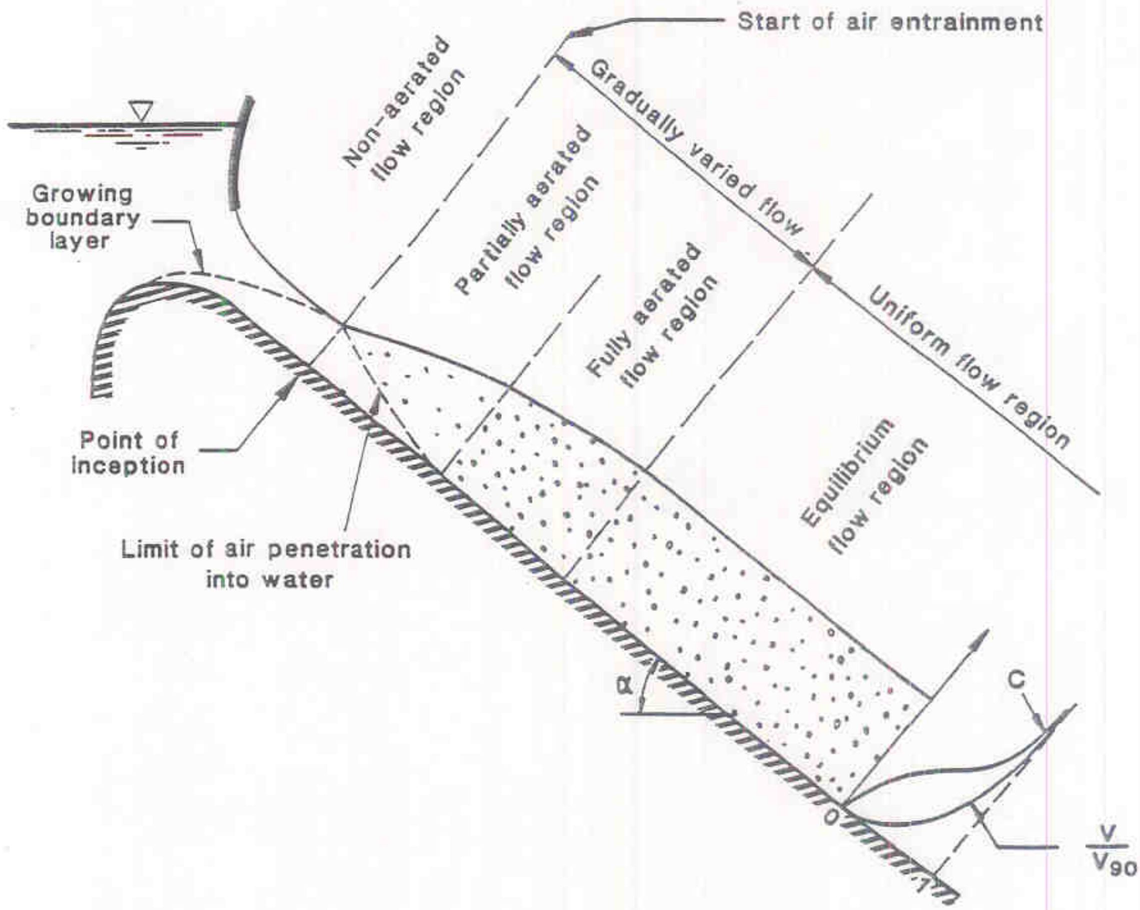


Fig. 4 - Free-surface aeration along a chute spillway



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