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Experimental study of drag reduction in flumes and spillway tunnels

Ying-kui WANG*, Chun-bo JIANG

State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, P. R. China

Abstract: Experiments in an open flume model and spillway tunnel model were carried out using drag reduction techniques. Two drag reduction techniques were adopted in the experiments: polymer addition and coating. The drag reduction effect of a polyacrylamide (PAM) solution and dimethyl silicone oil coating were studied in the flume model experiments, and the results were analyzed. Experiments were then carried out with a model of the Xiluodu Hydropower Station, the second largest dam in China. In order to reduce the resistance, the spillway tunnels were internally coated with dimethyl silicone oil. This is the first time that these drag reduction techniques have been applied to so large a hydraulic model. The experimental results show that the coating technique can effectively increase flood discharge. The outlet velocity and the jet trajectory distance are also increased, which enhances the energy dissipation of the spillway tunnel.

Key words: *drag reduction; hydraulic model experiment; spillway tunnel*

1 Introduction

Laboratory experiments constitute an effective method for investigation of complicated hydraulic problems, especially for large hydropower projects. Most experiments are carried out with physical models, which are built according to different similarity criteria. If the physical model is based on the Froude similarity criterion, roughnesss dissimilarity may occur in some model experiments. The roughness coefficient of material can affect the frictional head loss, especially for a long-distance flood discharge structure such as a spillway tunnel. In some hydraulic models, the surface is not smooth enough, which can lead to inauthentic experimental results. The investigation of drag reduction techniques is necessary for large hydraulic models, but there has been little previous research on this issue.

Drag reduction has been studied for almost 60 years. Early in 1948, Toms discovered the phenomenon of drag reduction when adding small amounts of dilute high polymers to the fluid (Toms 1948), which is why it was called the Toms effect. Subsequently, Meyer (1966), Virk (1971), Lumley (1969, 1973), Gordon (1970), Donohue et al. (1972), and Berman (1986)

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*Corresponding author (e-mail: *wangyk06@mails.tsinghua.edu.cn*)

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made many contributions to the understanding of this problem. Early experiments emphasized statistics of turbulent flow, such as the velocity profile (Virk 1971), and the change of the molecular structure of high polymer (Bewersdoff et al. 1986). Shah et al. (2006) set up an experimental system to study the effect of drag reduction using polymeric fluid with different concentrations, and obtained satisfactory results. Although direct numerical simulation (DNS) has also been used to study this problem (Li et al. 2006; Jovanovic et al. 2006; Sher and Hetsroni 2008), the experimental studies have continued over the last 60 years. Experimental studies can provide more supportive data and helpful information so that advanced research can progress.

Another drag reduction technique is adding an inner coating to the flume or the tunnel. This technique has been widely used in oil and gas transportation and navigation (Cai et al. 2008). Related research has been carried out by oil companies on their transport pipes, including the Zeepipe submarine pipeline and the Alliance pipeline. The internal coating technique may provide 5% to 20% drag reduction (Lin et al. 2002), increasing the transfer efficiency of the pipe so that it is more economically beneficial. However, little research has been conducted on the effect of coating water pipes. Zhu and Wang (2006) compared the drag reduction effect of several coating materials and concluded that dimethyl silicone oil is the most effective common coating material.

In this study, the drag reduction effects of the techniques described above were studied in flume model experiments. The investigation also included the application of the coating technique to a large hydraulic model, the first attempt of its kind. The effect and characteristics of the drag reduction techniques were discussed and analyzed, and the results demonstrate their application prospects.

2 Experimental setup

In hydraulics, the frictional resistance relates to water head loss, which is often called frictional head loss (h_{f}). The well-known formula for calculating the frictional head loss is the Darcy-Weisbach equation:

$$h_{\mathrm{f}} = \frac{\tau_0 l}{\rho g R} = \lambda \frac{l}{4R} \frac{v^2}{2g} \tag{1}$$

where l is length (m), R is the hydraulic radius (m), v is the average velocity (m/s), g is the gravitational acceleration, τ_0 is the shear stress, ρ is the fluid density, and λ is the resistance coefficient. When drag reduction techniques are applied, the resistance coefficient decreases, so the relative drag reduction (D_λ) can be defined as

$$D_\lambda = \frac{\lambda_{\mathrm{w}} - \lambda_{\mathrm{p}}}{\lambda_{\mathrm{w}}} \times 100\% \tag{2}$$

where λ_{w} is the resistance coefficient without any drag reduction technique, and λ_{p} is the resistance coefficient with a drag reduction technique.

The experiments were carried out in an open channel flume system, which is a water-circulating system. Water is forced up to the top tank by a pump from a pool at the lower end, and, after the water is stabilized in the tank, it flows into the flume. The flume is made from a piece of organic glass that is 11 m long, long enough to allow uniform flow to form and the placement of five point needles to measure the water depth. The width and height of the flume are 0.14 m and 0.25 m, respectively. At the middle of the flume there is a tackle that can lift or lower the flume in order to change the slope. The design of the experiment is shown in Fig. 1.

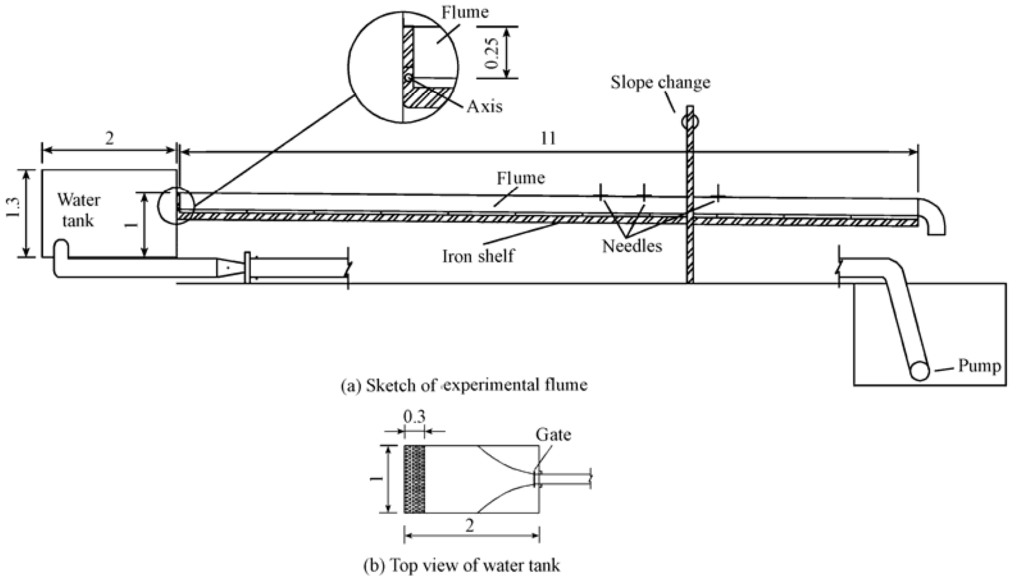

Fig. 1 Drawing of experimental model structure (Unit: m)

In this study, polyacrylamide (PAM) was used as the high polymer addition. It has been widely used in previous drag reduction experiments. In the coating experiment, the coating material was dimethyl silicone oil, whose efficiency has been verified by Zhu and Wang (2006).

3 Experimental results of polymer addition

It is well known that energy loss is not a constant value in turbulent flow. Thus, experiments must be conducted under varying conditions. In engineering practice, the Moody diagram is most widely used to modify the resistance coefficient λ (Yen 2002). Therefore, the experimental results were compared with the resistance coefficient curve of smooth pipe in the Moody smooth surface, as shown in Fig. 2, where i is the flume slope.

Generally, the resistance coefficient curve of smooth pipe in the Moody diagram shows that λ decreases as the Reynolds number (Re) increases. The tendency of the experimental results is reliable as compared with the resistance coefficient curve of smooth pipe in the Moody diagram. The results show that λ increases along with i. The variation tendencies of λ with change in Re and i can be explained by the following formula:

$$\lambda = 2g\frac{4Ri}{v^2} = 2g\frac{(4R)^2 i}{v^2 Re^2} \tag{3}$$

where ν is the kinematic viscosity. Eq. (3) shows that the tendencies of the experimental results are coincident: λ increases along with i and decreases as Re increases.

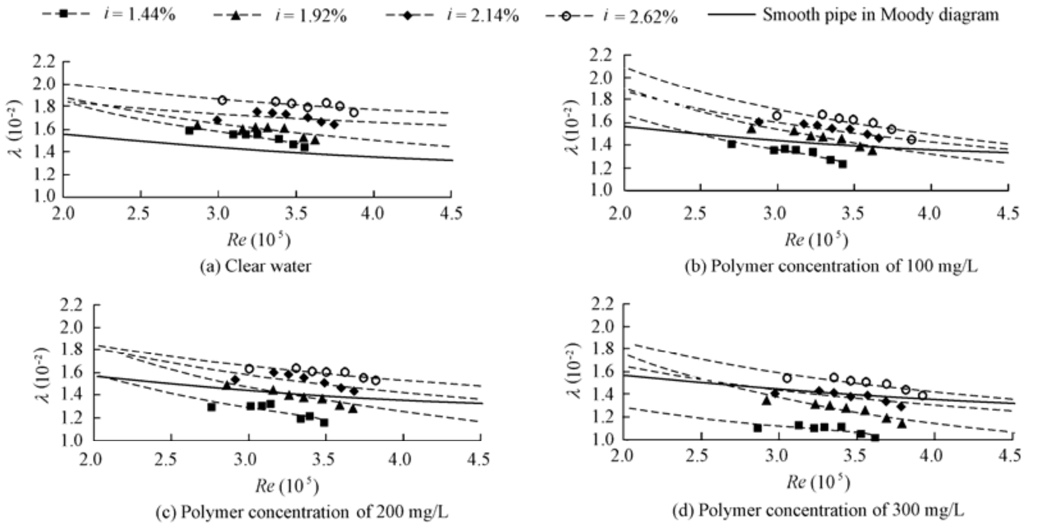

Fig. 2 Variation of resistance coefficient λ with Reynolds number Re for four polymer solution concentrations

As shown in Fig. 2, the ranges of λ are 1.30×10^{-2} to 1.85×10^{-2}, 1.24×10^{-2} to 1.80×10^{-2}, 1.16×10^{-2} to 1.63×10^{-2}, and 1.02×10^{-2} to 1.54×10^{-2} when the polymer solution concentration is 0 mg/L, 100 mg/L, 200 mg/L, and 300 mg/L, respectively. The experimental results show that the polymer PAM reduces the drag. The range of the resistance coefficient is much smaller with a higher polymer solution concentration, which means that the drag reduction effect is greater when the solution concentration is also greater.

In the experiments, the relative drag reduction (D_λ) is not constant; it varies with Re and i. Fig. 3 compares D_λ with different flume slopes when the PAM concentration is 300 mg/L. The ranges of D_λ are 14.65% to 17.32%, 13.21% to 15.60%, 12.05% to 13.99%, and 10.71% to 13.05% when the flume slope is 1.44%, 1.92%, 2.14%, and 2.62%, respectively. In short, D_λ is mainly influenced by the solution concentration and less influenced by the flume slope. In this experiment, the largest D_λ was 17.32%, obtained when the concentration was 300 mg/L and i = 1.44%.

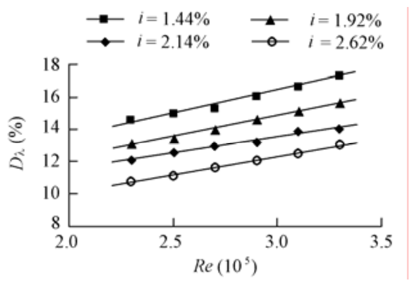

Fig. 3 Comparison of D_λ for different flume slopes with 300 mg/L polymer concentration

4 Experimental results of coating technique

The drag reduction technique of coating has been applied in engineering practice, but there has not been an experimental study in a water flume. In order to verify the drag reduction effect of the coating technique, model experiments were carried out. The experimental results are shown in Fig. 4 and Fig. 5.

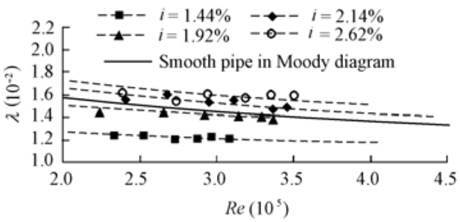

Fig. 4 Variation of resistance coefficient λ with Reynolds number for coating technique

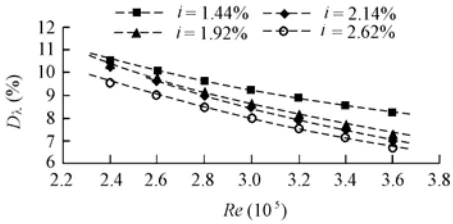

Fig. 5 Comparison of D_λ for different flume slopes with coating technique

The results show that the variation of λ has the same tendency as the resistance coefficient curve of smooth pipe in the Moody diagram, which means that the results are reliable. The coating technique provides an apparent drag reduction effect. The average value of D_λ is 8.18% and the maximum value is 10.6%. The D_λ value decreases as Re increases, which means that the turbulence intensity of the flow can weaken the effect of drag reduction. The value of D_λ shows little variation with the increase of i, which means that the drag reduction effect is stable. Meanwhile, the coating technique also has advantages in initial cost, implementation, and technology. These advantages make it widely applicable in engineering practice.

5 Model experiment for hydropower station

5.1 Design of experiments

Most experimental studies on drag reduction have been performed in a small water flume, which differs from real engineering situations. In a real project or a large hydraulic model, the flow pattern is complex and the parameters of the flow pattern are changing all the time. It is difficult to use the experimental results from a small-scale model in engineering practice. It is therefore necessary to carry out drag reduction experiments with large physical models; the results can provide more reasonable suggestions for solving real engineering problems.

A physical model of the Xiluodu Hydropower Station, which is under construction in southwestern China, was built. The dam's height is about 278 m. There are four spillway tunnels for flood discharge, which are all 14.0 m × 12.0 m at the cross-section and all over 1 600 m in length. The hydraulic model includes the upper reservoir, the double curvature arch dam, the spillway tunnels, the stilling basin, and the lower reaches, as shown in Fig. 6. The original purpose of drag reduction in this model was to make the roughness of the model similar to that of the prototype. The geometric scale of the model is 1:100, and the Manning roughness coefficient *n* needed for the model is so small that the application of drag reduction techniques is required.

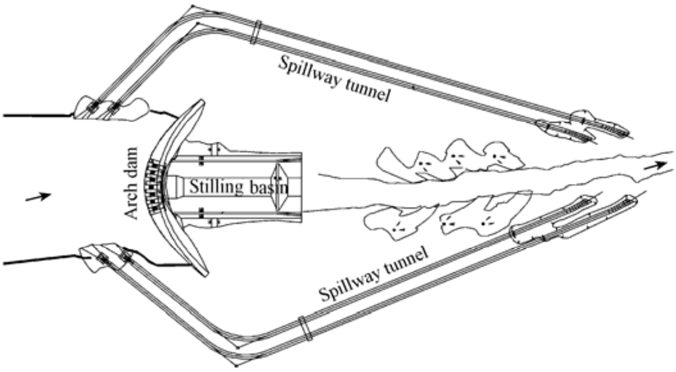

Fig. 6 Sketch of hydropower station model

As demonstrated in the discussion above, the polymer addition and the coating both provide significant drag reduction. However, the advantages of the coating technique make it more suitable for its application in large hydropower project models. Therefore, the coating technique was used for drag reduction, with dimethyl silicone oil as the coating material. Experiments were carried out to compare differences in the outlet velocity and the jet trajectory distance. Both are related to the flood discharge and the energy dissipation, and can be considered an evaluation of the drag reduction.

5.2 Experimental results of hydraulic model

5.2.1 Outlet velocity

The outlet velocities of four spillway tunnels were measured under different conditions. Since the four velocities were almost the same, the average velocity values are shown in Fig. 7.

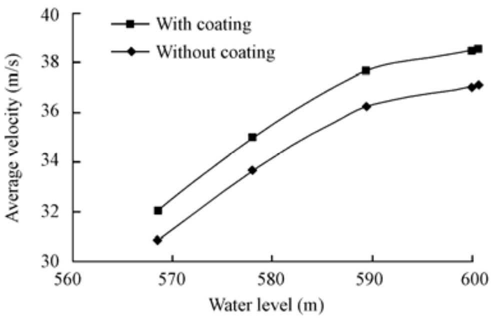

Fig. 7 Comparison of outlet velocities with and without coating

The results show that the outlet velocities increase significantly when the coating technique is applied, and the increment percentage ranges from 3.8% to 4.0%. That means that the coating technique is effective for drag reduction in a large hydropower model. The coating technique enhances the flood discharge of the spillway tunnel. Therefore, the drag reduction technique can be readily used in large hydraulic models, and also applied in engineering practice.

5.2.2 Jet trajectory distance

When the hydropower station discharges the flood, sufficient energy dissipation is necessary. The jet trajectory distance results are shown in Table 1.

Table 1 Comparison of jet trajectory distances with and without coating

Spillway tunnel	Jet trajectory distance without coating (m)	Jet trajectory distance with coating (m)	Difference (m)	Percent difference (%)
1#	209.2	214.6	5.4	2.6
2#	216.2	220.1	3.9	1.9
3#	194.8	198.9	4.1	2.1
4#	188.7	194.0	5.3	2.9

The results show that the jet trajectory distances were increased by 1.9% to 2.9% when the coating technique was applied.

The drag reduction experiments were carried out for the spillway tunnel model, and the coating technique had significant effects. The flow discharges, outlet velocities, and jet trajectory distances confirmed the stability and efficacy of the coating technique.

6 Conclusions

These drag reduction experiments demonstrate the effects of polymer addition and coating techniques. The drag reduction effects are significant both in the flume model and the spillway tunnel model. The conclusions are as follows:

(1) When using the polymer addition technique, the relative drag reduction increases mainly with the PAM concentration. The relative drag reduction increases with *Re* and decreases as the flume slope increases. The largest relative drag reduction value is 17.32% when the PAM concentration is 300 mg/L with a flume slope of 1.44%.

(2) The experiments that used the coating technique obtained drag reduction. The D_λ value is larger for smaller flume slopes; its maximum value is 10.6%. The relative drag reduction value stays almost constant as *Re* changes, which indicates stability of the drag reduction effect when the coating technique is used.

(3) The drag reduction experiments were carried out with a spillway tunnel model. With a complex flow pattern, the effect of drag reduction was confirmed by the flow discharge, outlet velocity, and jet trajectory distance. The experimental results show that the coating technique enhances the flood discharge and energy dissipation of the spillway tunnel, as well as the capacity for safe operation of the entire hydropower project.

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