Drag Reduction in Pipes Lined with Riblets

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Abstract

IN the present paper, experiments are reported establishing a maximum drag reduction of 5-7% in fully developed turbulent flow of water through 25.4 - and 50.8-mm-diam pipes lined with a film of grooved equilateral triangles of base 0.11 mm. The maximum reduction occurs when the height of the riblets is 11-16 wall units. This correlates well with the Taylor microscale of the fluctuating velocity gradient.

Contents

There is a large body of literature about drag reduction using riblets in turbulent boundary-layer flow over flat plates. Some of the earliest and more important results were obtained by Walsh.[1-3] He showed that drag reduction could be obtained when the height of the riblet structure expressed in wall units $S^+ = Su^*/\nu$ is below 30; the maximum of 7-8% occurred when S^+ is about 15. Here S is the height and base of the riblets, u^* the friction velocity, and ν the kinematic viscosity. Walsh also found that triangular grooves are among the most effective in reducing drag.

Less is known about the effect of riblets on drag reduction in pipe flow. Nitschke[4] studied airflow in a pipe with rounded peaks and flat valleys machined into the pipe surface. A maximum drag reduction of 3% was measured using pressure drop measurements over a length of 120 pipe diameters. Drag reduction was obtained when the riblet spacing was between 8 and 23 wall units, with the maximum in the neighborhood of 11-15.

The test section of our experimental apparatus consisted of two pipes in series: the test pipe and the control pipe. The test pipe was lined with 0.11-mm riblet film, whereas the control pipe was either a smooth PVC pipe or a pipe lined with smooth film. The flow was fed by a gravity-feed tank, which maintained a constant head of 11.6 m. The water flowed from the head tank first through a 7.6-cm (3-in.)-diam pipe, then turned in a 15.2-cm (6-in.) elbow toward the test sections. The large elbow helped to damp unwanted eddying before the flow entered the test section. The distance to the test section was 2.13 m (7 ft), or $84d$, where d is the pipe diameter. This large L/d ratio appears to suffice for achieving fully developed flow. We say that a flow is fully developed if it gives rise to a linear pressure gradient and passes the interchange tests discussed in the paragraph following Eq. (3).

The two pipes that constitute the test section were in series, each equipped with four pressure taps at equal distances. A flow meter was placed downstream from the test section, and a gate valve, to control the flow, followed the flow meter. Both the flow meter and the gate valve were located far enough from the test section to avoid any backflows or any effects on the pressure measurements.

Flow rates, pressure drops, and temperatures of the water were measured during the experiments. The pipes used were PVC, smooth, 50.8 mm (2 in.) and 25.4 mm (1 in.) in diameter, and 3.05 m (10 ft) long. For technical reasons only 1.5 m were lined with film in the 25.4-mm (1-in.) case and 2.4 m in the 50.8-mm (2-in.) case. The fabrication of good pressure holes was the most demanding part of the project. Poor holes lead to incorrect measurements. The pressure holes made in the unlined pipe have sharp corners and are free of burrs. It was more difficult to get good holes in the lined pipes. Counter pressure from inside the pipe was applied when drilling to prevent the film from separating from the PVC. After drilling with an end mill, the holes were trimmed of film debris and reamed with a dentist's end reamer. They were repeatedly trimmed with the reamer until constant pressure gradients were achieved.

We shall designate the Darcy friction factor by

$$f = \frac{\Delta P}{\rho g} \frac{2g}{U^2} \frac{d}{L} \tag{1}$$

where ΔP is the pressure drop over the length L of pipe, g gravity, d the pipe diameter, and U the average flow velocity. An effective riblets diameter was defined by

$$d_r = \sqrt{\frac{4A}{\pi}} \tag{2}$$

where A is the cross-sectional area of the pipe lined with riblets.

The measured values of the friction factor for the smooth unlined pipes and the pipes lined with smooth film were compared with the values given by

$$f = \left[1.8 \log_{10}\left(\frac{Re}{6.9}\right)\right]^{-2} \tag{3}$$

where the Reynolds number $Re = \mathrm{d}U/\nu$, which is an excellent approximation of Prandtl's formula for the range of our experiments. In computing Re, the measured values of the volume flow rate Q and the various diameters were used. There was found to be quite good agreement, with average differences of about 1% and a maximum difference of about 3%.

During the experiments, one section was smooth (lined or unlined) and the other lined with riblets. Each experiment was carried out twice but with test sections interchanged. In other words, the first time, the smooth pipe was downstream with the riblet pipe upstream and, the second time, the riblet pipe was downstream and the smooth pipe upstream. The purpose of the interchange was twofold. First, it insured that our data was repeatable. Second, it insured that both sections were in the fully developed turbulent-flow region, since the pressure drop was not affected by the position of the pipe.

The comparison between drag in smooth pipes and pipes lined with riblets is shown in Fig. 1. In these experiments, S is fixed but S^+ varies. The data do not determine a lower limit for drag reduction, although suggesting that the limit must be around $S^+ = 3$. The largest value of S^+ for which drag reduction was achieved is approximately 23. After this, at larger speeds with $S^+ > 23$, riblet linings lead to a drag increase.

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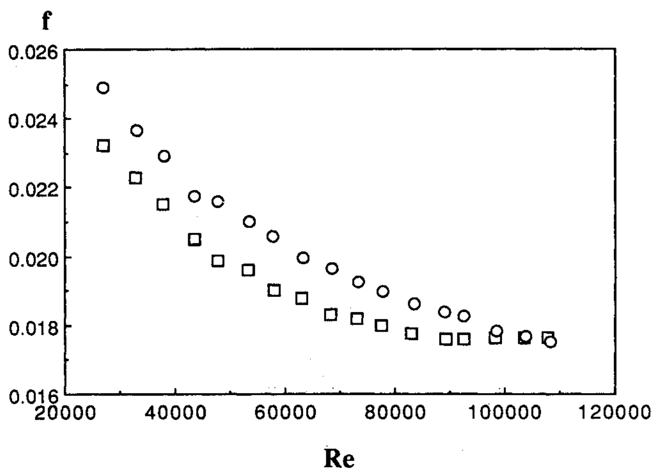

Fig. 1 Comparison of the measured values of the friction factor in the section with the smooth film with the 25.4-mm-diam pipe lined with riblets: □, riblet film; ○ smooth pipe.

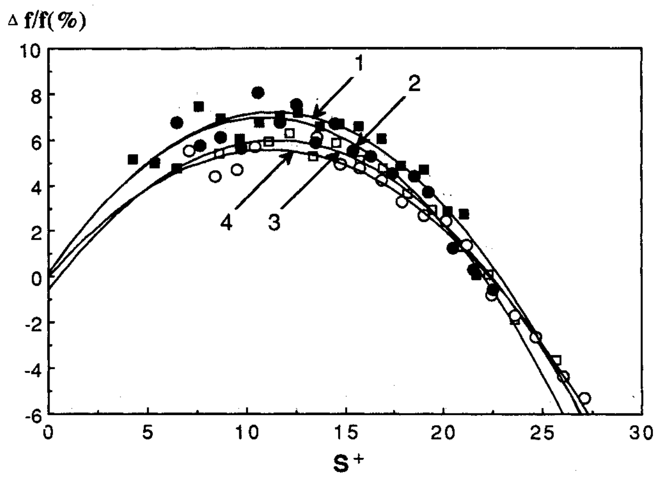

Fig. 2 Percent drag reduction due to riblets: line 1, 25.4-mm pipe lined with smooth film, ●; line 2, 50.8-mm pipe lined with smooth film, ■; line 3, 25.4-mm smooth unlined pipe, ○; line 4, 50.8-mm smooth unlined pipe, □.

Nearly identical results have been reported by Nitschke[4] in study of airflow in pipes with grooved walls.

The maximum drag reduction occurs for $S^+ \approx 11 \sim 13$ (see Fig. 2), in excellent agreement with previous investigations for pipe flow and boundary layers. The maximum drag reduction was 5–7%.

It seems not to have been noted before[§] that the Taylor microscale λ in the spanwise direction, determined from the quadratic approximation of the correlation function

$$R_{xx}(z) = 1 - z^2/2\lambda^2 \tag{4}$$

where x is the streamwise and z the spanwise coordinate, gives rise to $\lambda \sim S^+$, where

$$\lambda^2 = \overline{u_y^2} \Big/ \overline{\left(\frac{\partial u_y}{\partial z}\right)} \tag{5}$$

This microscale can be viewed as a spanwise correlation length for the fluctuating wall shear stress on smooth walls. Finnicum and Hanratty[6] have shown that the data from the experiments of eight different authors give rise to $\lambda = 12 \pm 2$.

Remarkably, this λ is also near the value of S^+, which maximized drag reduction with riblet linings in our experiments and in all the many other experiments on drag reduction due to streamwise grooves. Perhaps this is a striking result, both for drag reduction and the determination of important scales for sublayer turbulence. Certainly, the appearance of the same correlation length, about 12, in two groups of many experiments of very different types ought not to be dismissed out of hand. It is also of interest that maximum production of turbulent energy $-uv\mathrm{d}U/\mathrm{d}y$ peaks at $y^+ \sim 15$ in fully developed pipe and channel flows[7] and that the minimum spanwise distance between sensors that is required to sense structure in turbulence is reported to be 11 wall units.[8]

§Falco[5] appears to be the only other reference to mention Taylor microscales and drag reduction. He relates the microscales to pocket scales (his Fig. 17) and the pocket to riblet scales, without recognizing the importance of the spanwise microscale or the values $S^+ = 12 \pm 2$. The pocket scales do not correlate with drag reduction.

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